THE ECONOMIC VALUE OF GEOLOGIC EXPLORATION
AS A RISK REDUCTION STRATEGY
IN UNDERGROUND CONSTRUCTION

by

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(1981)

SUBMITTED TO THE DEPARTMENT OF CIVIL
ENGINEERING IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
DOCTOR OF PHILOSOPHY

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 1984

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DEC 27 1984
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Submitted to the Department of Civil Engineering on
June 30, 1984 in partial fulfillment of the
requirements for the degree of Doctor of Philosophy.

Abstract

Subsurface exploration is the most important strategy for reducing the
impact of geologic uncertainty on the cost of underground projects. The
timing, amount and reliability of the exploration observations, as well
as the methodology for allocating the geologic risk, play a crucial role
in determining the design philosophy and construction methods to be
adopted by the engineer and the contractor. This study examines the
effectiveness of exploration in general, and pilot tunnels in particular,
as the principal means for reducing design conservatism and construction
contingencies, given the contractual sharing of the geologic risk and
based on the opinions of practicing engineers and contractors.

The owner's financial decision problem to invest in the best exploration
program is presented, and possible solution approaches are suggested. In
order to quantify and compare the economic value of pilot tunnels, or any
exploration method, a detailed model based on a Markovian representation
of the geology and on the "threshold probability" decision rule is
developed. This model is implemented as a computer-based, decision
support system for the analysis of the expected value of sampled
information (EVS1) of alternative exploration programs and applied to a
specific case study. Given a description of the project's geologic
characteristics and the allocation of risks between the participants to
the contracts, this system enables the designer and the owner to evaluate
several exploration alternatives according to their effectiveness in
decreasing the project's cost, and to determine the best exploration
strategy.

Thesis Supervisor:  Herbert H. Einstein
Title:  Professor of Civil Engineering
To

Ioanna, Irene and George
Acknowledgements.

During the five years I spent at MIT I have been very fortunate to meet and work with many people whose interest, understanding and friendship have made my stay a very pleasant experience. In particular, I would like to express my sincere gratitude to the following people whose help has been instrumental towards the successful completion of my graduate studies:

- Professor Herbert Einstein for his sincere dedication, commitment and guidance in developing this research. His high standards and strive for excellence have been the driving forces behind this work. His interest, help and kindness in solving my research and personal problems are deeply appreciated.

- Professor David Marks for providing me with all the moral and physical support I could ever ask for. His availability, friendship and guidance in every aspect of my academic life is something that few people can match.

- Mr. Fred Gross for providing me with the most valuable resource in conducting this research. I never have received so much support from a person I know so little. "Lively" will always be remembered as a prime example of help and goodwill beyond the call of duty.

- The engineers and contractors participating in this research for their cooperation and generous contribution of time.

- Mrs. Connie Choquet for her friendship, care and support during my career as an instructor, for proofreading, typing and editing this thesis and for being so patient and understanding in sharing the same office with me. It's unfortunate that the good times with Mac and the boys have to end.

- Professor David Ashley for supporting me as a faculty advisor, a thesis supervisor and a good friend. His belief in me is greatly appreciated.

- Professors Robert Logcher, Ray Levitt and Henry Irwig for their interest, advice and friendship.
- Andreas Kridiotis for the exceptional plots and for the inspiring "pilots".

- Bill Nuttle for his constructive comments and for the "good ones" we have had while watching the traffic on Mass. Ave.

- My good friends Yeong, Massimo, Nabil, Gino, and Dimitris for their sincere interest and friendship.

- My wife Ioanna and our children Irene and George for their love and patience. It is time to make up for the lost time.
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Chapter 1

INTRODUCTION.

1.1 General.

Tunneling is a form of civil engineering construction carried out in an uncertain and frequently hostile environment and relying on the application of special knowledge and resources. As a result, the planning, design and construction of underground facilities is a process that encompasses many risks and uncertainties\(^1\) affecting all project participants. Most of these risks are direct consequences of the following aspects that typically characterize underground construction:

- The uncertainty in the nature of the project's geology, and its repercussions on technical optimality and cost effectiveness of the adopted design and construction methods.

- The project's organizational, contractual and environmental complexity.

The ground is the principal construction material, supplied by nature and seldom to the specifications that engineers or contractors would choose. Methods of construction are highly dependent on the ground and costs are a function of the rate of advance. An encounter with unforeseen ground conditions not only imposes large extra costs but may

\(^1\)For the time being, the term "risk" is defined as uncertainty about the occurrence possibility of an event, which, if it occurs, may lead to loss or injury. Throughout this report, the terms risk and uncertainty are used as substitutes for each other. The theoretical reasons for their equivalence are discussed in section 2.1.
also introduce additional hazards. Although similar circumstances may exist in other types of heavy construction, it is unusual for the difficulties to be so severe or the effects so acutely felt as in underground construction, where difficulties are unavoidably compounded by the limited and restricted access to working faces (CIRIA Report, 1979). As a result, the ground, more than any other single factor, determines the nature, form and cost of tunnels (Deere et al., 1969). Great importance therefore has to be attached to subsurface exploration, which is the best means for determining the properties of the ground relevant to site selection, the final design, the selection of tunneling methods and the estimation of production and cost. Crucial preconstruction decisions like the ones concerning the project layout, the excavation method to be adopted, the initial support and the design of the final lining are strongly influenced by the expected behavior of the ground and as such present a need for the best geologic information input possible. Otherwise, the project cannot be expected to evolve into a system that strikes a balance between economy, safety and performance. The degree to which this objective is accomplished is a direct function of the amount and quality of information available to the contracted parties and hence of the type, the timing and the intensity of the exploration program adopted. The latter is one of the basic means for risk reduction in underground construction and is the general subject of this research.

The importance of geologic uncertainty is also affected by the type, intent and administration of the contracts set forth for the project's design and construction. This is especially true because in most cases
the prevailing ground conditions have a marked influence on the interpretation of the contract and the progress of the work. Schedule delays, outstanding claims, costly legal advice, inequitable settlements and arbitration are all too often the outcome of prolonged or unresolved contractual disputes about ground conditions, which impair the satisfactory and economic completion of many tunneling projects. The object of conflict often centers on what the parties to the contract understand the tunneling conditions to be before the actual construction commences, as compared to the conditions actually encountered. Inadequate subsurface exploration programs coupled with the use of special contractual conditions, or disclaimers, are bound to give rise to such disagreements.

In addition to technical or contractual, geology-related risks, underground construction is also confronted with "institutional" risks. Major underground projects are typically of such physical and economic magnitude that they normally require the adoption of large and complex organizational and contractual structures. It is not unusual, for example, to have multiple design and construction contracts in a single project, where all the parties involved must continuously interface and coordinate their work. This aspect creates a need for efficient interorganizational communications for the prompt dissemination of information, and above all a rational and clear assignment of authority and responsibility complemented with a fast and fair dispute settlement procedure.

Typically, the main participants in underground construction are the owner entity (owner), the engineering design firm (designer) and the
construction firm (contractor). These entities, however, do not interact in a vacuum. Large urban projects usually affect the day-to-day operations of the local communities for a considerable amount of time. The affected public and its representing agencies react to this disruption by imposing external constraints on the available design and construction alternatives. Not only has the impact of these constraints increased recently, but in addition, their nature and timing can be quite unpredictable.

As expected, all the above factors contribute in establishing underground construction as one of the riskier undertakings in civil engineering today.

1.2 Underground Construction Risks.

To illustrate the wide spectrum of risks affecting the delivery process of underground construction, some of the most important risks are summarized below. This list is by no means complete. Typically, each project is associated with its own unique characteristics making a universal generalization far from possible. In order to identify some of the principal underlying causes, however, individual contractual risks have been identified and classified according to their source or consequences. These include, but are not limited to (Abrahamson, 1973):

1. "The physical work

   - Physical conditions:

   * naturally occurring conditions of the ground
* water (both subsurface and from surface flooding)
* ground gases and vapors

- Artificial conditions causing obstruction:
  * pipes and services
  * wells, pits, shafts, boreholes, etc.
  * contaminated ground
  * quarries - abandoned, existing and refilled
  * effects of mining subsidence

- Defective materials or workmanship of contractor

- Defective materials, workmanship or design by nominated subcontractor

- Costs of tests and samples.

2. Delay and disruption

- By owner or engineer giving late possession of site
- Late working drawings, instructions, etc.
- Contractor's inefficiency, plant breakdown, etc.
- Nominated subcontractor's inefficiency
- Delay outside both parties control
- Labor disputes.

3. Direction and supervision

- Incompetence
- Inefficiency
- Unreasonableness
- Partiality
- Omission's from, and misleading descriptions in the bill of quantities
- Defective design of temporary or permanent work.

4. **Damage and injury to persons and property**

- Due to negligence of contractor in designing or building temporary work, building permanent work, or otherwise
- Due to negligence of engineer or owner in design or otherwise
- Due to nominated subcontractor's negligence
- Due to matter's outside the parties' control but which are insurable
- Due to uninsurable risks - war, usurped power, etc.
- Consequential losses arising from an insurable event.

5. **Shortage of resources**

- Shortage of staff, labor, plant, materials, time or finance.

6. **Government policy**

- Taxes, labor, safety or other laws
- Delay or refusal of planning approval for project work, or temporary work, or contractor's arrangements
- Financial constraints
- Energy and pay restraints.

7. **Conflict**

- Cost of war, civil commotion, malicious damage, intimidation, etc.

8. **Payment**

- Devaluation
- Delay in settling claims and certifying
- Delay in paying certificates
- Insolvency of contractor, nominated subcontractor or owner
- Funding constraints
- Shortcomings resulting from the measure and value process.

9. Inflation

- Any element of cost not covered by a price escalation clause
- Replacement cost of plant and equipment.

10. Arbitration and law

- Delay in resolving disputes
- Injustice
- Uncertainty of result due to lack of records, unfair or ambiguous contract, or inefficiency of legal process
- Costs of obtaining decision."

Even though the above list includes most of the risk categories affecting underground construction, it unfortunately fails to provide some indication of each category's significance. In addition, some of the most important construction risks that have been identified during the course of this research have either been too briefly alluded to, or have not been pointed out at all. In particular, these risks are:

- The ground's behavior (as opposed to its nature) with regard to different excavation and support processes.
- The support's adequacy for short- and long-term stability.
- The productivity of labor and equipment under different geological conditions and excavation-support processes.
- The availability of on-site space for surface operations and for the storage of materials and equipment.
- Site accessibility for mobilization, the availability of dump roads, dumpsites and restrictions in hauling.

- The necessary actions and timing for the protection of adjacent structures and/or the relocation of utilities.

- The consequences of delays in meeting current and future multicontract construction interface milestones in the project's schedule, that are caused by other contractors under previous contracts.

- The nature and timing of the constraints imposed by the public on the project's design and construction alternatives (as opposed to established laws and procedures by governmental agencies).

- The actions necessary to prevent damage to the environment beyond the current provisions of the law.

It is worth noting that most of the above risks are either directly or indirectly related to the main underlying random variable: the project's geology. This is particularly true for all the risks associated with the direct construction cost items, such as excavation and support. In addition, the influence of geologic uncertainty extends to other issues, such as the amount of changed conditions claims and the resulting litigation, the protection of adjacent facilities against damage, construction progress and multicontract scheduling, etc. Consequently, it is generally agreed that the reduction of geologic uncertainty should have top priority in every underground project.

1.3 Problem Statement.

1.3.1 The General Problem.

There is a growing awareness that the present high cost of underground construction in the US prevents this country from enjoying
the many advantages that subsurface structures can afford. In contrast, other countries have, by determined effort, cut the cost of many underground facilities to a level competitive with surface alternatives (Lane, 1975). In fact, US transit rail systems have been estimated to cost three-to-five times as much as comparable European systems (Dallaire, 1976).

The reason behind the disparity between the state of the industry in the US, as opposed to that of Europe or Japan, can be found in the approaches used for managing the technical, contractual and organizational risks of underground construction (risk-reduction, risk-sharing). The objective of risk-reduction, risk-sharing strategies is to decrease the uncertainty on the likelihood of the risks' outcomes, to decrease the probability of extreme outcomes and to redistribute the risk impact between the project participants in an optimal manner. It presently appears that other countries not only have identified these strategies, but in addition they have also been successful in their implementation.

Past research has shown that the designer and the contractor, the entities responsible for the physical implementation of a project, are very sensitive to their perception of what the impacts of such risks may be on their organization (Levitt et al., 1979; Ioannou, 1980; Qaddumi, 1981). In particular, designers have adopted the strategy of "defensive engineering" (Kuesel) or "design conservatism" and contractors have been accused of including large contingencies in their bids, or of resorting to excessive claims litigation over "changed conditions".
Cost effectiveness should be one of the main objectives of any owner of an underground facility. Cost effectiveness, however, cannot be achieved unless the issues of risk mitigation are examined and new strategies are adopted.

Several research projects undertaken at M.I.T. have attempted either directly or indirectly to look into some of the above issues. The complexity and the magnitude of the problem along with the reality of how changes in philosophy and practice can be adopted by the tunneling industry, have dictated a staged approach of looking at individual segments of the problem, one at a time.

Past research at M.I.T. and elsewhere has examined the following related topics:

- The merits of the observational or adaptable design/construction as compared to conventional practices (Salazar, 1983; Tse, 1979).

- Improvement of current contractual practices between owner, designer and contractor (NAS, 1974; Stasiewicz, 1981).


- Field evaluation of advanced subsurface exploration methods (Thompson et al., 1980).

- Methodology for analyzing the allocation of risks in underground construction (Levitt et al., 1979).

- Modelling subsurface geologic conditions (Baecher, 1972; Chan, 1981).
1.3.2 The Specific Problem. Research Tasks.

On a global level, the risks faced by an underground project may be considered as competitors for resources in a limited time and budget process. Fortunately, there is a consensus among all researchers and project participants that reduction and/or sharing of the uncertainty in subsurface conditions should receive top priority. In this spirit, and in conformance with the strategy of segmenting the general problem, the major focus of this research is the decision on the employment and use of a pilot tunnel as an alternative in subsurface exploration.

In order to achieve its goal, this research investigates how exploration reduces the uncertainty on the nature of a project's geology and its behavior with respect to different design and construction alternatives and how this reduction in uncertainty results in the owner's benefit given a particular risk sharing arrangement (contract). Furthermore, this research examines the general decision making environment in underground construction and the influence of institutional factors on the willingness of the participants to make full use of the subsurface information available.

In order the analyze the usefulness of pilot tunnels as an exploration strategy (in comparison to other exploration methods) the following issues will be examined:

1. Prediction of geologic conditions.

   - Identification of the set of geologic parameters used for the design, construction planning and cost estimating of underground projects.
- Degree of accuracy in geologic parameters, required by current design, construction planning and estimating methods.

- Inference methods for establishing the probability of parameter states outside a pilot tunnel, or between location-specific observations.

- The reliability of the observations made in a pilot tunnel in comparison to the reliability of other exploration methods, and the effect of the pilot tunnel dimensions (relative to the size of the final opening) in forming geologic predictions.

2. Pilot tunnels as predictors of design performance.

- Experimentation and validation of different design approaches.

- Reliability of transferring design approaches from the pilot tunnel to the final main opening.

- The willingness to use pilot tunnels as design experiments under current contractual and legal conditions and their effect on design conservatism.

- The optimum timing for the construction of a pilot tunnel.


- The reliability of transferring observations on ground behavior from the excavation and support of a pilot tunnel to the construction of the main opening.

- The usefulness and reliability of the information provided by the excavation and support of a pilot tunnel in planning and estimating the construction of the main opening.

4. Pilot tunnels as mitigators of latent construction problems.

- Use of pilot tunnels for first-round testing of the specific "external" constraints that the main project will face (e.g. blasting vibrations, no blasting at night, routes and site for muck removal, etc.).

5. Pilot tunnels as an integral part of construction.
- Use of pilot tunnels for dewatering, grouting, excavating (blasting) and presupporting the main opening.

6. The role of pilot tunnels in the contractual and legal domain.

- Contractors' willingness to use the pilot tunnel information under current contractual and legal practices.

- The effect of the adoption of a pilot tunnel on the interpretation of the "differing site conditions" clause in the event of claim arbitration or litigation.

Most of the above issues are directly related to the organizational and contractual approaches for allocating the geologic risk between the owner, the designer and the contractor. As a result, this research examines some of the basic risk reduction/sharing approaches, and discusses how individuals and organizations react to the amount of risk they have to bear. This discussion is also necessary in order to present a strategy for the rational allocation of risks, that can help in improving the delivery process of underground construction. These recommendations are subsequently contrasted to the typical procedures used in current US practice, by presenting and discussing the delivery process of underground construction projects from the planning phase to construction. This presentation is aimed to illustrate the motivation of each party and the sometimes conflicting objectives that may exist.

Most importantly, this research examines the issue of the "optimum" exploration program and the possible methodologies that may be applied for the comparison of the economic value of different exploration alternatives. For this purpose, two models for the evaluation of different exploration programs are developed, which can serve as decision aids to either the designer and/or the owner in comparing specific
exploration alternatives. The first model can be used to determine the expected value of perfect information (EVPI) on "ground class extents", while the second can be used to quantify the expected value of sampled information (EVSII) associated with any exploration method. The latter model has been implemented as a computer-based decision support system, an application of which is illustrated in this report.
Chapter 2

Review of Risk Reduction/Sharing Strategies.

At a general level, this study explores the cost implications of risk and risk-sharing in underground construction. Any form of geologic exploration is indeed aimed at reducing the uncertainty on the project's geologic conditions and consequently of its cost impact to each participant entity.

As a result, it becomes necessary to present the definition and the nature of risks, the mechanism of risk pricing, and the procedures for reaching optimal risk reduction/sharing strategies. These would serve as background material for presenting the state of the industry and the recommendations of this research.

To this effect, this section will:

- Define risk and uncertainty, comment on their differences, and argue that both terms are equivalent under the subjective school of statistical inference.

- Explain the mechanism of risk pricing.

- Use the differentiation between controllable and uncontrollable risks to propose a rational strategy for risk allocation between the project's participants, based on the principle that controllable risks induce better performance if borne by the controlling party.

- Present the possible strategies for the reduction of construction risks in general.

This discussion essentially forms the theoretical foundation for structuring the methodology that should be used in evaluating the merits of subsurface exploration methods.
2.1 Risk vs. Uncertainty.

Classical, frequency-based, statistical theory differentiates between the notion of uncertainty and the notion of risk (Farrar, 1962). Although both risk and uncertainty refer to a situation in which event outcomes are imperfectly known, the two terms imply different knowledge about the decision maker's state of information on the underlying probabilistic process.

A situation is said to be characterized by risk, only if the probabilities of alternative possible outcomes can be estimated through "objective" sampling. To qualify as a risk situation then, an experiment must be repetitive in nature and must possess a frequency distribution from which observations can be drawn and about which inferences can be made through the use of frequency-based, statistical procedures. Virtually any of the contingencies against which insurance can be drawn may be classified as risks (to the insurance company but not necessarily to the insured).

As an example, consider a situation where the decision maker has to guess the color of a ball drawn from an urn. The situation would be characterized as a risk, when:

- either the number of different colored balls in the urn is known (perfect knowledge of the population),

- or, the experimenter is allowed to draw balls and observe their color a large number of times before the "crucial" draw takes place (a large sample is available).

In contrast, uncertainty is said to be present when the experiment in question cannot be replicated by (or upon) other persons, or at other
times or places; that is, when the situation is "unique". The frequency
distribution of the underlying random variable cannot be estimated
"objectively". This is undoubtedly the setting in which most of the
decisions concerning underground construction take place.

Returning to the urn example above, suppose that the urn in question
is itself drawn (randomly) from a large (and unknown) urn population in
which each urn contains a different mixture of colored balls. The color
of a ball drawn from the chosen urn is a situation characterized by
uncertainty if:

- The experimenter knows nothing about the urns' population or
  their contents (no information on the process).

- The experimenter is allowed to sample a "small" number of times
  (maybe once or twice) from a small number of urns (maybe one or
two) without any guarantee that the urns sampled are
representative of the one chosen for the main experiment (small
sample-non uniform population). Imagine the experimenter's
surprise if the sampled urns contain only black and white balls
whereas the urn for the main experiment contains blue and
yellow balls!

From the above examples, it is important to notice that the two
terms, risk and uncertainty, merely imply a difference in the amount of
information available to the decision maker at the time an experiment
takes place. According to the classical definitions presented, any
situation conceptually begins as an uncertainty, and can be transformed
to a risk through sampling, provided that the sample is "large". These
definitions, of course, lead immediately to the questions:

- What is a large sample?

- How is available (but not experimental) information treated?

In the urn situation, for example, how many times must the
experimenter be allowed to sample before the situation is transformed from an uncertainty to being a risk? If the experimenter is allowed to take a brief look at the contents of the chosen urn, how can he then formally use such imperfect and highly subjective information?

The school of "subjective" statistical theory founded by Bayes and Laplace provides an answer to the above questions by defining probability as a "personal degree of belief" on which a decision maker is prepared to base his actions (Benjamin and Cornell, 1970). This definition of probability allows the direct use of subjective judgment in statistical inference. In simple terms, this is accomplished by abandoning the notion that the parameters of a probability distribution are fixed, unknown constants. If the underlying random variable follows a known distributional form, the complete specification of which requires the estimation of n unknown parameters, then the decision maker can use all the information that he may have accumulated from past experience to subjectively assess n probability distributions, one for each parameter.² By using Bayes theorem, these "prior" parameter distributions are subsequently updated, given the new sample information, to give the "posterior" distributions. If the decision maker has no reason to believe that the random variable of interest follows a particular

²If the decision maker has no information whatsoever about the parameters of the distribution then he can simply specify a uniform distribution over the domain of the parameters' feasible values; this is known as a "vague prior". In this case, the parameter estimates for both the "subjective" and the "frequentist" approach are identical, because no use of subjectivity is being made.
distributional form, then he can assess its distribution directly\(^3\) (Spetzler, Stael von Holstein, 1972). Bayes theorem can then be used to update the random variable's distribution directly. Thus, the form of the posterior distributions on a process' parameters depends mainly on the prior distribution (which is highly "subjective") and the "likelihood" of the observed data (which is "objective"). As a result, there is no need to differentiate between risk and uncertainty; under this school of thought, both cases are completely equivalent since their only difference is the "relative proportion" of the subjective and objective information available. This proportion of the two kinds of available information does not affect the methodology for producing inferences about the probabilities and the outcomes of an experiment, be it classified as a risk or an uncertainty. Differentiating between the two does not serve any particular cause (Raiffa, 1970; Howard, 1970).

This is the approach adopted in this research. A large portion of the information available in underground construction comes from expert judgment (since tunneling is a prime example of an entrepreneurial undertaking). The use of sound expert judgment in underground construction is probably "the" determining factor between a successful and an unsuccessful project; this is especially true in the cases where a comprehensive exploration program is not adopted. As such, it must be

\(^3\)Although it has not yet been practiced or even well studied, it is also possible to identify a set of possible models and to assign subjective probabilities on the likelihood of each one being the correct choice. This approach introduces another level of updating and does not differ conceptually from the base case where the distribution is assumed to be known (Benjamin and Cornell, 1970).
used formally in any decision support model.

In conclusion, the terms, risk and uncertainty, will be used as substitutes for each other; differentiating their meaning would only serve to obscure the real issues, without serving any useful practical purpose.

2.2 Risk Pricing.

This section deals primarily with the basic ideas of Decision Theory that are necessary for understanding the behavior under risk of the entities involved in underground construction. A simple example will be used to introduce the reader to the pertinent concepts and terminology.

Assume a situation where a decision maker is faced with the option of "buying"\(^4\) the following gamble (lottery, risk). A ball will be drawn at random from an opaque urn that contains 2 red balls and 6 blue balls. The decision maker will pay \(H\) dollars if the drawn ball is red and \(L\) dollars if the ball is blue. The question then is, "What is the minimum amount of money that the decision maker would accept as a fee, in order to agree to participate in this lottery?". This is a simplified version of a contract involving risk.

This question cannot be answered unless one makes specific assumptions about the decision maker's preference for money under

\(^4\)In this context, the word "buying" does not necessarily mean that the decision maker will pay a certain amount of money for participating in the lottery; whether he will pay or receive money depends on the \textit{algebraic} values of the outcomes.
conditions of uncertainty. This is the domain of Utility Theory. The assumptions of this theory can be found in a multitude of publications (Raiffa, 1970; Howard 1970; DeNeufville and Stafford 1971) and will not be presented here.

In the context of this discussion, it will be assumed that the decision maker's preference for money can be completely described by his "utility" curve. Moreover, since most individuals and organizations behave in a risk averse manner this curve will be assumed to be concave (i.e., its second derivative is negative).

A utility curve maps the dollar payoffs of a lottery (X) to an artificial ordinal measure of preference called utility (U(X)). For the example above the payoffs are H and L and their utility is U(H) and U(L). The answer to the above question then, according to utility theory, is that the decision maker should be indifferent between facing the lottery or paying an amount CME (the Certainty Monetary Equivalent) such that the utility of CME equals the expected utility of the lottery:

\[ U(\text{CME}) = p \times U(H) + q \times U(L) \]

where: 
\[ p = \text{Probability of paying } H = .25 \]
\[ q = \text{Probability of paying } L = .75 \]

If the decision maker were risk neutral or equivalently possessed a utility curve which is a linear function of the attribute (in this case, money) then the CME would equal the Expected Monetary Value of the lottery, EMV:

\[ \text{EMV} = p \times H + q \times L \]

The difference between the CME required by a risk averse decision maker and the EMV required by a risk neutral individual is called the
Risk Premium, RP:

\[ RP = CME - EMV \]

The risk premium represents the amount of money that the decision maker includes as part of his fee (or, as protection) because of the very fact that he is risk averse. The more risk averse he is, the more his utility curve deviates from a straight line, and the more he demands as a risk premium.

There are two interesting features of risk aversion that are relevant to the general exploration problem at hand and must be discussed here. The first is the issue of the relative difference between the lottery's outcomes, H-L, and the second is the issue of decreasing risk aversion as a function of the decision maker's asset position.

By appropriately choosing the payoff outcomes, it is quite easy to construct several lotteries that have the same EMV and the same branch probabilities. In this respect, it can also be easily proven that as the difference between the lottery's extreme outcomes increases, so does the risk premium (even though the lottery's EMV remains constant). This phenomenon is very pertinent to tunneling; the less is known about the project's geology, the more extreme events become probable and are explicitly considered by both the designer and the contractor in establishing their policies (the design assumptions and the bid contingencies). Geologic exploration is indeed aimed at reducing the gap between the best and worst conditions that may exist at any particular
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point along the alignment of the project. As a result, the amount of geologic exploration conducted prior to construction, should be in inverse relation to the conservatism imbedded in the design and the contingencies charged by prospective contractors. The same argument can also be used for predicting the behavior of the designer and the contractor as a function of the contractual risk they have to bear. Contracts that allocate the risk of extreme events to either of these two parties (assuming a certain constant level of geologic information) result in inflated "risk premiums" in much the same way as an insufficient exploration program. Thus, the effectiveness of risk reduction through exploration is contingent on the risk sharing arrangement, and as a result, both strategies must always be evaluated in parallel.

The second issue related to risk pricing, that is relevant to underground construction, deals with the phenomenon of "decreasing risk aversion" (Raiffa, 1970). In the brief discussion above, and for that matter in most publications, the assessment of the CME of a lottery, is accomplished by taking the expected value of the utilities of the lottery's outcomes, and then inverting the utility function. In doing so, however, one makes the sometimes crucial (and usually implicit) assumption that, either the level of wealth that the decision maker

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5 This statement should not be confused with the spatial variability of the geology along the alignment of the project. Obviously, exploration cannot change what has already been determined by nature.
possesses when facing the lottery is irrelevant⁶, or that the utility
curve was constructed taking into account the decision maker's asset
position at the time he would face the lottery. It is common knowledge,
however, that both the utility of the lottery's outcomes and the required
risk premiums are usually in inverse relation to the decision maker's
asset position. The same individual may accept a certain lottery when
having a high asset position and may refuse it if his asset position
declines. This phenomenon also holds true in reverse, and this is the
more interesting case. As the lottery's outcomes become large in
comparison with the asset position of the decision maker, the required
risk premiums increase.

It is not uncommon for underground project costs to run in the tens
or even hundreds of million dollars, sometimes one or two orders of
magnitude larger than the net worth of either the designer or the
contractor. Given that it is also not uncommon for project costs to
overrun cost estimates, even by 400% (Straight Creek Tunnel), it becomes
evident that the mechanism of decreasing and sharing the geologic risk
will always have a most profound effect on how a project will be designed
and how much it will eventually cost.

Even though these observations may seem elementary and very close to
being common sense, they have not received the deserved attention and
implementation. The reason is not that the industry is unaware of the

⁶Mathematically equivalent to assuming that the decision maker's
utility is either linear or exponential.
above issues, but rather that their adoption and implementation has been delayed by contractual and institutional problems. In addition, the problem is compounded by the absence of a widely accepted decision making methodology that would permit the quantification of alternatives and thus the rational establishment of risk mitigation strategies.

2.3 Controllable and Uncontrollable Risks.

The definitions of the terms "risk" and "uncertainty" and the conclusion that the two terms are equivalent under the school of subjective statistical inference have already been presented. These definitions, however, are not particularly helpful in developing a rational strategy for risk allocation. For this purpose, it is useful to define two other types of construction risks, controllable and uncontrollable.

Uncontrollable risks are defined as "random variables whose underlying distributions do not depend on the actions of any of the parties involved in sharing the risk." Examples of uncontrollable risks are:

- A project's geologic conditions (profile)
- Weather conditions
- The future market price of steel, etc.

Controllable risks are defined as "random variables whose distributions depend on the actions of at least one of the parties sharing the risk." Controllable risks usually represent variations in
human performance that can be controlled through better management. Examples of such risks are:

- The number of design errors and omissions
- Labor productivity
- Material wastage rates, etc.

Some risk categories can be considered to be a combination of controllable and uncontrollable risks. Worker accident rates, for example, are affected by the safety program instituted by management, but also depend on the occurrence of random events that are beyond management's control (for example, the unexpected flooding of a tunnel). In such cases, the risk can be subdivided and redefined so that the resulting variables can be accepted as pure controllable or uncontrollable risks (accident rates if flooding occurs and accident rates if no flooding occurs).

2.4 Rational Assignment of Risk, Risk-sharing.

When a risk eventuates in construction a loss may result - no matter whose responsibility7 it is. The purpose of defining a risk in nature, extent and liability is so that planning, safety and financial provisions

7Responsibility is distributed according to interpretation of the physical conditions and the terms of the contract. Uncertainty as to liability can arise because of failure of the contract documents to define the areas and incidence of risk and the boundaries of responsibility between the parties to the contract. Reduction of this uncertainty is achieved by contracts that are explicitly drafted (CIRIA Report, 1979).
can be made. The definitions of controllable and uncontrollable risks serve the purpose of establishing a general principle for the rational assignment of risk between the project's participants. This principle is closely related to the organizational cause-effect axiom of matching authority with responsibility.

In general terms, the principle for the rational assignment of risk states that:

- Controllable risks should be shared by the parties influencing the risk outcomes. Controllable risks, by their very nature, can thus motivate better performance from the influencing party and therefore provide an incentive value. In particular, it is suggested that a contracting party should bear a risk if:

1. "The risk is due to the contracting party's willful misconduct or lack of reasonable efficiency or care.

2. He can cover a risk by insurance and allow for the premium in settling his charges, and it is most convenient and practical for the risk to be dealt with in this way.

3. The preponderant economic benefit of running the risk accrues to him.

4. It is in the interest of efficiency to place the risk on him.

5. If the risk eventuates, the loss falls on him in the first instance, and there is no reason under the four above headings to transfer the loss to another" (Abrahamson, 1973).

- Uncontrollable risks should be borne by the party initiating the influence of the risk on the project; i.e., the owner. These risks by definition represent pure gambles to the bearing party and do not provide any incentive value.

Any risk mitigation strategy, aimed at reducing the total cost of underground construction, should then attempt to:
- decrease the uncertainty on the risk's outcomes, no matter whether the risk is controllable or uncontrollable (risk reduction),

- allocate the impact of the remaining risk and the cost of risk reduction between the project participants so that:

  * the incentive value of controllable risks is preserved,

  * the sum of the risk premiums required by the parties sharing the risk is minimized (i.e., allocation of uncontrollable risk).

These general statements can be clarified further if one considers the mechanism of risk pricing. Both the designer and the contractor price the risk they have to bear (be it controllable or uncontrollable) by either including contingencies (or risk premiums) in their fees, or by adopting defensive strategies (conservative design and construction methods). In either case, the owner is charged with a direct or indirect risk premium that represents the difference between the value (or cost) attributed to the risk by the designer or the contractor and the risk's true expected value (or cost). Risk premiums are direct functions of the degree of risk aversion of the party bearing the risk, as well as the ability of this party to absorb losses (or equivalently the risk's magnitude in comparison to the party's assets). This is the principle on which all forms of insurance are based.

From a total risk premium optimization viewpoint, one can safely argue that risks should be shared in such a way so that the total of the risk premiums charged is minimized. This is certainly valid for uncontrollable risks. In the case of controllable risks, however, one must also take into account the "incentive to perform" value of the risk.
In the particular setting of underground construction, with designers and contractors undercapitalized relative to the risks they face, the risk premiums charged by these parties should be higher than those acceptable to the owner (who should typically be less risk averse). The owner should also bear in mind that he will eventually end up paying whatever the designer or the contractor charge as risk premiums in their fee structures, irrespective of the risk outcomes; i.e. if the worst risk outcomes do indeed occur, the owner may be faced with "changed conditions" claims and thus pay twice for the same thing. In general, however, the owner should not bear all the risks. A portion of the controllable risks must still be borne by the influencing party (the designer or the contractor). The objective is not to minimize the sum of the risk premiums but rather to minimize the bottom line, that is, the total cost of the project to the owner.

The above observations constitute the theoretical background for the rational assignment of risk. In principle, if all risks could be broken down into a set of controllable and uncontrollable risks, one could envision conditioning all controllable risks on specific outcomes of uncontrollable risks (like the worker accident rates risk mentioned earlier). One could then attempt to allocate the conditional controllable risks to the influencing party in an optimal manner. Such an approach, however, is practically impossible due to the resulting complexity of the contractual arrangement, the tight interrelationship between risks and the difficulty of monitoring and resolving cause and effect relationships between outcomes. A typical example in tunneling involves the amount and cost of the initial support required. The amount of support required is
basically a function of the prevailing geologic conditions, the project's characteristics (size, use, location, etc.) and the excavation method and its effect on the stability of the rock. Even if the bidding schedule includes quantities and unit prices for support items based on every conceivable combination of geologic conditions (a questionable assumption), the fact still remains that the contractor:

- has responsibility for the project's safety and short-term stability and thus he can (to a certain extent) assess a different support need because of unpredicted ground behavior,

- can decrease the ground stability through improper excavation (deliberately or not),

- may stand to gain (because of bid unbalancing) if large quantities of heavy support are installed (in the name of safety).

As a result, it is very difficult to distinguish to what extent the support installed is actually necessary, and how much of the ground's weakness is due to the contractor's inexperience or incompetence during excavation. It is even more difficult to establish that the bid prices reflect the true estimate of the cost and that the contractor has not unbalanced his prices.

One should also keep in mind that the optimum risk sharing arrangement depends on the risk aversion of the particular parties involved. Since construction contracts are usually prepared before the contractor is selected, the use of negotiation in reaching Pareto optimality in risk sharing is eliminated. Nevertheless, it is important to keep these basic observations in mind while contemplating the structure of any risk mitigation strategy.
2.5 Mitigating Risks, Risk-reduction.

Closely coupled with the strategy for the optimal sharing of risk is the complementary strategy of risk reduction.

In the closing comments of the section on risk vs. uncertainty, it was mentioned that the distinction between the two terms is the amount of information available on the risk's underlying probabilistic process. In any decision problem, risk reduction is a strategy concerning both the amount of information available on a particular risk (before a decision is made), as well as with the timing of the decision itself.

A risk (or uncertainty) can be thought of as a random variable possessing a certain probability distribution that is uniquely defined by the specific values of its parameters. The risk's process is completely defined if both the distribution and its parameters are known.

In practice, of course, this is rarely the case. Decision makers have to resort to statistical inference in order to determine both the risk's distribution and its parameters. At first, it is customary to assume the general nature of the risk's distribution (if data on the risk are available, the choice of the distribution can be judged through "goodness of fit" tests). Statistical estimation, then, deals primarily with the assessment of the parameters of the assumed distribution, as well as with testing the distributional form itself. This process involves the use of judgment and the collection and compilation of data.

With respect to the latter, it is important to emphasize that in some cases a risk may represent an event that has already occurred (e.g.
a coin has already been tossed; the outcome exists, but the decision maker does not know what it is). In this case, it is much more important to the decision maker to get information on the specific outcome of the risk (the top face of the tossed coin) rather than to estimate the parameters of the generating process (the probability of heads). This distinction is made here because it is of particular importance in geologic inference as explained below.

Given these observations, a risk reduction strategy can have any of the following objectives:

2.5.1 Reducing the Uncertainty About the Parameters of the Risk's Process.

This is the basic strategy for reducing the impact of a risk whose specific outcomes cannot be controlled or identified a priori. An example would be future material prices. One can gather information on the process by observing material prices in the past, estimate the process's parameters and construct a model that predicts what such prices will be in the future.

2.5.2 Reducing the Uncertainty about the Specific Outcomes of the Risk.

This is the strategy applicable to risks whose outcomes are already predetermined, but not exactly known at the time a decision is to be made. Geologic conditions would be an example of such a risk. The geology of the project, even though unknown exactly before construction commences, is nevertheless predetermined by nature. What is important about this risk is assessing the outcomes of the process that generated
the geology, and not its parameters. The latter would be of great interest to geologists but much less important to practicing engineers.

Geologic exploration is indeed aimed at identifying the location specific geologic conditions as they explicitly exist at the site. This, of course, does not imply that inferences on the underlying geologic process are not required; on the contrary, such inferences are the only means for extrapolating away from direct observations. As a matter of fact, the models for the evaluation of exploration programs proposed by this research are based on the adoption of particular probabilistic models, whose parameters have to be estimated from the available general and specific geologic information.

2.5.3 Postponing the Decision Influenced by the Risk.

This strategy is closely associated with the above two strategies, and its adoption is basically a matter of economics. In certain cases, a decision can be postponed (at a certain cost) until information about an influencing risk can be revealed through the natural course of events in the project (usually at a reduced cost). This strategy entails trading off the cost of postponing the decision and the reduction in the cost of obtaining information on the risk.

The adaptable or observational approach in geotechnical engineering (pioneered by Terzaghi and used, for example, in today's New Austrian Tunneling Method (NATH)) can be considered as an example of this strategy. Under the adaptable method and based on exploration during the design phase, a set of alternative designs is produced without any
commitment as to the specific design to be used at each point along the project's axis. This decision is postponed and made dynamically during the construction phase when the true geologic conditions are revealed. This strategy is optimized by trading off the cost of exploration during the design phase against the number and nature of the design alternatives that should be considered as possible candidates during the construction phase. To a certain extent, the more exploration is conducted during the design phase, the more suitable the design set will be and the less delays will occur when shifting from one design to another.

2.5.4 Insuring Against the Risk's Outcomes.

A risk can not only be reduced but it can be completely eliminated if it is sold to an outside insurance carrier. Entities that insure many independent risks of the same general nature usually require a smaller risk premium for bearing a risk than the value attributed to the risk by the insured. Examples of this strategy are the errors and omissions insurance purchased by the designer, and the performance bond, worker's compensation insurance, etc., purchased by the contractor.

In the same context, a risk can be eliminated through other means resembling insurance. Prepurchasing and storing of materials for future project use and labor stabilization agreements between the owner and the unions fall into this category.
2.6 Summary.

This chapter has presented the main general strategies for risk reduction. Which is the best for a particular type of risk is a question of economics, feasibility and individual preference.

All the risk reduction techniques entail some cost for reducing the risk's impact. Who will share in this cost and in what proportion is an issue of risk sharing. Generally, the owner should have a share in the cost of any risk reduction strategy since he will be the ultimate benefactor of the resulting savings. Some of the cost, however, especially for controllable risks, must still be borne by the designer and/or the contractor as a means of utilizing the risk's incentive value to perform.

In conclusion, this section sets the foundation for understanding, sharing and reducing the risks involved in underground construction. The principles for risk sharing and the strategies for risk reduction provide the general guidelines for reducing the impact of risks on the total project cost to the owner. Further work remains to be done on the feasibility and relative effectiveness of these methods in order to reduce the high costs currently associated with underground construction.
Chapter 3

The Delivery Process of Underground Construction.

3.1 Introduction.

The delivery process of underground construction can be divided into four general phases: planning, design, construction planning (bidding) and construction. The contents and importance of each of these phases varies from project to project, depending (among other factors) on whether the project is private or public\(^8\). In the former case, the owner is more or less free in adopting the project organization and contract type that is deemed appropriate. In the latter case, the project's delivery process is constrained by the corresponding legislature and by the federal and/or state agencies involved. In addition, the policies and requirements of these agencies change as a function of time depending on:

- who is currently in office, and
- how the need served by a particular project compares to national or local priorities.

As a result, it is very difficult to present a detailed description of each project phase that is pertinent to every project.

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\(^8\)In public projects, for example, the mechanism for project funding is a very important factor because most of the financial burden is carried by a federal agency and not the owner as is the case for private projects. In addition, the procedure and the level at which the federal agency contributes is a function of the type of project involved (e.g. public transit vs. highways).
3.1.1 Project Organizations and Contract Types.

The owner's objectives (i.e. cost, accountability, flexibility for changes, speed of construction, and quality) are fundamental in determining the organizational and contractual structure of a project. In addition, the extent of risk accepted at the outset in achieving any of these objectives is largely determined by the type of contract accepted, as well as by the project organization chosen to carry out the undertaking. Organizational methods may be considered under four headings (Frijlink, 1975):

2. In-house.
3. Project management.
4. Turnkey.

**Conventional:** The owner retains a consulting engineer to represent his interests, as well as to prepare the design and the contract documents, obtain the bids, select a contractor and supervise the work. This is the method most often adopted for underground construction projects, whether the contract is lump-sum, unit-price, or cost-plus-fixed-fee.

**In-house:** The owner uses his staff for the planning, design, preparation of contract documents, appointment of a contractor and the subsequent direction of the project. This method usually adopts one of the types of contract mentioned above.

**Project management:** The owner appoints a firm to direct and coordinate the planning, management, design, procurement, construction
management and commissioning of the project; in addition, the same firm may conduct the feasibility studies and assist in securing financing. The firm prepares and may negotiate contracts with professional and construction firms and manages the construction as the owner's representative. The project management arrangement offers a variety of types of contract and is usually applied to the more complex and larger projects that require and benefit from the skills and experience of large-scale organization and multidisciplinary coordination.

Turnkey: A contract is made with a single company for the design, construction and commissioning of a complete project. Financing the project may also be included. In this case, the owner states his requirements in terms of performance of the finished facility and does not take any responsibility for specifying or measuring the work, thus transferring the risk of designing and carrying out the work to the contractor, usually for a predetermined sum.

Each of the above four methods of project organization provides alternatives for the amount of risk that the owner wishes to carry, the control he may wish to have over the project's cost and the extent of his own participation. The choice of contract also influences the allocation of risks between the parties to the contract. Apart from the obvious aim of constructing the facility the owner may have other aims of great importance in the formulation of his risk philosophy. He may wish to complete the project as quickly as possible, regardless of cost, or as cheaply as possible, regardless of time, or perhaps to complete within a fixed time and/or within a fixed budget. Each of these objectives leads to a different risk policy.
Where time is of essence, priority must be given to immediate access to resources to vary plans as the risks occur without delay and not necessarily in the cheapest manner. If minimum cost is the owner's aim, he must decide whether to pay the contractor to take the risk, or to take the risk himself. Projects to be carried out within rigid budgets often employ contract types that transfer the risk away from the owner.

The types of contract most often used in tunneling may be arranged in a hierarchy dependent on the way they allocate risks (figure 3-1). Contracts where the contractor has the responsibility for the design and construction (i.e. turnkey) and lump-sum contracts allocate little risk to the owner and may be quite appropriate in some cases. On the other hand, the direct employment of the labor force and the elimination of the contractor transfers the whole risk to the owner. In these extreme cases, the allocation of risk is clear and no secondary uncertainty is introduced by vagueness in the contract forms. In most tunneling projects, however, the objectives of the owner can best be served by an intermediate choice of contract. In fact, most of the projects in the US, especially public ones, use the conventional organizational approach and a unit price contract.

3.1.2 Chapter Objectives.

The objective of the following sections is to highlight the important aspects of the background in which the owner, the designer and the contractor have to interact and exercise their decision making. This background is necessary for understanding the motivation and the objectives of each party.
Figure 3-1: Contracts and the Allocation of Risks (CIRIA Report, 1979).
To this effect, and given the variety of organizational forms and contract types presented above, these sections present some of the important issues affecting decision making in underground public construction under current normal practices. This choice is justified by the following observations: Most public projects have a very similar delivery process and thus can serve as a uniform basis for discussion. Typically, the organizational form adopted is conventional, whereby the construction contract is of the unit price type and is awarded based on competitive bidding at the conclusion of the design phase. In addition, most of the criticism concerning inefficiencies in underground construction has been directed towards public projects and their delivery processes. Private projects, on the other hand, enjoy much greater freedom in the development of contract types and organizational structures and thus can bypass some of the problems to be presented; their peculiarities will be discussed on an exception basis.

3.2 The Planning Phase.

Since the decision on adopting a pilot tunnel, or any other major exploration program, is usually made during the design phase, the planning phase will be discussed relatively briefly. This, however, does not diminish the importance of this phase in structuring the engineering decisions and the overall economics of the project.

The importance of the planning phase is threefold: setting project objectives, establishing relations between the components of the task
environment (such as the owner, engineering firms, contractors\textsuperscript{9}, community groups, city, state and federal agencies) and developing the bases for the design and construction processes. In other words, it defines the setting, the constraints and the decision-making domains for both the design and the construction phases that follow.

Probably the most important decisions made during the planning phase (beyond the adoption of the project per se) deal with the topology of the project, that is its vertical and horizontal alignment and the structural sizing of its components. These decisions have the greatest impact on the cost of the facility, because they determine both its magnitude and the nature of its geologic environment; once the project site is chosen, exploration can only serve to further define the details of this environment, but not change it. As long as the project is undergoing its conceptual formulation, the decision makers have the greatest amount of flexibility in exploring alternatives concerning all facets of the project. This is particularly true for public transit projects, where the extensive involvement of third parties in the planning phase makes it next to impossible to change the project's layout, or size, once the planning phase is completed. As a result, the decisions made during the planning phase form the constraints that limit the options subsequently available to the designer towards technical and economic optimality.

Unfortunately, the reality of how decisions are made during the

\textsuperscript{9}In the planning phase and for public projects the contractors can only act as consultants; the construction contracts are awarded after the completion of the design phase.
planning phase (especially for public projects) often leaves much to be desired. In particular, it has been argued that some of the decisions in the planning phase are made by persons who are not experts on tunnel design or construction; furthermore, planning decisions are made on the basis of very limited geotechnical information (Sutcliffe, D'Eramo). A majority of the engineers interviewed in the course of this research supported the above observation and expressed the opinion that in order for the planning phase to fulfill its function in an optimal manner, it has to reflect the technical views of both the designer and the contractor. The latter are usually the most familiar with the details and difficulties of implementing subsurface projects and can pinpoint issues in the form of expected problems and cost suboptimization to the planners.

Most of the problems attributed to the planning phase have been associated with its formal outcome: the project's Environmental Impact Statement (EIS). The topics dealt with in the EIS include the following (Johanning and Talvitie, 1976):

1. Description of the proposed project.

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10. The National Environmental Policy Act requires that any project involving action, permit or grant from a federal agency must be assessed for its environmental impact. The disposal of excavated material, the use of federal land as part of the site operations, the effect on the aquifer level and on the quality of underground water and the water or air pollution caused by either the construction or the operation of the facility, are all factors requiring environmental assessment. Some states, Massachusetts being one of them, require a State Environmental Impact Report for cases that are similarly associated with the state rather than the federal government (Cook).
2. The relationship of the action to land-use plans.

3. The probable impact of the proposed action on the environment.

4. Alternatives to the proposed action.

5. Probable adverse environmental effects that cannot be avoided if the project is implemented.


7. Irreversible and irretrievable commitments of resources if the proposed action is implemented.

8. Comments by other agencies and the public.

In addition, some crucial decisions are made and written into the EIS. The EIS for a public transit project, for example, includes decisions on the exact alignment of tunnels, both vertical and horizontal, the tunnel cross section size, the location of access and ventilation shafts and the location and size of stations (figure 3-2). Given today's legislative structure and the public and political participation in developing the EIS, there is little that subsequent parties can do to change these decisions towards more optimal solutions without drastically increasing the project's cost or delaying the project's schedule. In fact, the rigidity of the EIS has been identified as a major cause of design suboptimality because of the constraints it imposes. In general, the EIS does not serve the purpose for which it was originally intended, that is looking at all the possible alternatives from an engineer's point of view and attempting to optimize the public's benefit. Instead, it has become a quasi-legal document that constrains the engineering decisions. This statement is reinforced by recent attempts by UMTA to limit the EIS to 40 pages (Sutcliffe).


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<td>- Assess cost effectiveness and impact of initial set of alternatives.</td>
<td>- Assess alternative systems/technologies for similar level of performance and lower level of impacts as the preferred alternative.</td>
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<td>- Choice of preferred alternative.</td>
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**Engineering Data on Each Alternative.**

- **System segments**
  - **Physical:**
    - Horizontal Alignment
    - R.O.W. Map
    - Vertical Alignment (Elevation & Grades)
    - Typical Sections
    - Vehicle Technology
    - Station Location and Preliminary Design
  - **Construction:**
    - Methods (tunneling, structural)
    - Resource Demands (material and labor)
    - Sequence of Operations
    - Schedule
    - For Impact Assessment:
      - Equipment
      - Waste - Excavation Disposal
      - Protection of Existing Structures
      - Maintenance of Traffic
  - **Costs:**
    - Construction: labor and materials by major category (structural, mechanical, etc.)
    - Contingency Amount for Design & Management Fees.

**Figure 3-2:** The EIS and Capital Grant Application Process for Rapid Transit Systems (adapted from Qaddumi, 1981).
DECISION GATE: FINAL E.I.S.


Final E.I.S.: Contents
- Description of preferred alternative
- Comments from interested parties
- Modifications in response to comments
- Measures to mitigate adverse impacts
- Alternatives Analysis as Appendix

Engineering Data & Decisions
- Modifications to data presented in draft E.I.S.:
  Segment Sequencing
  R.O.W.
  Alignment
  Stations
  Level of Service
  Supportive Actions (feeder service, parking, etc.)
- Mitigating measures to short-term impacts (construction):
  Protection of existing structures
  (especially historic and public).
  Schedule of Operations (equipment to be used, allowable
  noise levels, etc.)
  Source and Disposal Methods for fill and excavation material.

Changes to the final E.I.S require a revision, official approval from
federal, state and local agencies and a public hearing.

Figure 3-2 (continued).
DECISION GATE: CAPITAL GRANT APPLICATION

Preliminary Engineering

Design: Horizontal Alignment.

Vertical Alignment: Grades and Elevations.
Typical Sections: Structure of tunnel support (options)
Vehicles: Design speed, dimensions.
Station Location, Plan, Section, Access (preliminary).
Preliminary design of control and fare systems.
Project breakdown for subconsultants.
Design Specifications.

Construction:

Sequencing of operations.
Schedule
Tunneling methods
Flow of materials, equipment and manpower.
Project breakdown by major contracts.

Costs: Design - Task breakdown and Fees
Management, Supervision & Reporting (CM)

Construction:
- R.O.W. acquisition.
- Task Costs by Contract.

At this point the contract schedule and costs are fixed for the Federal decision on funding:
- Total Federal Share
- Amount of Annual Grants

Figure 3-2 (concluded).
Another important issue that is mostly applicable to public projects is the mechanism for project funding. The cost for preparing the EIS and the initial exploration program is basically supported by the owner. Usually, federal approval and funding for these projects does not occur before the 30% design level. As a result, the owner has great reservations as to the use of (out-of-pocket) funds for geologic exploration, before a federal commitment is secured. Thus, the most crucial decisions are made on the basis of the least amount of information. This practice, when coupled with the rigidity of the EIS, makes it next to impossible to arrive at a project configuration that is close to the best possible solution; instead, it contributes significantly to today's high cost of underground construction.

Private projects can usually bypass the above problems by incorporating the designer's and even the contractor's input within the EIS. This can be accomplished by either forming the complete project team at the planning phase, or by utilizing the services of engineering and/or construction management consultants from the beginning of the project. In addition, the amount of exploration undertaken is not constrained by a contingent appropriation of funds and thus it can be chosen to accommodate the specific needs of the project.

3.3 The Design Phase.

For the purposes of this research, the design phase is defined as the period of time between the completion of the Environmental Impact Statement (end of the planning phase) and just prior to the public
invitation for construction bids. This definition is applicable to most public and private projects where the construction contract is awarded after the completion of the final design plans and specifications.\footnote{Turnkey contractual arrangements and variations thereof do not fall into this category. These contract types are rarely utilized by public US agencies, even though they are occasionally adopted by private owners.}

In general, the design phase includes the following key tasks:

- Selection of the engineering design firms.
- Securing funding for the project.
- Geologic and geotechnical exploration.
- Preliminary design.
- Detailed design.
- The preparation of the plans and specifications and the preparation of the construction contracts.

The objective of this section is to present, in some detail, the above general aspects of the design phase, with the emphasis placed on the issues that affect the effectiveness and value of subsurface exploration. The decisions concerning:

1. which exploration methods to use,
2. where to conduct the exploration, and
3. how much money to spend,

are all usually made during the design phase. Most of the practical use of the exploration results is also made within this phase. Consequently, the design phase is the most crucial with respect to exploration related decisions, and it is important to understand the climate within which
these decisions are made.

3.3.1 Selection of the Engineering Firms.

Design contracts and contracts for other professional services (such as geologic and geotechnical engineering) are normally awarded through competitive negotiations, rather than on the formally advertised, fixed-price basis normally utilized for construction contracts. The main criteria in this selection process are:

- The engineering firm's experience and reputation, and
- The engineering firm's fee for providing the required services.

As an example, the architect/engineer selection process normally adopted by the Urban Mass Transportation Administration (UMTA) and other public contracting agencies is to:

- Publicly announce requirements and solicit statements of qualifications.
- Discuss with usually not less than three firms the concepts and methods for providing their services.
- Rank the firms based on their qualifications to provide the services.
- Negotiate with the most qualified firm for a fair and reasonable fee.
- Terminate negotiations and approach the next firm on the list if unable to agree on a fair price. The process is then repeated until a mutually satisfactory contract can be drawn.

This selection process constitutes the owner's basic risk-reduction measure against firms that either have limited experience in underground construction design, or may be unaware of the unique aspects of the construction problems involved. The selection of competent engineering
firms at this stage is quite important because, even though "the design phase normally consumes 5% to 10% of the total project cost, it controls 90% to 100% of the capital cost" (NAS, 1978).

3.3.2 The Designer's Role.

The specific role of every engineering firm contracted by the owner during the design phase varies according to the adopted project organization (i.e. the number of firms contracted, their specialty, and their position and scope of work within the organizational structure). The allocation of specific tasks to each individual entity is of secondary interest to this research. Instead, the term "designer" is adopted to collectively reference the engineering entities, their responsibilities and decision making.

In general, one can identify two main technical tasks that have to be performed by the designer. These tasks can be classified as geotechnical and structural. Among others, the former deals primarily with the acquisition of geologic information and the evaluation of the ground characteristics that are relevant to the design and construction of the project. The tasks involved include:

- The design of the exploration program.

* The selection of exploration methods (boreholes, observation shafts, pilot tunnels, geophysical methods, etc.).

* The selection of locations for sample recovery, or site testing (specific location, inclination, depth, size, instrumentation and use of each borehole and observation shaft; configuration, design, instrumentation and use of pilot tunnels; arrangement and interaction of geophysical
tests with the above direct methods, etc.).

- Field and laboratory testing of the site geology.

* Contracting the services of site investigation contractors.

* Supervision of the field operations.

* Preparation of geotechnical reports, including:

  Complete site plans indicating the locations and logging of all borings or geophysical testing equipment.

  Soil strata classification and mapping.

  Mapping of rock strata and discontinuities (joint set characteristics, faults, etc.)

  In situ soil and rock permeability tests.

  Piezometer and observation wells' logging.

  Soil laboratory tests: Natural water content, unit weights, Atterberg limits, grain size analyses, consolidation tests, unconsolidated undrained tests, triaxial tests, permeability tests, etc.

  Rock laboratory tests: Megascopic identification, petrographic analyses, unit weight determination, hardness, abrasiveness, unconfined compressive strength, elastic moduli, durability tests, joint characteristics, etc.

- Interpretation and analysis of test results, including:

  * The performance of the unsupported opening.

  * The ground loads and water pressures that the final structure has to withstand.

  * The water inflow expected during construction.

The above geotechnical results form the main input for the structural analysis and design which, in turn, deals with the form and stability of the structure itself. Other considerations for the structural design are, of course, the use of the facility, its location,
the required safety, the budget alloted for construction and the design criteria imposed by the owner entity.

It is important to stress here that the designer usually retains responsibility for the structure's long-term stability, safety and performance, but passes the responsibility for short-term safety and stability to the contractor. The reason for this is that because of the uncertainty in geologic conditions and the inherent latent instability risks, the designer cannot hold himself contractually responsible for the safety of the contractor's labor force and equipment during construction. After all, the risk of instability during construction is partly controllable by the contractor, since it depends not only on the existing geology but also on the contractor's expertise and prudence in implementing excavation and support procedures. Consequently, the structural design plans prescribe the final form of the facility but usually do not dictate exactly how the contractor will operate on a short term, day-to-day, basis. Instead, in order to achieve the ground-structure interaction assumed during the design development, the designer imposes constraints on the construction procedures in the form of design and construction specifications.

This practice often leads to underground projects that employ two distinct support systems: the "initial support" and the "final lining". The initial support is basically the contractor's responsibility and its function is to provide the necessary stability of the opening (and thus the necessary safety to the contractor's labor, equipment and adjacent structures) before the installation of the final lining. It is interesting to note that the design of the final lining is usually based
on the premise that the initial support does not contribute to the opening's stability. This practice has produced structures with "double" the support required, where at least in the short term, the final lining may not carry any load at all; it is also questionable whether the final lining does indeed develop the full design loads in the long term.

In summary, the design decisions included as part of the plans and specifications are:

- The exact location, orientation, shape and size of every structural element of the project.

- Detailed description of the final lining, as a function of location within the project and within each cross section.

- Recommendations and constraints on excavation sequence and methods. For excavations in rock these may include:
  
  * The maximum round length.
  * The maximum distance of the support to the excavation face.
  * The maximum blasting vibrations allowed.
  * The spacing and explosive charge (especially for perimeter blasting).

- Recommendations for the treatment of water infiltration during construction and specifications as to maximum allowable water infiltration after project completion.

- Recommendations on initial support methods and specifications as to the minimum support required during construction as a function of the prevailing geologic conditions.

- Relocation of utilities interfering with the project's construction.

- Underpinning, and protection in general, of adjacent structures.

The designer's role, of course, is not limited to the design phase.
As a rule, the designer is also involved in the supervision of construction during the construction phase, as explained later.

The above description of the designer's tasks has concentrated mainly on technical issues. In addition, the designer may also be responsible for nontechnical issues, like the implementation of the necessary organizational structure for interfacing with external regulatory agencies, the public, and the funding entity. The designer may also be appointed by the owner as the specifications writer for the owner-contractor contract. The latter is a very important task in allocating the risks of underground construction and will be examined in the following sections.

3.3.3 Project Funding.

The procedure and the impact of securing funds for private underground projects do not usually differ from those for other privately constructed facilities, and as such they are not discussed here. Instead, this section focuses on the funding of public projects where the major financial burden is not carried by the owner entity (as one would expect), but rather by a federal agency.

Funding for the preliminary design phase is partially provided by the funding agency (for public transit projects UMTA), after or during the period required for the local and federal approval of the project's EIS. The funding of this phase, however, does not constitute a guarantee that the funding authority will indeed commit full funds for the construction of the project; it is rather intended to allow the
requesting owner to conduct a more in-depth review of the proposed project to determine its feasibility both in terms of cost and services provided. The capital grant application and the decision whether the project will receive federal support are made after reviewing the preliminary design results.

The capital grant application by the owner agency is normally submitted at the 30% design level, based on the engineer's estimate at that time. Depending on the engineer's ability to accurately forecast the project cost and potential contingencies, as well as any owner involvement to reduce the estimate, there may be cases where the initial request is insufficient. In this case, additional requests for federal funds must occur during the construction phase. Not only is the approval of these supplementary funds not guaranteed, but in addition the process for obtaining them is quite time consuming. In general, owners would prefer to have at their disposal more money than needed, rather than to run the risk of having to request for additional funds.

Once a project has been submitted and approved, UMTA will commit federal funding for 80% of the project cost based on the engineer's estimate. Normally 15% is provided by the state and the remaining 5% funded by the local community benefiting from the project's services.

Over the past years the UMTA guidelines for the utilization of capital funds were such that the agency monitored the entire operation to ensure compliance with all requirements. Recently, there has been strong support for the adoption of a full funding procedure by UMTA, whereby, if a grantee is certified to manage its own third party contracting, funding
would be provided without pre-award review processes at the federal level. This concept has the potential of reducing the design approval time, since all documents would not require UMTA review and approval. Under the full funding concept, however, no additional funds would be provided by the federal funding agency above and beyond the initial commitment. The latter is obviously necessary for preventing fraud in handling federal funds at and below the state level.

3.3.4 Subsurface Exploration.

The designer must begin his task by obtaining an understanding of the environment influencing his design. To accomplish this, an extensive subsurface site investigation is needed.

There is a general consensus among engineers that the proportioning and issuance of funds for subsurface exploration during the preliminary design phase is often insufficient. Some owners have the tendency to set budget criteria that limit the amount of exploration to the minimum necessary to permit the feasibility study and preliminary section design (Byrne, 1972). This is particularly true in public projects, where the owner entity does not want to commit too much of its own funds before the acceptance of the federal grant application.

This practice, however, even though not entirely unreasonable, does not produce the best possible results. The timing for conducting subsurface exploration is a very important variable in determining its value. The earlier the exploration results are embodied into the design, the higher its informational value. As the design progresses, certain
design criteria and assumptions have to be established and carried forward. These assumptions shape the project's general design philosophy and have to be based on the best geologic information available at the time. The less the information on which these assumptions are based, the more conservative the designer has to be. This conclusion not only makes intuitive sense, but has also been verified through past research (Qaddumi, 1981; Stasiewicz, 1981; Lane, 1975).

Subsequently, the owner and the designer are left with basically two practical options:

- either the design assumptions will have to be reviewed and updated as time progresses so that they reflect the complete volume of the information collected (irrespective of whether the new information leads to more favorable or unfavorable design criteria),

- or, the design assumptions will remain unchanged (provided that the newly acquired information would not mandate even more conservative action).

It is evident that in either case, the amount of time and cost consumed in redesign work increases as a function of the time interval between the beginning of design and the time the new information is made available.

Given the above two options, the first is seldom chosen. In many cases the owner does not provide the designer with enough time and money to permit the review and improvement of design decisions made in the project's early stages and under limited amounts of geologic information. Reconsiderations of the design assumptions are usually made only if there is sufficient evidence that the actual conditions are indeed worse than assumed. In other words, it is common that the latter phases of
subsurface exploration are used to confirm earlier design decisions rather than to make new decisions in an optimal manner.

In addition to the issue of exploration timing, the issue of exploration intensity is of equal importance. In the case of exploration timing, the general conclusion can be simply summarized as "the sooner exploration is conducted, the better". In the case of exploration intensity, the optimum strategy is a little more complex.

In general, designers would rather have as much subsurface exploration as possible so that they can validate all their assumptions and thus eliminate any possibility that their design decisions could be wrong. Owners, on the other hand, do not fully appreciate the benefits of an extensive exploration program and often try to limit this expense to the minimum required. The former is basically the consequence of the designer's willingness to hedge against potential liabilities; the latter has to do with the project's funding and the lack of concrete evidence on whether further exploration would yield a net benefit to the owner.

The designer's liability issue is presented in detail in the following section. In simple terms, exploration helps decrease the designer's liability exposure by ensuring the adequacy of the design and by providing a strong basis defending engineering assumptions in the event of disputes and/or litigation.

On the other hand, the owner usually has quite a different point of view. Owners typically consider subsurface exploration as an investment of funds, and as such it must have a positive net present value to be acceptable. The difficulty is that the investment in exploration usually
has very uncertain benefits (from the owner's perspective) and certain costs. To illustrate the uncertainty of the benefits (again from the owner's perspective), one only needs to consider the major contributions of exploration.

The potential benefits are basically:

- the reduction of design conservatism
- the reduction of bid contingencies
- the reduction of changed conditions claims or any other time consuming litigation or arbitration.

The problem becomes evident when one realizes that the above benefits are in essence part of the designer's and/or the contractor's domain of decision making; a domain over which the owner has little or no explicit contractual control. In other words, the value of exploration to the owner can be considered a risk, whose outcome is very much controlled by the designer's and the contractor's behavior. Consequently, this risk is very difficult to quantify so that an intelligent decision on the intensity of exploration can be made.

Compounding the above problem is the mechanism for funding public underground projects in the US. As explained earlier, the major partner in funding such projects is a federal agency. If one considers the case of public transit projects as an example, then the federal grant approval (for 80% of the project cost) is typically made at the 30% design level, based on the engineer's estimate at the time. As a result, the project's budget is established on the basis of sometimes limited information and may prove to be inadequate. In addition, since the issuance of
additional funds is neither guaranteed nor desirable, the owner usually adopts staying below the budget as his main objective (as opposed to cost optimization). In this pursuit, owners consider exploration as a contender for money that has be to kept at a minimum (unless, of course, a separate budget for the cost of exploration is secured from the funding agency; this, for example, is the case for the pilot tunnel for the Porter Square Station). This attitude manifests itself not only in the issuance of exploration funds but also in the structure of the project's risk sharing arrangement (i.e., the contracts - this issue is discussed later).

In contrast to the above practice, the decision on the optimum exploration intensity should be based on cost optimization. In principle, the optimum amount of exploration can be defined as that which minimizes the combined cost of design, exploration and construction. Since no formal means are used (or have been developed) to achieve such optimization, this work is aimed at providing the necessary framework so that exploration related decisions can be made in a rational manner.

3.3.5 The Issue of Design Conservatism.

Typically undercapitalized as compared to their liability exposure, designers have, as a rule, adopted conservative design approaches in order to protect themselves against any potential liabilities.

This section will discuss the issue of design conservatism and its underlying causes. Several factors inducing design conservatism can be cited. The variables influencing the technical engineering decisions
(conservatism) and the attributes considered in the designer's decision framework are shown in the influence diagram of figure 3-3 (Ioannou, 1980; Qaddumi, 1981). These factors, depending on their nature can be classified into two broad categories: technical and institutional.

3.3.5.1 Technical Factors.

From an engineering point of view, conservatism in design is primarily induced by two factors: an insufficient knowledge of the project's geologic conditions and the imperfect science of predicting the minimum support required for short- and long-term stability and safety. These are two distinct, although interrelated, problems.

The first deals with the uncertainty in the exact geologic conditions that will be encountered during construction and with which the structure has to interact in the long run. In other words, the designer is faced with a dynamic geologic inference (or prediction) problem where the estimation of extremely unfavorable outcomes is of prime interest; after all, the adequacy of the design will be tested against such extreme events. Design conservatism induced by geologic uncertainty is at its worst when the design has to be fully completed before construction begins, without any provisions for alternate (adaptable) designs. Typically, adaptable designs are developed on the basis of alternative hypotheses on the nature of the actual ground conditions; the decision on which to employ is made dynamically during construction on the basis of additional (and nearly perfect) information. Unfortunately, this approach, although conceptually appealing, is not usually adopted in public underground projects. Instead, the standard
Figure 3-3: Factors Influencing Design Conservatism (Ioannou, 1980; Qaddumi, 1981).
(non-adaptable) procedure used in the US is to "design for the worst conceivable geologic conditions". Even though this philosophy is not without merit, it has been accused of being a major cause of cost suboptimization. As mentioned earlier, the problem of geologic uncertainty can be alleviated (but usually not completely) through the employment of a comprehensive exploration program.

The reduction of geologic uncertainty, however, does not eliminate the second problem. The ground-structure interaction, and especially its behavior over time, are still not perfectly known (even if one assumes the extreme case where the information on the project's geology is perfect). Mitigation of this problem can only be achieved through the employment of instrumented and well-monitored test sections that can form the data base for the development and validation of better analysis and design approaches. This is in fact the philosophy behind the "observational" design-construction method. This method basically attempts to "kill two birds with one stone", by (i) postponing design decisions until construction reveals the actual geologic conditions, and (ii) reviewing the design on the basis of information on the ground-structure interaction collected through instrumentation of already constructed sections (Lane, 1975).

3.3.5.2 Institutional Factors.

In addition to the technical factors cited above, design conservatism is also induced by institutional factors. A major concern of the engineering firms involved in the design phase of any project is their firm's financial liability exposure. Since the capital worth of
most engineering firms is usually small as compared to the cost of major projects, liability becomes a key issue. If the designer is found to be at fault, or negligent, in exercising his duties (as defined by current legal interpretations), there is a good chance that the required financial compensation by the owner, the contractor, or recently by a third party, may exceed the engineering firm's worth. In order to hedge against this risk, engineering professionals purchase liability insurance, usually in the form of Errors and Omissions Insurance. In recent years, however, the premiums for this coverage (as is the case for the medical profession) have become exorbitant. Some firms have to accept high deductibles just to afford the premiums alone. The case of many geotechnical engineering firms, which until recently were considered such a hazard that they could not even buy insurance, illustrates the severity of this problem.

Consulting engineering firms engaged in soils and foundations engineering were virtually uninsurable fifteen years ago. In 1969 they created the Association of Soil and Foundation Engineers (ASFE) which developed a loss prevention program for its members and recommended liability limitation to them as a standard operating procedure. The ASFE established its own insurance program, leading to the foundation of Terra Insurance Ltd., an insurance company formed entirely by members of the ASFE to provide professional liability insurance solely for soil and foundation engineers participating in the professional liability loss prevention program conducted by ASFE. This insurance program has experienced an enviable success (Bjarnason, 1980).

The designer's financial liability exposure is one of the major
in institutional factors supporting conservatism, an attitude that ultimately impacts on increased construction costs. General practice in the US has been to use already proven, conservative, conventional construction methods for underground design with no incentive to be innovative and cost effective at the risk of increasing the designer's liability. Past research examining the institutional causes of design conservatism has shown that it is indeed a major problem and one of the main reasons why the cost of US underground construction appears to be much higher than in Europe or Japan (Lane, 1975; Ioannou, 1980; Stasiewicz, 1981; Qaddumi, 1981).

There currently exist several institutional factors that, along with the already mentioned technical factors, aggravate the designer's liability problem and promote what has been coined as "defensive engineering" (Kuesel). Such factors are:

- The owner-designer contracts, and the owner's policy and reputation in dealing with design firms.
- The imposed design criteria.
- The engineer's position within the design organization.
- The legal interpretation of the designer's duties.
- Third party involvement.
- Contractor selection process, and
- The fee-for-services structure.

**Risk sharing - The owner-designer contract.**

In most cases, the owner's philosophy in allocating risks through the owner-designer contracts (especially public ones) can be summarized by the following colorful statement: "You are the designer, so you take
the risk" (Sutcliffe). In other words, the owner's typical strategy has been to allocate as much of the risk as possible to the designer, and in succession to the contractor, in an attempt to achieve a risk-free position. For public projects, this attitude can be traced back to the mechanism for project funding and the owner's interest in taking full advantage of the federal funds available.

The owner's underlying hypothesis appears to be that the more the liability is placed upon the designer's shoulders, the more his attention will be drawn towards both the ability of the design to conform to the owner's operational intents and the "accurate" estimation of the project's cost. The former is aimed towards the minimization of the maintenance and operational costs which are completely borne by the owner entity and not by the federal funding agency. Even though this policy may lead to higher initial capital expenditures than necessary (only 20% of which are perceived as "out-of-pocket" funds), they are outweighed by the expected savings in running the facility (the cost for which is 100% out-of-pocket).

In addition, the increased liability imposed upon the designer is also expected to reduce the probability that the initial budget may prove to be insufficient and supplementary funds have to be requested (a clearly undesirable situation). This is accomplished through the compilation of a more accurate (conservative) engineer's estimate (used for funding purposes) and the utilization of proven design and construction techniques that have minimal cost variability.

The concern of staying within the budget is by no means limited to
public owners or to underground construction. The cost of any project has to remain below an upper limit for the project to have a positive net present value. The adoption of a conservative design approach, however, may not be the best approach to this objective. An interesting example testifying to this effect is the design and construction of the earth embankment for the Great Salt Lake railroad crossing (1955-1959)\textsuperscript{12} (Casagrande, 1965).

Compounding the contractual shift of risk from the owner to the designer is the owner's reputation and intent in enforcing the spirit of the contract. Owners that have in the past been unsupportive or have excessively criticized the wisdom of the designer's decisions will obviously induce conservative design behavior in the future. From the discussion on the designer selection processes, it can easily be seen that one of the most important objectives in the designer's decision making is the preservation and enhancement of the engineering firm's reputation.

\textsuperscript{12}In this case, the owner (Southern Pacific) had arrived at a maximum budget of $50 million, above which the project was not economically justified. The initial (1955) design of the embankment (based on laboratory tests of the unconfined compressive strength of the clay foundation that overestimated the in situ strength) called for a total cost estimate of $30 million. Further tests revealed the inadequacy of the original design and the existence of brittle salt lenses; as a result, the board had to adopt full-scale test sections and based on the resulting experience (through an observational approach) and extensive design revisions, managed to complete the project a year ahead of schedule and with maximum economy (given the true conditions). The final cost was $50.5 million. Had the designers realized the weakness of the embankment's foundation from the very beginning and designed the embankment accordingly, the normal factor of safety (barring the observational approach) would have been too high, the initial estimate would have been above the maximum budget and the embankment would have never been built!
In many instances (depending on the proposed risk allocation structure) the engineer has to resort to defensive strategies in order to safeguard his firm's reputation (and financial stability), which are obviously endangered by the creation of any adversary relationship with the owner. If the owner does not provide the engineer with a contractual and organizational buffer that shelters the latter from excessive liability, there is little that the engineer can do but to respond with "defensive engineering".

**Design Criteria.**

In addition, the engineer may have to resort to design conservatism because the owner or another party higher up in the design organizational structure specifies design criteria that cannot be met otherwise. For example, the thickness of the final lining in many public underground projects is dictated not by the required stiffness or strength (as one might expect) but rather by the required imperviousness to water inflow. This is a prime example where public owners trade the expenditure of federal funds during construction, against the use of their own money during operation; in this case for pumping the water out. In fact, the imposed design criteria may be the binding constraints that force the designer to suboptimize the use of materials.

**Professional and legal liability.**

Closely coupled with the above problems is the legal interpretation of the designer's professional responsibility. Up to now there are no standard codes for the design of major underground structures. Such codes would not only help the designer's task, but would also provide benchmarks supporting the designer's decisions in the event of design
inadequacy litigation. In a court of law the common law in the U.S. stipulates that designers are only expected to possess and exercise the care and skill of those ordinarily skilled in this field. In other words, since lawyers and judges are not design experts, the legal system makes heavy use of "precedence" in its interpretation of what is considered adequate practice. By utilizing past conventional and conservative approaches and by avoiding potentially cost effective innovations, the designer reduces his risk exposure at the owner's expense. Furthermore, designers are seldom accused (if ever) of excessive conservatism. Since cost comparisons between projects are very difficult to make due to each project's unique features and geology, such conservatism is very difficult to detect and even more so to prove.

The designer's third party liability.

It must be noted here that under today's legal practices the designer's legal liability is not limited to, or by, his contractual obligations to the owner. Any third party that has a grievance that can, either explicitly or implicitly, be attributed to an engineering decision may file a claim against the designer directly: "the engineer can now be sued, and is sued, by anyone and everyone; the legal concept of 'privity

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13 Codes have a negative aspect, also; they make it very difficult to introduce innovative approaches.
of contract'\textsuperscript{14} does not exist anymore" (Sutcliffe). In fact, third parties play a significant role in the development of the design philosophy for many public projects. The location and sizing of tunnels, access and ventilation shafts and stations for public transit projects are sometimes made under considerable public and political input and pressure. Thus, third party involvement can limit the margin for engineering optimality considerably. As a result, some of the engineers interviewed wondered whether anybody would have any incentive to optimize the project's cost in such a decision-making environment.

Lack of design-construction integration.

Another major drawback a designer has in public contracting is that while he is preparing the contract documents, he does not know who will actually construct the project. Often, the contractor is selected purely on a cost basis, without any input from the designer regarding technical qualifications. As a result, the designer must build into the contract specifications various "fail safe" conditions in the event that a less-than-desirable contractor is awarded the project. He generally must write the specifications and prepare the drawings expecting the worst contractor to do the construction. Significant time is devoted in the specifications preparation to thoroughly review the wording and the

\textsuperscript{14}At one time, the absence of "privity of contract" (i.e. the absence of any connection (=privity) with the underlying contract) between the design professional and any other party besides the owner, made it impossible for third parties to sue the design professional (i.e. they could only sue the owner who in turn could, at his option, turn around and sue the designer). Although it can still be an obstacle, it is no longer an absolute barrier. (Sweet, 1970; Dunham et al., 1979; Bjarnason, 1980.)
interpretation that may be drawn by any low bidder. The intent is to protect both the owner and the designer from either accidental or deliberate misinterpretation of the documents, that might lead to litigation or arbitration. Usually this is accomplished through a "cut and paste" approach; old specifications are researched to find contract clauses that represent, or closely resemble, the requirements of the present contract. Hence, many of the "boiler plate" clauses seen in contracts five or more years ago are still utilized without any modification in today's contracting (Stasiewicz, 1981). This practice is mainly due to:

- lack of adequate knowledge and experience of the specifications writer to be creative and more project oriented,

- a sense of security in utilizing clauses that passed the test of time by being acceptable on previous projects.

Since there are no nationally standardized specifications for underground construction, each owner through his design firm drafts his own forms of "standard contract" general requirements and guidelines. Normal practice has been for the owner to divide the risk between the designer and the contractor hoping to isolate himself from potential liability. Since the designer is responsible for drafting the project specifications he will (under current practice) write them in such way that not only the owner's liability is reduced but also his own. The use of exculpatory language and disclaimer clauses are the means by which the designer achieves this goal.

In addition, the fact that the designer has no prior knowledge of the contractor's identity has a profound effect on the design philosophy
itself. A "fine tuned" design that is not properly implemented, because of inexperience or incompetence on the contractor's part, may also drag the designer into litigation defending his design decisions. Thus, the adoption of a less conservative, cost efficient design may backfire at the designer, who evidently has little to gain and everything to lose. For example, a recent audit by the inspector general of the US Department of Transportation has disclosed numerous deficiencies in the administration and construction of the Buffalo, NY, $450-million light-rail transit line:

- A section of the tunnel was not constructed in accordance with contract specifications and the structural integrity of some portions of the project may have been adversely affected.

- Concrete poured did not always meet water- and air-content specifications.

- Sections of the tunnel lining do not meet concrete thickness specifications of 12 in. At one site, the tunnel crown was only 2.5 in. thick (ENR, Feb 16, 1984).

Even though no action has been taken against the designer in this case, the deficiencies cited are indicative of the problems that promote defensive engineering.15

The problem of the construction industry's inexperience with new methods is also a factor inhibiting design innovation. As an example, slurry walls got a bad name when they were first introduced in the US because the contractors at the time did not have enough experience with

15 An interesting question stemming from the above article would be: "How large should the specified thickness of the lining be so that an acceptable minimum is certain to be achieved during construction?"
this type of construction. Another example where the contractors' inexperience led to increased costs is the shotcrete tunnel lining option at the WMATA rapid transit system. Because shotcrete was a relatively new lining for the US industry, the bids came in too high and the owner ended up paying "400% of what he should have" (Kuesel). The preparation of design alternatives to invoke cost effectiveness through market competition has been suggested as a possible remedy to this industrywide problem. The basic idea is simple: whenever possible, the design should be split into two options featuring both innovative cost-saving techniques and standard procedures. The competition in the bidding process should then be based on either of the design alternatives. The bid prices and the actual field experience will subsequently show whether the state of the industry can cope with the innovations proposed. This procedure will inevitably lead to the economic survival of the most efficient methods, as contractors learn through the accumulation of experience which methods make their bids more competitive (Kuesel).

The engineer's fee.

Finally, the method for compensating the designer for his services can also be a passive factor for conservatism by inhibiting innovation and cost effectiveness. The fee paid to a design firm typically covers the design cost plus a fixed fee with or without an upper limit, or it could be a lump sum figure. It is usually based on historical accounting records and on fees charged by other firms on similar jobs. This fee, however, does not often reflect the problems encountered in the implementation of the project at hand. The more restricted the engineer is as far as the fee is concerned, the more reluctant he is in searching
for better alternatives. Without invoking organizational theories on the effect of assessment and reward systems, it can simply be said that most compensation methods in use today do not provide the designer with any financial or intangible motive to innovate or to be "excessively" cost conscious (beyond the ordinary):

"The problem with each (compensation) method is the correlation between fees and construction costs. Lower construction costs mean lower fees, thus no incentive for engineers to create design solutions below estimated construction costs.

A new more equitable method would encourage rather than discourage lower construction costs. The engineer's final fee should include three parts:

1. Fixed fee

2. Percentage of the construction costs savings, and

3. Percentage of the life-cycle (operational) cost savings."
(Biggs, 1981)

Along the same lines, Fead (1980), adds that:

"Another factor stifling innovation is the standard fee system for (design) consultants. It will normally be faster (and thus cheaper) for a consultant to follow an established, routine design procedure. Normally, standard fees do not provide sufficient funds to pay for the full evaluation of complex innovative alternatives. And under competitive bidding for design services, the situation is more likely to be aggravated. Politically, it would be all but impossible to rule a bidder incompetent because his work followed routine standard practice rather than innovative techniques. The lowest cost design will seldom lead to the lowest cost project. In fact, the total cost generally - within limits - will be an inverse function of the design cost."

3.3.5.3 The Cost Impact of Design Conservatism.

The cost implications of design conservatism has been the subject of another research (Ioannou, 1980; Qaddumi, 1981) the results of which are
briefly presented here. From the institutional variables presented above, the ones that are most important in affecting the engineer's decision framework have been identified to be:

1. The integration of design and construction.
2. Design criteria.
3. Engineering firm's responsibility.

Furthermore, the levels at which these variables are usually encountered in practice are what engineers perceive to be the worst possible (Sutcliffe). Changing these variables into what was considered to be their "best" values has been shown to produce substantial construction savings, in the order of 20% of a project's cost.

This estimate is certainly commensurable with the one assessed subjectively by the contractors participating in this research which ranged from 5% to 25%. Given this potential for cost savings, one of these contractors stated that:

"The owner should probably concentrate on reducing design conservatism rather than the contractors' contingencies, especially in today's market where contractors are not taking the precautions [i.e., contingencies] that they used to take in the past".

On the other hand, most contractors "sympathize" with the designer's position and argue that given the current owner attitudes there is nothing else the engineer can do to protect his organization. Most engineers try to do the best they can, but:

"You have to break some eggs to make an omelett!" (P.A. O'Neill)

In this respect, it has also been shown that it in order to produce
significant reductions in design conservatism, and hence to the project's cost, the three variables cited above must simultaneously be taken into account and improved. Partial improvement does not foster a significant change in design practices because any factor can singlehandedly control the engineer's behavior (Qaddumi, 1981).

Of more interest to this research is the fact that risk sharing appears to be most effective when the project's geologic conditions appear to be favorable. The implication is that the designer would truly need a conservative design in bad ground, even with the most favorable risk allocation. In favorable ground conditions, on the other hand, part of the cost of current designs is actually due to (unnecessary) overdesign, as a result of excessive liability placed upon the engineer. This is the situation in which large savings are possible if owners restructure and share in the project risks, as shown in figure 3-4. This figure represents the project's cost as a function of geologic and institutional conditions. The cost surface is relatively steeper (implying larger marginal savings) at the end where favorable geotechnical conditions exist. At the other extreme (worsening geologic conditions) the surface becomes flat implying minor marginal changes in cost. This fact assures owners that engineers are not "frivolous" and will still be conservative in bad ground, even if improved institutional conditions do exist (Qaddumi, 1981).

3.3.5.4 Design Strategies.

In principle, the engineer's main objective is to promote the owner's interests by producing a design that meets the desired functional
Figure 3-4: Schematic Representation of Potential Cost Savings from Improving Institutional Conditions as a Function of Geotechnical Conditions (Qaddumi, 1981).
requirements at a minimum of cost. From the above discussion, however, it becomes clear that the engineer's decision making can be adversely affected by a multitude of factors, most of which are controlled by the owner, and few of which promote cost optimization under today's contractual practice. The designer has virtually nothing to gain by reducing the project's cost; such action bears little reward while at the same time it increases the potential that, if things go wrong, the designer will be the one to blame. As a result, the designer's main objective is to minimize his own risk exposure by ensuring that the design will indeed meet every party's requirements (not only the owner's) while keeping the cost of the work within a reasonable budget. In other words, instead of minimizing the project's cost given a set of functional specifications, the prevailing design approach is to maximize the likelihood of meeting, or exceeding, the desired performance while not inflating cost to an obviously unreasonable level; i.e., the objective function and the constraints have switched places leading to different optimal strategies.

This is clearly reflected in the geologic assumptions used in formulating the design. The currently prevailing strategy is basically to assume that the worst possible geologic conditions will indeed be encountered and to design accordingly. Since the actual location of the "worst conditions" is not known beforehand (otherwise there would be no conservatism) the above assumption has a marked effect on the spatial variability of the design and the resulting project cost.

The designer must begin his task by dividing the project into "homogeneous" segments each of which may require a different design.
There are two main decisions in this process, both being interdependent. The first deals with the extent of each "homogeneous" segment, while the second involves the assessment of an adequate design for each segment. These decisions can be summarized under the heading of "design adaptability". Since each segment is associated with a different design, increasing the number of segments produces a design profile that matches more closely with the variability of the project's geologic conditions. Even though this translates into lower construction costs, design adaptation has traditionally been kept at very low levels in order to minimize the possibility of either misjudging the geology, or that human (i.e. the designer's and/or the contractor's) errors may lead to design inadequacy. As a result, the prevailing design strategy is to choose the design and its extent so that the probability of making the "wrong decision" is minimized.

Several technical examples of how this strategy manifests itself in practice were cited by the contractors participating in this research. In their opinion symptoms such as the following can and should be identified and corrected:

1. "Design decisions:

- Resistance to innovative support methods, such as the New Austrian Tunneling Method (NATM).

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It must be noted, however, that matching the design to a highly variable geology may prove to be inefficient because of the resulting frequent changes during construction and the implied increase in the likelihood of human error. Frequent design changes may end up costing more than the conservative alternative of reducing design adaptation and increasing the extent of each segment.
- Misuse of innovative methods such as NATM.¹⁷
- Composite linings; initial support not used as part of permanent support.
- Design of the final lining: type, thickness, strength, reinforcing, loading.
- Use of precast concrete tunnel liners.

2. Constraints on construction:

- Construction methods.
- Schedule.
- Sequencing.
- Blasting.
- Vibrations.
- Round lengths.
- Support application - timing.
- Locations - work areas.
- Access to project".

Furthermore, the contractors' subjective assessment of the potential for cost savings that can be achieved by identifying and eliminating the engineer's conservatism in areas like the ones cited above, are best shown in the following two statements:

"The above (issues) are very important in terms of cost; up to an estimated 25-35% of total project cost".

¹⁷Quoting a contractor's remarks concerning the design of the Porter Square Station: "NATM in Porter Square utilized the shotcrete method in principle but used what seemed to be excessive bracing (steel) in conjunction. Advantages and cost savings of NATM seemed defeated. Method was in direct contrast to what is used in Europe. Why?"
"Recent projects incorporating some of the (recommendations) above have shown drastic reductions in costs, as much as 20 to 30%".

3.4 The Construction Planning - Bidding Phase.

Under conventional US practice the construction planning and bidding phase occupies the relatively short period of time (60 to 90 days) from the completion of the design plans and specifications, to the commencement of construction. As a result, most of the groundwork for this phase is established by the owner and engineer during the design phase.

The bidding phase begins with the release of the "Invitation to Bid", a public notice issued by the awarding agency to solicit interested bidders and ends with the selection of the successful contractor. In general (but not always), the following requirements are either set forth in the invitation to bid, or apply as a matter of law (NAS, 1974):

- Public agencies will require that sealed bids be submitted, accompanied by a bid bond or cash deposit to guarantee execution of the contract documents by the successful bidder. In the private sector, however, bid bonds are seldom required.

- All bids are publicly opened by public agencies at the time and date specified in the invitation. At that time, prices are announced with the engineer's estimate and the bids are immediately made available for inspection by the public. Private owners very seldom open bids publicly, publish the engineer's estimate, or make bids available for public inspection.

- All public agencies and most private owners require that the bid be responsive to the invitation, i.e., that it must not be qualified or restricted concerning quality, quantity, price or time for performance of the work.

- After bid opening, the low bidder must satisfy the owner (if he
has not already done so) that he is responsible, i.e. has a satisfactory record performance of like work, and the management capability, financial strength and equipment availability to assure timely performance of the job as specified.

- Award by public agencies is made to that responsible, i.e. qualified, bidder who submits the lowest responsive bid. A responsive bid is defined as one that proposes to perform the work in strict accordance with the contract terms and provisions, plans and specifications as issued, i.e., without qualification as to price, quality, quantity, or time for performance. Private owners are not bound by any such legal requirements concerning acceptability of bids.

- On award of contract, the contractor must, in public agency contracts, furnish performance and payment bonds in the amounts called for in the invitation to bid.

3.4.1 Contractor Eligibility.

In general, not every contractor can bid a particular underground project. In order for a contractor to be eligible to submit a bid he must present some evidence that he can actually complete the work successfully. This is not unexpected, since every owner wishes to insure that he will receive the product at the specified quality level and in the time allocated, and thus must ascertain that the contractors bidding the work have the ability to follow through with the project's construction, if indeed they are awarded the contract. This can typically be achieved by utilizing:

1. Specified performance and payment bonds, and

2. Prequalification programs.

Owner agencies without a prequalification program consider a contractor eligible for bidding if he can acquire the necessary bonding to perform the work. Since bonding companies thoroughly investigate a
has not already done so) that he is responsible, i.e., has a satisfactory record performance of like work, and the management capability, financial strength and equipment availability to assure timely performance of the job as specified.

- Award by public agencies is made to that responsible, i.e., qualified, bidder who submits the lowest responsive bid. A responsive bid is defined as one that proposes to perform the work in strict accordance with the contract terms and provisions, plans and specifications as issued, i.e., without qualification as to price, quality, quantity, or time for performance. Private owners are not bound by any such legal requirements concerning acceptability of bids.

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2. Prequalification programs.

Owner agencies without a prequalification program consider a contractor eligible for bidding if he can acquire the necessary bonding to perform the work. Since bonding companies thoroughly investigate a
client's financial position prior to insuring him, it is felt that this is adequate prequalification. In case of default on the part of the contractor, liability falls upon the bonding company to complete the work at no additional cost to the owner. Hence, under a bonding program the owner's interests are protected through an insurance policy that warrants to the owner that if the contractor fails to complete the work, the bonding company will take over the existing contract. Thus, the risk for additional expenses, above the original contract amount that may be necessary for completing the work, is borne by the underwriter and not the owner.

To further insure eligibility, some owner agencies require contractor prequalification which is presently another in-depth review of the potential contractor's financial status. Under the present programs the contractor evaluation may be conducted:

- prior to the issuance of bidding documents (process utilized by the Boston MBTA), or

- during the bidding process, requiring the contractors to submit the evaluation questionnaire with the bid (process utilized by the Baltimore MTA), or

- by requiring only the low bidder to submit the questionnaire after bidding, but prior to award (process utilized by the Washington WMATA). (Stasiewicz, 1981)

In addition to financial data, most prequalification questionnaires require supplemental information such as the experience of the principals of the firm, projects that were completed over recent years, and the size of the projects. This information serves as an indicator of the contractor's technical expertise and thus of his ability to complete the work successfully. To further insure the best possible construction
results, private owners may even specify that a contractor will not be considered eligible unless certain key individuals from the contractor's organization be assigned to the project.

3.4.2 The Contractor's tasks.

A prospective bidder can begin his review and estimating process as soon as he obtains copies of all the contractual documents and bidding information. These include (NAS, 1974):

- General contractual provisions, which are included by the owner in all construction contracts of the type named in the invitation.

- Special provisions applying particularly to the specific project being advertised for bids.

- Technical specifications and plans or drawings, which, depending on the particular circumstances involved, have been developed in differing amounts of detail for the particular project.

Most reputable contractors have a company policy not to bid a project unless it has been thoroughly estimated and reviewed. This means that during the 60-90 days normally allocated for bid preparation the contractor must:

- Thoroughly review all contract requirements and contractor responsibilities.

- Do a thorough take-off on the actual work.

- Negotiate with prospective subcontractors.

- Review the geotechnical data and determine the construction method, dewatering system and design of the excavation and initial support system.

- Anticipate any problem areas that could result in additional time and money above the original construction costs.
- Prepare a preliminary construction schedule to determine expected construction time, including delays due to strikes, material delivery, bad weather, etc.

- Consider the potential for liquidated damages, rework and other owner claims.

The most important issue during the construction planning phase is to determine the construction method and means of excavation and support. The reason for this is that approximately 40% - 60% of a project's capital cost is associated with excavation and support processes. In order to properly analyze the requirements for excavation and support, a good knowledge of the expected geology and ground conditions is imperative.

In order to assist the contractor as much as possible, most owner agencies schedule a pre-bid conference several weeks after the issuance of the "invitation to bid" where all interested bidders can meet jointly with the owner and engineer to discuss and clarify various aspects of the project. During the pre-bid conference, questions of constructibility may be a point of contention that is addressed. Unfortunately, in order to maintain a competitive edge over the other bidders, some contractors may not fully question pertinent elements of constructibility, since this may divulge their construction methods to other competitors.

An equally important use of the pre-bid conference is to provide the contractors with a better perspective of the owner's and designer's attitudes. By questioning the validity of various clauses in the contract, contractors can make broad generalizations about how cooperative the designer and owner will be in the future. The working attitudes derived from past and present experiences can significantly
influence the contractors' perception of how the risks will actually be shared and how they should formulate their bidding strategies.

3.4.3 The Bidding Schedule.

Most public underground construction projects are awarded on the basis of a unit price construction contract. For the most part this type of contract utilizes a unit price bid schedule that breaks the construction processes into major construction elements. In addition, this schedule may also include lump sum bid items for portions of the work that are clearly defined and thus unlikely to be changed during the construction phase. These include such items as mobilization, landscaping, mechanical and electrical work.

The work items principally associated with the tunnel construction phase are normally bid on a unit price basis. This includes excavation, dewatering, initial support and the final tunnel liner. The quantities of work for each of these items are considerably influenced by the actual geologic conditions to be encountered during construction and as a result are subject to a considerable amount of uncertainty. Thus, a unit price contract relieves the contractor of having to bear the full extent of this risk\textsuperscript{18} over which he has very little control. In fact this is the major advantage of a unit price contract as compared to a lump sum contract. At least in principle a unit price contract guarantees the

\textsuperscript{18} The contractor still bears some of the risk because the true cost of unit-priced work still depends on its quantity and the economies of scale that can be achieved.
contractor that he will be reimbursed according to the work in place.\textsuperscript{19}

Unfortunately, this purpose is often defeated by contracts that utilize a single bid item for tunnel construction; this item includes the cost of all excavation, dewatering, initial support and final lining. The result is a "lump sum per linear foot" bid item that aggregates the cost of many separate construction activities into a single unit price. Since the project has a fixed length, this practice amounts to little more than disguising a lump sum contract under a different name.\textsuperscript{20}

In addition to the expected work items, some of the bidding schedules also include "excess-quantity" bid items. This refers to quantities of a specific bid item like steel supports, rockbolts or shotcrete, that may be required above and beyond the quantities specified in the contract documents. For a example, the Baltimore MTA-ML contract included a bid item titled "Steel Rib Supports in Excess of 268 W8x31". Two objectives are achieved with the inclusion of this excess-quantity bid item:

- First it specifies to the contractor that under the conditions of the basic contract, he will be required to furnish up to 268 W8x31 steel rib supports under the "Rock Tunnel" bid items.

\textsuperscript{19}Whether he will make a profit, though, is a different matter depending on how well the unit prices were estimated and whether the prices were unbalanced.

\textsuperscript{20}This practice is often adopted by owners that operate within a restricted budget and thus have to secure that the cost of the project does not exceed the original estimate. Even though the owner may consider this to be to his own advantage, the truth of the matter is that, in all probability, he will end up paying more since the contractor will counteract by inflating his contingencies.
- Second, it specifies that should a change order be initiated for additional steel rib supports in excess of the 268 W8x31, then payment will be based on this excess-quantity bid item.

The use of excess-quantity bid items is common when there is uncertainty as to the actual quantities that will be required during construction. Most recent public transit projects utilized excess-quantity bid items for the tunnel construction operations relating to the initial support system (Stasiewicz, 1981). The underlying principle, however, can unfortunately be misused by certain contractors who view the deployment of excess-quantity bid items as a way of making money. This is usually accomplished by:

- underpricing the quoted standard support items (an act that lowers the overall bid price), and

- overpricing the excess-quantity support items (an act that does not directly affect the competitiveness of the bid, since by definition these items are not associated with fixed quantities).

The contractor can thus increase his chance of being the low bidder while expecting to increase his profit through the excessive use of these items during construction. To counteract this possibility, many owner agencies fix the prices for the excess-quantity bid items ("owner-plugged" or "upset" unit prices) rather than let the contractor establish his own. This approach, of course, can be misused by the owner who may set these prices at an unrealistically low level.

3.4.4 Geologic Information.

Historically, little or no site investigation information was made available to contractors, and that given was specifically disclaimed. The
contractor was free to make such investigations as time and his inclination allowed and took the full risks arising from the ground not behaving in accordance with the model he had formulated. This system of placing the entire geologic risk on the contractor is still used throughout the world and is found to be satisfactory in conditions where the ground is familiar, or where the owner is willing to pay the price for the high-risk contingencies charged by the contractor. In return, the owner secures the cost and duration of the work, while the contractor has the chance of making a large profit. On the other hand, however, the contractor must have enough financial reserves to withstand the greatest extent of possible loss, otherwise the owner may end up with the project in difficulty and a bankrupt contractor.

3.4.4.1 Differing Site Conditions.

Modification of this situation led to the concept of "unforeseen conditions" and the wide acceptance of changed conditions clauses. A good example of such a clause is the one contained in the Government Construction Contracts Standard Form 23-A, entitled "Differing Site Conditions". The language of the federal clause is recommended, because a body of judicial interpretation sufficient to provide owners, engineers and contractors with good information concerning the effect of including such a clause is now available (NAS, 1974). This clause reads as follows:

"Differing Site Conditions (1968 FEB)

1. The Contractor shall promptly, and before such conditions are disturbed, notify the Contracting Officer in writing of:
a. subsurface or latent physical conditions at the site differing materially from those indicated in this contract, or

b. unknown physical conditions at the site, of an unusual nature, differing materially from those ordinarily encountered and generally recognized in the work of the character provided for in this contract.

2. The Contracting Officer shall promptly investigate the conditions, and if he finds that such conditions do materially so differ and cause an increase or decrease in the Contractor's cost of, or the time required for, performance of any part of the work under this contract, whether or not changed as a result of such conditions, an equitable adjustment shall be made and the contract modified in writing accordingly.

3. No claim of the Contractor under this clause shall be allowed unless the Contractor has given the notice required in (1) above; provided, however, the time prescribed therefor may be extended by the Government.

4. No claim by the Contractor for an equitable adjustment hereunder shall be allowed if asserted after final payment under this contract." (Armed Services Procurement Regulations 7-602.4)

Such clauses when operated in the spirit of their intent, provide a fair framework for equitable settlements and lead to lower and more realistic bid prices, because contractors would not have to include large contingencies in their bids for self protection. In fact many contractors consider the use of a changed conditions clause as a necessary prerequisite for bidding the work. Without this clause, the contractor has little in the contract to fall back on in the event of unexpected occurrences. However, the "foreseeability" of any situation may be difficult to define in relation to what was encountered (and should have been expected) and what was originally anticipated, especially if a basis for such determination is not established a priori. As a result, most engineers and contractors agree that even though the
inclusion of a changed conditions clause in the contract is important, it is not the most significant factor considered by a prospective contractor bidding the work. Rather it is the owner's attitude and reputation for recognizing legitimate changed conditions that define the value of this clause to the contractor. (Stasiewicz, 1981)

3.4.4.2 Geologic Information - Disclosure and Disclaimers.

Most owners/designers today make available to the contractors all geotechnical data and reports prepared and reviewed for design purposes. In some cases, the contractor may even be provided with the engineering-design interpretation of this data. Even though this practice is certainly commendable, most contracts also include disclaimer clauses holding the owner and the designer harmless for any conclusions the contractor may draw from these professional interpretations.

In general, a contract can include disclaimer clauses for both "factual information" and its "interpretation", even though the former is much rarer than the latter. Prospective bidders are normally expected to base their bids on all available factual data that might affect the work. When the owner disclaims responsibility for some or all of the data that he has accumulated and furnished, he places on the bidder the responsibility of verifying the data at his own expense. In the short time usually allocated to bid preparation, this is more than should be expected. The premise that contractors have means of access, or the time to carry out any meaningful investigation during the construction
planning period is false and should be abandoned. In addition, disclaimers on responsibility are often literally interpreted by contract administrators as preventing them from allowing legitimate changed conditions claims. The result, more often than not, is expensive litigation, wherein the owner usually is the loser (CIRIA Report, 1979).

The distinction between factual information and interpretation often has severe contractual implications because of the difficulty in distinguishing between the two. Very little of a site investigation report would remain if it were stripped of its interpretative contents since even the classification of soils and rocks involves some degree of interpretation. One may even argue that, for all practical purposes, factual information and some degree of interpretation are indeed inseparable:

"Geotechnical interpretation involves geological assessment of:

1. geophysical exploration,

2. assessments of soil or rock characteristics such as relative strengths, hardness, induration, and degree of weathering or alteration,

3. geological maps and sections,

4. soil profiles, and

5. all recommendations and comments pertaining to the design and construction of the work, based on examination of the factual data" (NAS, 1974).

Special cases exist where such investigations are made by contractors, e.g. turnkey or project management projects.
A practical division, therefore, between factual data and interpretation ought to be made at the point where opinion or judgement is introduced, in which there may be significant differences in the views held by equally informed individuals. It is generally recognized that a disclaimer of responsibility for accuracy is appropriate with respect to the following categories of information, interpretation and opinion (provided that identification of the specific item is made and notice given to the contractor) (NAS, 1974):

- Information obtained by others, perhaps at other times and for other purposes, which is furnished to prospective bidders in order to comply with the legal obligation to make full disclosure of all available data.

- Interpretations and opinions drawn from basic subsurface data (because equally competent professionals may reasonably draw different interpretations from the same data).

Information, interpretations and opinions such as described above should be specifically identified as such and differentiated from the basic subsurface data being furnished. This does not mean, however, that the contractor should not be furnished with the designer's interpretation, even though the accuracy of the latter may be disclaimed. Since the principal aim of site investigation is to establish a reference basis against which the subsequent behavior of the ground may be judged, the possibility of important and unavoidable uncertainties is introduced if the contractor is left to draw his own inferences from the purely factual data of the site investigation report. An example of what could potentially happen is presented in a case study by P.E. Perry (1976):

"Straight Creek Tunnel (now renamed the Eisenhower Tunnel) in Colorado provides an interesting example of what may occur when all the design data are not made available to the bidders
during the bidding phase. A report prepared by the Straight Creek designer a year before bids were received stated specifically that a shield was not a practical way of excavating the fault zone. Subsequently, the contractor based his bid on using a shield and the owner was placed in the difficult position of approving a construction method recommended against by his designer."

In addition, if the design is based on a specialist's interpretation, most engineer's agree that this information should also be made available to the contractors. Possible exceptions are cases where this interpretation is only partially accepted by the designer; the availability of such information may confuse rather than enlighten the contractors. It should also be realized that the engineer may have to take a more conservative view of the ground conditions for design purposes than the one he may genuinely anticipate as most likely to prevail. Similarly, a reluctance is felt by engineers to supply information which, because of over-simplification or lack of clarity, is capable of different interpretations. In contrast, if the designer possesses a report suggesting a special risk in relation to the ground, he could find himself subsequently in some difficulty if this were withheld from the contractor.

From the above discussion it becomes evident that a contractor has to make a major decision at the outset of the construction planning phase concerning the reliability of the information provided and the extent to which this information is contractually warranted. This decision is crucial for the formulation of the necessary assumptions for planning and estimating the work. Depending on the situation, the contractor can accept the geotechnical data (and its interpretation if available) as given, provide his own interpretation and conclusions, or hire a
geotechnical consultant to review the data and make interpretations. This decision is usually made on an individual project basis.

3.4.4.3 Willingness to Use Geologic Information.

Occasionally, the adoption of a comprehensive exploration program provides the contractors with a multitude of geological and other specialized data. Unless adequate time is given to the contractor to study this information, the economies that should result during construction may not be realized. In other words, the contractor must be sufficiently motivated to make full use of this information when assessing the construction method and developing his bid; otherwise most of the value of exploration may be lost.

It has been suggested that many contractors may, to some extent, have allowed the concentration of their skills to shift too far into the managerial functions of their organizations and so leave the technical and engineering matters to insufficiently experienced staff. This imputation is related to a view also expressed that site investigation reports are not adequately studied and applied during the bidding phase and only seriously brought into use in order to sustain claims for extra costs when things have gone wrong (CIRIA Report, 1979).

The consequent reaction of providing the contractor with less subsurface information would simply aggravate the situation. A satisfactory solution to this problem is to provide the contractor with the clearest possible description of the conditions anticipated and with enough time to review and formulate his own interpretation. In return, the contractor should provide a method statement indicating full
appreciation and understanding of the supplied information. This has in fact been adopted by private owners as a prerequisite for bid acceptance and contract award.

3.4.5 Contractor Financing and Bid Unbalancing.

In preparing a bid the contractor has to do more than just consider the actual costs of material, labor and equipment, as well as indirect costs, contingencies and profit. A very important part of his bid also concerns the financing of the work. In general, most contractors prefer the financing to come directly from the project itself; usually, however, the actual payments for work completed lag behind actual expenditures and thus the contractor has to acquire external financing for the resulting deficit in cash flow. Besides utilizing financing and paying the present high interest rates for this borrowed money, some contractors utilize a bidding strategy called "front-end loading" and "bid unbalancing". Through this scheme they attempt to break their unit prices down in such a way that early phases of work have unit prices exceeding actual costs and unit prices on later work are below cost to allow for early cash flows to compensate for this deficit in funds. Some owner agencies try to prevent this scheme by providing a bid item for mobilization to allow the contractor due compensation once he sets up on the project site.

Another factor the contractor must be concerned with, is the retainer that the owner withholds from partial payments. During the first 50% of the project this retainer is normally 10% of the partial payment amount, such that at the 50% complete mark the owner has a retainer equal to 5% of total construction cost. If progress proceeds
satisfactorily, thereafter, the owner utilizes several schemes that include:

- retaining the present funds and not withholding from future payments (i.e. retaining a fixed 5% of construction cost through last half of project)

- retaining an amount equal to 10% of the amount of the work remaining to be completed

- retaining an amount ranging between 2% - 10% of construction cost.

The owner normally retains, as a minimum, about 2% of the construction cost to ensure that the contractor has adequate incentive to complete the project.

3.4.6 Contingencies.

The final element that will be considered in the bidding phase is the contingencies normally incorporated into each bid. The amount of these contingencies usually varies with each contractor; most contractors, however, thoroughly assess the potential contingencies in three broad categories (Stasiewicz, 1981):

- Design,

- Construction, and

- Interface.

In the design contingency, the contractor has to consider the many issues that restrict and/or specify the flexibility that may be applied to the construction process:

- Do the contract documents allow the contractor to apply his own
construction know-how through performance specifications, where the construction criteria establish only what the finished product should be; or, do the contract documents specify in detail how the contractor is to proceed giving him little or no flexibility in applying his own expertise?

- Is the design, as presented along with the specified construction methods, feasibly constructible or are there gray areas in the contract documents where disputes may arise?

- Are there potential errors and omissions in the drawings that will require additional contractor effort?

- Another factor to consider is the attitude of the designer. How cooperative will the designer be in working with the contractor in smoothing out problem areas?

These are major questions that must be answered prior to establishing the size of contingency that will be added.

Construction contingencies are included to protect the contractor against his own omissions or errors made in the bid preparation phase and the construction phase. If insufficient time is allocated for bid preparations, some contractors may include contingencies to protect against any miscalculations in preparing a bid. In the bidding phase, the contractor may be uncertain whether the construction method he chooses will be adequate, thus he may include a contingency to cover costs (or at least a portion of the cost) associated with modifying
construction methods. The construction process most likely to include contingencies are the excavation and initial support as well as the dewatering process. Even though geotechnical interpretations, irrespective of their source, must include a prediction on how the ground will respond to the chosen excavation and support methods, there is a considerable amount of uncertainty associated with this estimate. As a result, the contractor typically includes a considerable amount of contingency to protect against the risk of differing ground behavior. This risk may necessitate significant changes in the excavation, support and dewatering procedures, any of which can decrease the anticipated advance rate and increase the final cost of the work. Also to be considered in this contingency are potential delays in equipment and materials delivery, labor delay, "no damage" owner caused delays, and weather delays. One must also provide contingencies to protect against escalation costs on labor, material and equipment.

The interface contingency is commonly referred to as contingencies for conflict between contractors that either require the same working space, or depend on each other because the commencement of work by one contractor is contingent on the completion of work by the other. For example, one contractor may be responsible for providing access shafts for another contractor; a delay in the availability of an access shaft can postpone the commencement and severely hamper the schedule of all future construction projects, especially if subsequent contracts must also interface with other project milestones. In determining this contingency the contractor must recognize the potential problem areas as well as the limits of compensation provided by the contract.
In addition, the definition of interface contingency can be expanded to include the working relationships and attitudes of the three parties to the contracts - the owner, the designer and the contractor. Some of the most significant disputes result from the lack of compatibility and cooperation among these parties. Thus, incorporated into the interface contingency should be the delays and costs expected to result from disputes settlement and decision making.

There is obvious overlap between the interface contingency involving working relations and attitudes and the other two types of contingency (design and construction). For example, the amount of flexibility in the specifications may be contingent upon how well the contractor and designer work together. Usually, a highly reliable and respected construction firm can interpret a lot more flexibility in the contract language than another firm which may not be considered as reputable by the design firm. Similarly, many of the construction contingencies involve the owner's fairness in recognizing claims for legitimate differing site conditions. If an owner has a reputation of denying every claim presented by the contractor, then contractors may include contingencies in their bids to insure that they are, at least partially, compensated for legitimate claims not recognized by the owner.

3.5 Construction Phase.

The construction phase of the project is the final phase to be reviewed in the project life cycle. In the general discussion of this
phase the following key issues will be presented:

- Owner's field organization.
- Adverse relationships.
- Dispute settlement.
- Decision making authority.
- Value engineering proposals.

3.5.1 Owner's Field Organization.

There are actually three alternatives available to the owner for organizing his field staff. The owner can use his own in-house engineering personnel to perform the project management functions. If the owner agency has well-qualified tunnel engineering on staff then it is advantageous to perform the project management functions for the following reasons:

1. There is a tendency for independent project management firms to be concerned about their own liability and interests.

2. It is more costly to contract out the work than if it can effectively be done in-house, and

3. By eliminating an independent project management firm, the decision making process is reduced by one level of review.

Another alternative is to hire an independent project management firm. If such action is taken, it is imperative that the firm selected

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22 A detailed discussion of this phase can be found in Stasiewicz, 1981.

23 The Army Corps of Engineers is a primary example of an effective in-house project management operation.
have past experience in tunnel construction and in particular that the personnel assigned to the project possess this knowledge. The main disadvantage to this alternative is that a project management firm that had no input into the design process is responsible for interpreting the intentions of the design for construction. Thus there is the potential of conflict between the design and project management firms about the design intent and feasibility.

The third alternative is to let the design firm perform the project management function. Unless the design consultant has past construction management and tunneling experience, it may be better to separate these two functions. The primary advantage to this approach is that the field staff fully understands the design intentions presented in the documents. A disadvantage to this alternative is that there is no "checks and balance" process to insure that the designer has performed his function properly. By having a separate project management organization, either with in-house personnel or an independent firm, design deficiencies can be contended with directly, in fairness to both the designer and the contractor.

3.5.2 Adverse Relationship.

The adverse relationship that is considered common in today's contracting can be primarily attributed to two specific factors:

1. The groundwork already established by the earlier phases of the project life cycle, and

2. The field-representative relationships between the owner and contractor.
Most of the foundation upon which the working relationship is built is founded in the project specifications. It is this document that sets the initial attitudes and behavior of the designer (owner) toward the contractor. In particular,

- the lack of authority of the owner's resident engineer,
- the abundance of documents the contractor is required to submit,
- the restrictions placed on the contractor to apply his general construction know-how without first asking permission,
- the inequitable distribution of risk and disclaimers for responsibility.

These can usually be found in most contracts documents. By incorporating these conditions into the contract documents the owner feels his interests are better protected, without realizing the significant detrimental effects that they have on the working relationships.

Another element in the life cycle that could increase the adverse relationship is inadequate bid preparation time. Some contractors may compress their normal bidding process in order to meet the bid opening deadline. As a result, they may overlook a major cost item or miscalculate. If this occurs, then it is the contractor who adds to the tension. A contractor who is losing money on the project may search for loopholes in the specifications in an attempt to recoup his losses. The end result of this action could be increased tension between the field representatives and more rigid compliance with contract documents, citing even minor deficiencies for non-compliance.

The recognition (or lack of recognition) by the owner of legitimate differing site condition claims, is a major area that affects the working
relationship considerably. Some owners have the tendency to forget the purpose of the changed conditions clause, which is to induce bidders to reduce their contingencies because due compensation will be made during construction (Rubin, 1975). Instead, they act as if there is no basis for legitimate claims to arise.

3.5.3 Dispute Settlement.

A recent survey of public transit contracts (Stasiewicz, 1981) stated that all contracts reviewed, with the exception of the Boston MBTA, specified the disputes settlement procedure and the levels of appeal possible to the contractor. The general appeals route frequently utilized is from the Engineer, to the Contracting Officer, to the Board of Directors, to the Civil Court. The attitudes and effectiveness of the disputes settlement process is directly related to:

1. The reasonableness of both the owner in recognizing legitimate claims and the contractor in submitting only justified claims, and

2. The fairness of both the owner in making due compensation and the contractor in submitting realistic cost estimates for the work.

If these criteria are met, then the disputes settlement process will be effective in the timely processing of claims.

3.5.4 Decision Making Authority.

It is fairly common to find a clause like the one below, taken from the Baltimore MTA-ML Project Supplemental General Provisions (Stasiewicz, 1981):
"Before starting work, the Contractor shall designate in writing the name, title, qualifications and experience of this proposed representative who, upon approval by the Engineer, shall have complete authority to represent and act for the Contractor."

There is, however, no reciprocal condition pertaining to the qualifications and authority of the owner's representative. Basically, the owner's representative is there to conduct inspections and insure compliance with the contract requirements. Unlike the contractor's representative, the owner's field staff normally has limited decision making authority and no expenditure authority. The function of the owner's representative is to report to higher organizational levels, which in turn may have to report even higher, depending on the issue at hand and the amount of money involved. As a result, the speed at which even minor decisions can be made can be very sluggish, a factor that may induce the contractor to recover smaller claims by "packaging" them with larger ones. An exception to this rule is the Army Corps of Engineers, whose field staff typically has decision making authority for any changes involving up to $25,000. Most other public owners provide no expenditure authority to their field staff and limited authority to organizational levels just above the field operation.

3.5.5 Value Engineering Proposals.

All contractors are required to base their bids on the contract drawings and specifications. These documents spell out in detail the procedures and responsibilities passed to the contractor. The contract does, however, provide a means by which the contractor performing the
work can alter these guidelines and use other methods, procedures, and designs, provided that this alternate contractor proposal is more cost effective and is approved by the owner. The means available to the contractor is the Value Engineering Clause of the contract. In accordance with this clause, the contractor can submit alternate cost-saving proposals to the owner for incorporation into the contract. If accepted by the owner, the net savings are usually shared equally between the owner and the contractor. On paper this concept appears to be a viable means of achieving cost effective underground construction.

The contractor who decides to submit a value engineering proposal must do a significant amount of initial design and cost estimating before he officially submits the proposal. In addition, some proposals may require the use of special equipment that, due to long delivery lead-time, the contractor may purchase in anticipation that his proposal will be accepted. The time and money spent during the initial phase can only be recovered if the owner accepts the proposal; otherwise, the contractor must absorb these costs, thus reducing the expected profit margin for this project. Some acceptable proposals may not be implemented if the approval process is lengthy, or the contractor fails to submit the proposal for review sufficiently prior to the commencement of the construction phase affected. If a contractor constructs a project in accordance with the drawings and specifications provided with the work, then he is not liable for the adequacy or feasibility of the design. If he submits a value engineering proposal that alters this design, however, then he becomes liable for its adequacy and thus carries additional risk.
3.6 Summary.

This chapter has presented the delivery process of underground projects from the planning phase to construction. The objective of this discussion was not to present all the details involved in this process, but rather to highlight some of the important aspects of the environment in which the owner, the designer and the contractor have to interact and exercise their decision making.

From this presentation several conclusions may be drawn:

The most important decisions influencing the cost of underground construction are made in the planning phase, during which the physical dimensions and the horizontal and vertical alignment of the project are determined. These decisions define the nature of the geologic conditions to be encountered during construction, as well as the range of feasible design and construction methods that may be adopted. Unfortunately, these decisions are sometimes made by persons who are not experts on tunnel design and construction, and on the basis of very little geologic exploration. As a result the decisions made in the planning phase do not always lead to the adoption of the most cost-effective alternative. Consequently, the degree to which the cost of underground projects may be optimized by the adoption of a comprehensive exploration program during the design phase, is limited by the decisions made in the planning phase.

The design phase begins following the completion of the project's Environmental Impact Statement. The engineer typically begins his task by obtaining the geotechnical information necessary for the development of the project's design. In public projects, the mechanism of project
funding places a considerable constraint on the amount of exploration that may be conducted during the initial design stages. As a result, the original design assumptions are frequently made on the basis of very limited information leading to the adoption of conservative assumptions and the development of a defensive design strategy. Even if a considerable amount of subsurface exploration is conducted during the later stages of design development, the original assumptions have a marked influence on the designer's willingness to review the design philosophy on the basis of new information. In most cases, the designer does not have the time or the incentive to review conservative assumptions and reduce the project's cost. Changes in design typically occur only if additional exploration reveals that the original design assumptions were inadequate. Design conservatism is not only induced by the amount of undertaken exploration. Several institutional factors have a negative influence on the designer's willingness to adopt innovative approaches and to optimize the cost of the work. These factors are primarily the designer's role in selecting a competent contractor, the design criteria imposed by higher levels of authority and the extent of the design firm's liability. As a result, the value of geologic exploration is significantly affected by the timing for conducting the exploration, as well as the amount of risks and liabilities imposed upon the designer by the owner-designer contract. The designer's most typical reaction to the amount of risk he has to bear is reflected in the common design philosophy of "designing for the worst possible geologic conditions and assuming that a less than desirable contractor will actually do the work".
The construction planning and bidding phase begins after the completion of the final design plans and specifications. During this relative short period of time the contractor has to determine the necessary construction methods for excavation, support and dewatering, and in addition estimate the total cost of construction. In this respect, the contractor is the entity that typically bears most of the financial risk of underground construction. In an attempt to achieve a risk-free position, most owners allocate to the contractor the full risk of geologic uncertainty. Even though most owners/designers today provide the contractors with all the geotechnical data and reports prepared and reviewed for design purposes, the validity of this information is sometimes disclaimed. As a result, the verification of this information, as well as the collection of additional information necessary for construction planning and estimating, becomes the contractor's responsibility. Since contractors have neither the time nor the resources required for this purpose, they have to adopt a conservative approach in planning and estimating the cost of the work. This is typically achieved by including considerable contingencies in their bids in order to cover their costs in the event that the project's geologic conditions are worse than assumed.

In conclusion, the delivery process of underground construction as currently practiced in the US. is characterized by excessive conservatism from both the designer and the contractor. Thus, the cost of underground projects cannot be significantly reduced unless the principles of risk reduction and risk sharing presented in the previous chapter are consciously adopted by the owners of these facilities. The remainder of
this report contributes to this cause by examining the economic value of exploration and in particular the usefulness of pilot tunnels as a risk reduction strategy.
Chapter 4

Subsurface Exploration Methods.

The ultimate goal of an efficient subsurface exploration program is to obtain the maximum amount of geotechnical information at a minimum of cost. This information will affect the feasibility, design, construction and performance of the proposed engineering structure.

Although the costs associated with conducting a conventional exploration program have been increasing at a rapid and uniform rate over the past 10 years, the level of recoverable information has increased at a slower rate (Thompson et al., 1980). As a result, optimal use of the available exploration funds should be made in order to collect all the necessary information on ground characteristics that are required for design and construction planning purposes. These characteristics have been subjectively grouped into a set of priorities for soft-ground and hard-rock tunneling and are shown in Table 4-I (Schmidt et al., 1976; Thompson et al., 1980).

Geotechnical engineers have at their disposal a wide range of data collection techniques with different costs and capabilities. These techniques range from the utilization of primitive and inexpensive equipment to today's sophisticated experimental technology. For example, some form of rotary core drilling was practiced by the Egyptians as early as 3000 B.C., while on the other hand, the Soviets have reported the development of a rocket drill capable of penetrating 60 feet of overburden in 18 seconds (Thompson et al., 1980).
PRIORITY A:

SOIL
- Stratigraphy (including groundwater level)
- Permeability
- Rock surface
- Obstructions, man-made or natural
- Cohesion of granular soils

ROCK
- General rock quality
- Groundwater
- Permeability

PRIORITY B:

SOIL
- Shear strength of cohesive soil (undrained)
- Water pressure
- Modulus, short term
- Soil classification, in general

ROCK
- Rock weathering
- Orientation of major planes of weakness

PRIORITY C:

SOIL
- Modulus, long term (consolidation characteristics
- Water chemistry
- Stress state (at rest pressure)
- Gases

ROCK
- Lithology and hardness
- In-situ rock stress
- Gases

**First Priority Characteristics

Table 4-I: Important Soil and Rock Characteristics
(Thompson et al., 1980).
The various field exploration methods available may be grouped into two general categories. "Direct" methods provide data relative to geotechnical parameters and stratigraphy from direct measurements made in the field. "Indirect" methods provide physical evidence of subsurface conditions but require correlations with known conditions through direct measurement. Borehole drilling, exploration shafts and pilot tunnels fall into the direct methods category, whereas most geophysical methods fall in the indirect category.

There currently exists a multitude of direct and indirect exploration methods. Each of these methods is basically characterized by the range of its applicability in different geologic formations and general project conditions, the nature and reliability of the observations provided, and by its availability and cost (Table 4-II).

Borings have been the most widely used method for subsurface exploration. They can provide data through field observations on stratigraphy, the general state of geologic strata, the subsurface water conditions, along with disturbed or undisturbed samples for laboratory testing. Borings are also relatively inexpensive (table 4-III). The major problems in the use of borings is the depth of the overburden above the project's elevation and the ability to observe actual conditions only within the small diameter of the hole. The last problem can be bypassed by the use of observation wells which employ a larger, but still relatively small diameter, sometimes allowing for direct visual observation by a geotechnical expert.

The information provided from boreholes can be enhanced by the use
<table>
<thead>
<tr>
<th>EXPLORATORY METHOD</th>
<th>URBAN APPLICABILITY</th>
<th>CURRENT USAGE</th>
<th>AVAILABILITY IN EXPLORATION PROGRAM</th>
<th>VALUE ADDED</th>
<th>RELATIVE COSTS</th>
</tr>
</thead>
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<td>INDIRECT</td>
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<td>4</td>
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<td>Medium</td>
</tr>
<tr>
<td>Observation Wells</td>
<td>High</td>
<td>High</td>
<td>1</td>
<td>1</td>
<td>Low</td>
</tr>
<tr>
<td>Piezometers</td>
<td>High</td>
<td>High</td>
<td>1</td>
<td>1</td>
<td>High</td>
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<tr>
<td>GEOPHYSICAL SURVEY</td>
<td>DIRECT</td>
<td>INDIRECT</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Resistivity Logging</td>
<td>High to Medium</td>
<td>2</td>
<td>3</td>
<td>2,4,5,6</td>
<td>High</td>
</tr>
<tr>
<td>Electric Logging</td>
<td>Medium to Low</td>
<td>2</td>
<td>3</td>
<td>2,4,5,6</td>
<td>Medium</td>
</tr>
<tr>
<td>Seismic\Enhanced Seismic Val.- Subsurface</td>
<td>High to Medium</td>
<td>2</td>
<td>3</td>
<td>2,4,5,6</td>
<td>Medium</td>
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<tr>
<td>Seismic\Enhanced Seismic Val.- Surface</td>
<td>Medium</td>
<td>2</td>
<td>3</td>
<td>2,4,5,6</td>
<td>Low</td>
</tr>
<tr>
<td>RESEARCH EXPLORATORY TECHNIQUES</td>
<td>DIRECT</td>
<td>INDIRECT</td>
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<tr>
<td>Horizontal Drilling</td>
<td>Medium</td>
<td>4</td>
<td>4</td>
<td>4,5,6</td>
<td>High</td>
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<tr>
<td>Thermometric Surveys</td>
<td>High</td>
<td>3</td>
<td>4</td>
<td>4,5,6</td>
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<tr>
<td>Acoustic Erosion Logging</td>
<td>Medium</td>
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<td>4</td>
<td>4,5,6</td>
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<td>4,5,6</td>
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<td>Low</td>
<td>3</td>
<td>4</td>
<td>4,5,6</td>
<td>Medium</td>
</tr>
</tbody>
</table>

**NOTES:**

1. High usage in exploration for transit tunneling.
2. Low usage in exploration for transit tunneling but medium to high usage in non-transit tunneling applications.
3. Low usage in exploration programs.
4. Low usage - under-development.

**A**

1. High availability.
2. High availability, requires specialized equipment.
3. Medium availability, requires specialty consultant and specialized equipment.
4. Low availability, requires specialty consultant and/or specialized equipment.

**B**

1. Base method.
2. Improvement in rate of exploration.
3. Improvement in quality of samples obtained.
4. Provides increased continuity of data.
5. Provides compilation of data obtained using other methods.
6. Provides new data.
7. Method of little value and generally should not be used.

**D**

Relative costs are compared within each category of exploration method, and also reflect necessary preparatory work prior to the implementation of the method. Any decision on exploration method should not be based solely on cost, but on obtaining the maximum information consistent with project objectives, subsurface conditions, and cost.
<table>
<thead>
<tr>
<th>ITEM NO.</th>
<th>DESCRIPTION</th>
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</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4&quot; - 6&quot; &quot;UNSAMPLED&quot; OVERBURDEN AND ROCK DRILLING PER FT.</td>
<td>7.90</td>
</tr>
<tr>
<td>2</td>
<td>4&quot; - 6&quot; &quot;SAMPLED&quot; OVERBURDEN DRILLING PER FT.</td>
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<tr>
<td>3</td>
<td>NW-3 DOUBLE TUBE ROCK CORE PER FT.</td>
<td>19.00</td>
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<tr>
<td>4</td>
<td>NW-3 TRIPLE TUBE ROCK CORE PER FT.</td>
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</tr>
<tr>
<td>5</td>
<td>2&quot; SPLIT-SPOON SAMPLES PER EACH ATTEMPT</td>
<td>23.00</td>
</tr>
<tr>
<td>6</td>
<td>3&quot; SPLIT-SPOON SAMPLES PER EACH ATTEMPT</td>
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</tr>
<tr>
<td>7</td>
<td>3&quot; O.D. PITCHER SAMPLES PER EACH ATTEMPT</td>
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</tr>
<tr>
<td>8</td>
<td>3.5&quot; O.D. DENISON SAMPLES PER EACH ATTEMPT</td>
<td>120.00</td>
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<tr>
<td>9</td>
<td>CREW AND DRILL RIG RATE FOR INSTALLING INSTRUMENTATION TESTING, ETC. PER RIG HOURS</td>
<td>60.00</td>
</tr>
<tr>
<td>10</td>
<td>WATER PRESSURE TEST, PER EACH</td>
<td>95.00</td>
</tr>
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<td>11A</td>
<td>ISM TESTING INCLUDING OVERBURDEN AND ROCK PER RIG HOURS</td>
<td>68.00</td>
</tr>
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<td>11B</td>
<td>ISM EQUIPMENT RENTAL, LUMP SUM, 30 DAYS</td>
<td>4400.00</td>
</tr>
<tr>
<td>11C</td>
<td>ISM TECHNICAL REPRESENTATIVE PER DAY</td>
<td>370.00</td>
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<tr>
<td>11D</td>
<td>ISM DIAMOND BIT WEAR PER FOOT</td>
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<td>12A</td>
<td>BUFFALO ROADWAY BOXES, 5&quot; DIAMETER PER BOX</td>
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</tr>
<tr>
<td>12B</td>
<td>CEMENT PER 94 LB.</td>
<td>5.00</td>
</tr>
<tr>
<td>12C</td>
<td>2.5&quot; I.D. SCHEDULE 40 P.V.C. FLUSH JOINT PIPE PER FT.</td>
<td>1.65</td>
</tr>
<tr>
<td>12D</td>
<td>2.5&quot; I.D. SCHEDULE 40 SLOTTED P.V.C. FLUSH JOINT PIPE PER FT.</td>
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</tr>
<tr>
<td>12E</td>
<td>3/4&quot; P.V.C. SCHEDULE 80 PIPE PER FT.</td>
<td>0.85</td>
</tr>
<tr>
<td>12F</td>
<td>BENTONITE M PELLETS PER 50 LB. BOX</td>
<td>50.00</td>
</tr>
<tr>
<td>12G</td>
<td>OTTAWA SAND PER 50 LB. BAG</td>
<td>7.50</td>
</tr>
<tr>
<td>12H</td>
<td>FINE &quot;PEA&quot; GRAVEL PER CUBIC YARD</td>
<td>10.00</td>
</tr>
<tr>
<td>12I</td>
<td>CALCIUM CHLORIDE PER 50 LB. BAG</td>
<td>10.00</td>
</tr>
<tr>
<td>12J</td>
<td>COMMON SAND PER CUBIC YARD</td>
<td>10.00</td>
</tr>
<tr>
<td>12K</td>
<td>CALCIUM CARBONATE PER 50 LB. BAG</td>
<td>3.00</td>
</tr>
<tr>
<td>12L</td>
<td>BUFFALO ROADWAY BOXES, 2.5&quot; DIAMETER PER BOX</td>
<td>15.00</td>
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<td>13</td>
<td>MOBILIZATION AND DISMANTLING PER RIG</td>
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<td>14</td>
<td>MOBILIZATION AND DISMANTLING FOR &quot;ODEX&quot; EQUIPMENT PER RIG</td>
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</tr>
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<td>15</td>
<td>&quot;ODEX&quot; EQUIPMENT RATE FOR OVERBURDEN AND ROCK DRILLING, PER RIG HOURS</td>
<td>125.00</td>
</tr>
<tr>
<td>16</td>
<td>UTILITY CLEARANCE, PERMITS, INSURANCE, BONDS LUMP SUM</td>
<td>1400.00</td>
</tr>
</tbody>
</table>

Table 4-III: Summary of Exploration Unit Prices (Thompson et al., 1980).
of indirect exploration methods. These methods utilize the observations from boreholes to extrapolate to areas away or between direct observations. This is accomplished by using correlations between the indirect and direct observations. Table 4-IV shows some geophysical techniques along with their range of applicability.

4.1 Pilot Tunnels as an Exploration Strategy.

Pilot tunnels are, as the term implies, tunnels constructed before the design of the project is completed in order to provide additional geologic information to both the designer and the contractor.

Pilot tunnels typically have a smaller cross section than the main opening and run in parallel to the project axis. They may be located near the crown, invert, or center of the main opening or they may even be located outside and parallel to the project axis at various elevations. There are no set rules as to the size of the cross section, the location and the length of pilot tunnels. These decisions are usually made on a project by project basis; it is customary, however, for the pilot tunnel to have a cross section that is large enough to allow labor and equipment to function efficiently during its construction. As an example, figure 6-1 shows a cross section of the Porter Square Station and the adopted pilot tunnel.

Pilot tunnels have been considered as the most accurate means of subsurface exploration, probably second only to excavating the actual project itself (Stasiewicz, 1981). Pilot tunnels enjoy many advantages in comparison to boreholes, not only because they provide a much larger
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<tbody>
<tr>
<td>3-D Velocity (A)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Acoustical Imaging (A)</td>
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<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
<td>x</td>
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<tr>
<td>Seisviewer (A)</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td>x</td>
<td></td>
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<tr>
<td>Velocity (A)</td>
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<td>x</td>
<td>x</td>
<td>x</td>
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<td>Wave Amplitude (A)</td>
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<td></td>
<td></td>
<td></td>
<td>x</td>
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<tr>
<td>Gamma Ray (N)</td>
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<td></td>
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<td>x</td>
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<td></td>
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<td>Neutron (N)</td>
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<td>Density (gamma-gamma) (N)</td>
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<td>Nuclear Magnetism (N)</td>
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<td>Induction (E)</td>
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<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
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<tr>
<td>Spontaneous Potential (E)</td>
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<td></td>
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<td>x</td>
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<tr>
<td>Borehole Gravimeter (M)</td>
<td></td>
<td>x</td>
<td></td>
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<td></td>
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<tr>
<td>Microlog (E)</td>
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<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>SP Dipmeter (E)</td>
<td></td>
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<tr>
<td>Guard and Laterologs (E)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>Caliper (M)</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
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<td>x</td>
</tr>
<tr>
<td>Borehole Television and Camera (E)</td>
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<td>x</td>
<td>x</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

(A) - Acoustical  (N) - Nuclear  (E) - Electrical  (M) - Mechanical

Table 4-IV: Geophysical Borehole Logging Techniques and Capabilities  
(Ash et al., 1974).
sample of direct observations, but also because these observations are 3-dimensional, whereas observations in boreholes are linear. Subsurface water conditions can only be inferred when using boreholes and/or geophysical methods; pilot tunnels allow a much better understanding of the true water conditions and the treatment necessary to alleviate any potential problems. On the other hand, a pilot tunnel alone provides no information about the geologic conditions beyond its outline, whereas boreholes can provide information from the ground surface to almost any depth. As a result, a pilot tunnel is seldom used as a substitute for borings, unless some physical constraint exists that prevents exploration from the ground surface.

Furthermore, pilot tunnels differ from all other exploration methods in that they provide the designer and the contractor with direct observations, not only on the nature of the geology, but also on its behavior under different excavation and support methods. In this capacity, pilot tunnels can be designed as small scale, real life experiments for testing the applicability and performance of new or specialized design and construction techniques. Even if no experimentation is undertaken, the compilation and availability of the pilot tunnel construction records provides benchmark information which can be used by the prospective contractors in choosing their construction strategies and estimating the associated production and cost of the work. Finally, in addition to its informational value a pilot tunnel can also be used as an integral part of construction. For example a pilot tunnel can be used for the installation of presupport in the project's crown, for dewatering and treating the rock ahead of the tunnel face, for
ventilation, blasting, etc.

From this brief description it can be seen that a pilot tunnel can have many potential uses. Thus, the decision to adopt a pilot tunnel must not only take into account its value as an exploration method; in addition, its contribution in providing design and construction information, as well its usefulness during the construction of the main opening must also be considered. These issues are examined in the next chapter.
Chapter 5

Subsurface Exploration - Pilot Tunnels.

The Contractors' Perspective.

5.1 Contractor Interviews - Questionnaire.

One of the basic tasks of this research is to provide realistic answers to some of the questions posed in the context of the problem statement regarding the value of geologic exploration and its use in construction planning and estimating. This task was accomplished by basically two means:

1. Personal interviews with contractors.

2. The development and distribution of a "Contractor Questionnaire".

In both cases the contractors were selected on the basis of having first-hand experience with the planning and estimating (but not necessarily with the construction) of urban or transmountain projects that utilized a pilot tunnel. In fact it was desirable to have a set of contractors that represented both unsuccessful and successful bidders on projects whose exploration program utilized a pilot tunnel. This approach was deemed necessary in order to acquire a representative spectrum of opinions on the issues of interest and thus to avoid the biases that inevitably arise when using a small number of experts. This is of particular importance in this case because some of the successful contractors tend to discount their state of information prior to
construction in the light of the actual experience.

The names of the individuals involved in this effort and their companies can be found in Appendix A. The "Contractor Questionnaire is shown in Appendix B.

The questionnaire was divided into 12 sections dealing with the following topics:

1. Perfect information on geology.
2. Subsurface water conditions.
4. Geologic prediction.
5. Definition and use of ground classes.
6. Initial support prediction.
7. Excavation and advance rate estimation.
8. The definition and importance of cost classes.
9. The location and size of a pilot tunnel.
10. The benefits and problems resulting from the use of a pilot tunnel.
11. Extrapolating from a pilot tunnel's observations.
12. Risk sharing - Contracts - Bidding behavior.

This section will present the responses and comments made with regard to each of the above issues. Every effort will be made to present the undistorted views of the participating contractors without introducing any unnecessary bias. In order to preserve the right of the respondents' opinion and since the objective of this study is to assess the general and unbiased state of the industry, the group of respondents
will be treated as a whole without associating specific comments with a particular individual.

5.2 Perfect Information on Geology.

One of the basic objectives of this research was the assessment of the contractors' definition of a "sufficient" set of geologic parameters and descriptors. This set would provide the contractor with all the information necessary to completely alleviate the geologic uncertainty affecting his tasks in construction planning and estimating. In a contractor's words the question is to determine "a wish list of geologic descriptors". Besides stating these parameters the contractors were also asked to rank them according to their importance.

The responses of four contractors are shown in Tables 5-I, 5-II, 5-III, 5-IV. These tables indicate a general agreement on which parameters are considered to be the most important. It is easy to see that the 7 most important geologic descriptors are:

1. Rock type.
2. Joint density (RQD).
3. Fault characteristics.
4. Joint appearance.
5. Degree of weathering.
7. Water pressure.

Even though a definitive list seems to be evident, the relative
<table>
<thead>
<tr>
<th>GEOLOGIC PARAMETERS</th>
<th>CR1</th>
<th>CR2</th>
<th>CR3</th>
<th>CR4</th>
</tr>
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<tbody>
<tr>
<td>1. Rock type (hardness, compressive strength)</td>
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<td>1</td>
<td>1</td>
<td>1</td>
</tr>
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<td>2</td>
<td>2</td>
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<td>3</td>
</tr>
<tr>
<td>3. Fault characteristics</td>
<td>3</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>4. Joint appearance</td>
<td>5</td>
<td>7</td>
<td>2</td>
<td>4</td>
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<tr>
<td>5. Degree of weathering</td>
<td>4</td>
<td>9</td>
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<td>5</td>
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<tr>
<td>6. Ground water inflow</td>
<td>6</td>
<td>4</td>
<td>1</td>
<td>6</td>
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<tr>
<td>7. Ground water pressure</td>
<td>7</td>
<td>5</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>8. In situ stresses</td>
<td>9</td>
<td>9</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>9. Joint orientation</td>
<td>8</td>
<td>8</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>10. Abrasiveness</td>
<td></td>
<td></td>
<td></td>
<td>10</td>
</tr>
<tr>
<td>11. Bedding planes</td>
<td></td>
<td></td>
<td></td>
<td>6</td>
</tr>
</tbody>
</table>

Ranking convention: 1 signifies the most useful parameter.

- : parameter is not required.

(blank): no ranking provided.

Table 5-I: Overall Ranking of Geologic Parameters.
<table>
<thead>
<tr>
<th>GEOLOGIC PARAMETERS</th>
<th>CONTRACTORS' RANKING</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CR1</td>
</tr>
<tr>
<td>1. Rock type (hardness, compressive strength)</td>
<td>X</td>
</tr>
<tr>
<td>2. Joint Density (RQD)</td>
<td>-</td>
</tr>
<tr>
<td>3. Fault characteristics</td>
<td>X</td>
</tr>
<tr>
<td>4. Joint appearance</td>
<td>-</td>
</tr>
<tr>
<td>5. Degree of weathering</td>
<td>-</td>
</tr>
<tr>
<td>6. Ground water inflow</td>
<td>X</td>
</tr>
<tr>
<td>7. Ground water pressure</td>
<td>-</td>
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<tr>
<td>8. In situ stresses</td>
<td>-</td>
</tr>
<tr>
<td>9. Joint orientation</td>
<td>-</td>
</tr>
<tr>
<td>10. Abrasiveness</td>
<td>X</td>
</tr>
</tbody>
</table>

Ranking convention: X signifies a required parameter.
- : parameter is not required.
(blank) : no response provided.

Table 5-II: Ranking of Geologic Parameters Used for Excavation Construction Planning.
ranking of some of these parameters appears to be questionable. This is not really surprising. The relative importance of each of these parameters is closely associated with the state of the parameter itself and its resulting consequences with respect to tunneling. For example, the parameter "water pressure" may very well be the most important variable if the water pressure is expected to be extremely high, controlling thus all major construction decisions and outcomes. It must also be kept in mind that by breaking down these parameters and then ranking them one loses the effect of parameter combinations. As an example consider the parameters "fault characteristics" and "water pressure". Independently these parameters have a very different scope of meaning than they might when weighed simultaneously. In probabilistic terms this is equivalent to considering the difference in the marginal and the conditional distributions between jointly distributed random variables. Given that a severe fault exists, the probability of having major water inflow and pressure problems increases and so does the expected economic importance of treating the resulting water problems. As a result, the importance of the parameters describing the water conditions increases considerably.

5.3 Subsurface Water Conditions.

In certain types of projects, the rate of water flow and the total quantity of water can present a severe handicap to the work. In a slope being driven downgrade and in a vertical shaft relatively small flows of water can severly impede progress. In a large tunnel driven on an
upslope, fairly large flows may be drained by gravity, while in a small
tunnel the same flows might have to be pumped because there is no room
for drainage ditches.

Unless there is past experience in a given locality and in the same
geologic formation, it is impossible to predict with reasonable accuracy
the rates of flow, or the total quantity of water that might be
encountered. It is equally difficult, under such circumstances, to make
an advance determination, or even to evaluate in advance the measures
that might be successful in handling it. In those projects where the
total quantity or the rate of flow of groundwater is a real contingency,
it is recommended that the contract provide bid items related to its
control and handling. These could include items for the furnishing and
installation of pumping equipment of certain specified capacities; the
pumping or handling of water from headings, portals or shafts; drilling
and grouting at the tunnel face, and drilling and grouting from the
ground surface. Usually a certain amount of water per day should be
handled free of specific charge to the owner, with the bid items applied
over this minimum. If large quantities are a possibility, a sliding scale
might be provided, as well as lump sum payments for the specified
capacities for plant and equipment for pumping and handling water. To
prevent abuse of the pumping and grouting items, a certain maximum
payment in any one day could be specified, or "upset" unit prices could
be used. The objection to these expedients is that the contractor may not
feel that these prices were properly estimated (NAS, 1974).

To this effect, the contractors participating in this research were
asked to classify the ranges of water inflow that can can be considered
"insignificant", "moderate" or "problematic". Unfortunately, their responses were in considerable disagreement, probably due to the fact that each respondent had made unstated assumptions about the geometry, size, location and use of the hypothesized project. In particular, one of the contractors expressed the opinion that this question does not have a general answer. Instead he stated some of the conditions that must be known in order to be able to make a meaningful classification:

1. Is the tunnel of sufficient size to allow a drainage ditch large enough to carry all the water out of the way of tunnel traffic?

2. What type of tunnel traffic and equipment is involved (rubber-tired, rail, electric, diesel, etc.)?

3. What type of rock is involved? Does it stand up well to water and/or water with traffic? Does it erode? How much clay exists? Does the water carry sand? etc.

With respect to prediction, most contractors agreed that the reliability of predicting the true water conditions to be encountered during the construction of the main opening is strongly affected by the available information on the regional geology. Depending on the situation, the reliability of either boreholes or a pilot tunnel may be expected to be anywhere between 99% (very reliable) to 20% (very unreliable). If a relatively short tunnel (cavern) in very homogeneous material is explored by a full length pilot tunnel, the reliability of the findings would be considerably different from those obtained from another pilot tunnel used in a similar project that is located in cavernous limestone.

For most geologic formations, however, the general rule with respect to the reliability of exploration methods is that "a pilot tunnel is
expected to reveal the true water conditions whereas boreholes are not". No absolute reliability figures can be given for each of the methods for the reasons presented above.

Regardless of the actual quantity or rate of flow, the mere presence of water may adversely affect the prosecution of the work. In rock tunnels, even small quantities of water can lubricate joints and shear planes, causing a loss of ground stability. Also, small quantities of water under pressure can sometimes wash materials from gouge zones or other weak strata, causing cleanup and equipment maintenance problems as well as ground instability. An interesting issue concerning pilot tunnels is their effect in dewatering the rock mass and relieving some of these problems. If there is a significant amount of time lag between the completion of a pilot tunnel and the commencement of excavation for the main opening, the pilot tunnel can serve as a dewatering system for the surrounding rock, acting as a buffer against the impact of excessive water flow or pressure. The contractor can take notice of this effect and plan accordingly. In addition, the dewatering effect can help the contractor reduce his estimate of dewatering costs considerably. This is particularly true for the costs related to pump operation and maintenance which, in fact, represent the bulk of dewatering costs. With respect to equipment selection, the opinion was voiced that the contractor should still use pumps that are able to handle the maximum capacity, since this adds marginally to the project cost.
5.4 Parameter State Prediction.

Almost all of the geologic parameters and descriptors vary along the axis of the project in two ways:

1. There exists variability from one point to an adjacent point because of the way these parameters are defined or measured. For example, two adjacent samples will probably yield two slightly different values of RQD. This variation may be considered as noise around the true mean value of the parameter being estimated. Probabilistically, this situation deals with the sampling variability inherent in a random process when the value of the independent parameter is fixed. In this case, the independent parameter is the observation location.

2. At a more aggregate level there also exists the macroscopic variability of the expected value of the parameter as a function of location. If the distribution of the underlying random process is known, then this variability would be amenable to deterministic calculation. This is in contrast to the location specific randomness described above which still remains intact.

The problem here is one of statistical estimation of the states of a random process given a set of observations. As mentioned in the section describing the possible risk mitigation strategies in underground construction, the contractor's concern is not to estimate the
distribution of the underlying random process per se, but rather to estimate the sequence of geologic parameter states as they actually exist at the site. This represents a nontrivial statistical estimation problem that lies beyond the analytical capabilities of most contractors. The most popular alternative that almost all contractor's appear to adopt is to use a conservative envelope curve on parameter states based on:

1. The available observations on parameter states.
2. The description and prior knowledge of the regional geology.
3. Subjective expert judgement.

The degree of conservatism embedded in the estimation of this envelope curve (which is similar to the choice of a confidence level in standard one-sided interval estimation) varies depending on:

1. The number and the quality of the observations available.
2. The homogeneity of the geology.
3. The amount of prior information concerning the regional geology.
4. The size of the project and the effect of regional extremities.\(^2^4\)
5. The contractor's estimating techniques.
6. The perceived economic consequences of misjudging the true state, which of course is a function of:

\(^2^4\) As an example consider the case of a cavern to be constructed through an expected 50 ft. fault zone. The cavern is perpendicular to the fault and the fault dips steeply. This single fault will have a much larger bearing on the overall construction of the project if the project is a cavern that is 100 ft. high, 60 ft. wide and 200 ft. long, as opposed to a 25 ft. horseshoe tunnel that is 20,000 ft. long.
5.5 Geologic Prediction.

In considering the effectiveness of pilot tunnels as compared to other direct exploration methods, such as boreholes, one must at first consider their differences with respect to the information they provide.

Boreholes provide location-specific information concerning the geology encountered across their full length. In this respect, each borehole provides limited information in the horizontal direction due to its small cross section, but can be extended (at least theoretically) to any depth that is required. Pilot tunnels, on the other hand, provide information that is continuous over their (horizontal) length but they are restricted in that they they do not allow observations beyond their outline. Since by definition neither method covers the whole volume of the future main opening it is obvious that neither method can be generally assumed to provide perfect information on the project's true geologic conditions.

There are two important issues to be considered with respect to geologic prediction. In either case it is necessary to distinguish between the prediction of a geologic parameter state and the prediction

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25For the sake of simplicity it will be assumed for the time being that boreholes are vertical whereas a pilot tunnel is horizontal; In fact, this assumption represents the majority of cases.
of a state's persistence (extent) along the main axis of the project. This is necessary because the effectiveness of each method depends on the quantity being estimated. In addition, it also depends on the geologic formation at hand.

In particular, if the project is located in a horizontally bedded formation that is highly variable in the vertical direction (i.e. the future opening lies completely in "mixed face" conditions) then a pilot tunnel would be a very poor predictor of both states and extents, whereas a set of boreholes would provide a very good description of all the encountered strata. On the other hand, if the formation is highly variable in the horizontal direction then the situation would be reversed. As a result, it is very difficult and even questionable to compare the effectiveness of each method without taking into account the nature of the geology.

The problem becomes even more complicated when one considers that in most cases a pilot tunnel is almost always complemented with a comprehensive borehole program (at least in urban projects). In these cases one has to consider the incremental value of the pilot tunnel observations, an issue that can easily become quite controversial since most people cannot discriminate between (or agree upon) what was actually known before and after the construction of the pilot tunnel.

Given the above observations, none of the contractors participating in this effort was able to provide general conclusions that would have universal applicability. The only exception to this, was the question concerning the linear density of borehole locations that would provide a
contractor with the same amount of information as a pilot tunnel. In particular, there was general agreement that, at least for tunnels, a horizontal borehole spacing between 50 to 200 ft. (depending on the project's geology) should be enough to make the two methods equivalent. This conclusion, however, does not apply to subway stations, cross passages, vent areas or other major caverns.

Finally, it must also be pointed out here that beyond comparing pilot tunnels to any other exploration method by considering each method's "potential" capabilities, it is equally important to consider the source and completeness of the information as presented to the contractor in practice. In this respect, there was unanimous agreement that a pilot tunnel provides the most complete information in the sense that a contractor can see for himself what "the rock looks like and how it behaves". In all other cases the contractor has to rely on the information provided by the designer. Even though the designer tries to anticipate the contractor's needs as much as possible, the information may not always be as complete and easy to understand or interpret as the contractor would like. In addition, since the contractor is only given a limited amount of time (normally 60 to 90 days) within which he must prepare his bid (with no guarantee that he will indeed construct the project), he cannot devote as much time in evaluating each project's geologic conditions as the owner or the designer can. It is the general consensus among contractors that the employment of a pilot tunnel alleviates some of this problems. Although the amount of published material may expand with the construction of a pilot tunnel, most contractors "feel more comfortable in relating the pilot tunnel field
observations to the actual project conditions, as opposed to just using only published information”. As a result, the major advantage of a pilot tunnel (beyond its usefulness as a powerful exploration method) is that it provides each contractor with a “quick and reliable means of determining what he should plan for”.

Some contractors definitely opposed the idea of using a pilot tunnel as an economically justifiable exploration strategy, and explained their position by reversing the above argument:

“If a contractor does his homework properly then there is no need for a pilot tunnel; it is just too expensive (if its sole purpose is to let the contractor take a look at the geology) as compared to other (equally effective) exploration methods”.

This statement, however, implies certain assumptions and can be interpreted to mean that if the contractor:

- acquires as much general information as possible about the regional geology,

- studies the results of all direct and indirect exploration methods that are available (assuming that the location of the project is such that exploration can be conducted from the ground surface),

- employs his own geotechnical consultant if the need arises,

- has good knowledge of the external constraints and requirements that he should plan for,

- and the pilot tunnel is not used as: an integral part of the main project; i.e. the pilot tunnel is not used for:

  * instrumentation, monitoring, or experimentation,

  * presupposing the main opening,

  * dewatering or treating the rock ahead of the face,

  * blasting the rock,
* ventilation,
then the contractor should be able to get all the information he needs from other "traditional" sources. If this information is still inadequate then additional "inexpensive" observations can be acquired for far less than a pilot tunnel would cost.

This disparity of opinion as to the economic value of a pilot tunnel does not imply a fundamental disagreement among the contractors; instead, the disagreement appears to be superficial since each of the respondents made a different set of assumptions when expressing his point of view. Indeed, the consideration of these assumptions provides the guidelines under which, at least from a contractor's point of view, a pilot tunnel should or should not be considered.

5.6 Ground Classes.

A contractor does not base his decisions with respect to construction planning and estimating on the prediction of geologic parameter states alone. Instead, he must also take into account the interaction of these parameters in much the same way as the designer does when he contemplates the final design considerations.

In order to assess construction parameters like the advance rate and the initial support requirements the individual geologic parameter states must be grouped and considered jointly. The term "ground classes" has been used to represent the set of such parameter state combinations that require the same excavation and support methods. Such an approach is used by most, if not all, of the empirical methods for tunnel support
prediction.

Even though most designers use the existing empirical classification schemes for the definition of ground classes, at least as a decision aid, this uniformity of approach does not appear to be the case for contractors. Some contractors do use the standard classification methods and some do not. In response to which methods are used in practice one of the contractors cited the following:

- Bischoff and Smart Equivalent Rock Reinforcement Analysis.
- Norwegian Geotechnical Institute (NGI) "Q" System.
- Bieniawski's Rock Mass Rating (RMR) System.
- Terzaghi's Rock Load System.
- Deere's Rock Quality Designation (RQD) System.
- Heuer's Shotcrete Design Analysis.

Other contractors responded that they primarily use Deere's RQD system whereas others responded that they do not employ any of the standard methods.\textsuperscript{26} Since all the above methods are empirical and as such were developed by observing "cause and effect" in the behavior of different types of rock (from observations in several projects), it is not surprising to find that most experienced contractors have developed their own criteria for classification. As a matter of fact, some

\textsuperscript{26} This may not be an accurate statement. Most contractors do (at least) use the RQD system. It is very likely that some contractors responded that they do not use the standard methods because they have developed their own criteria for the interpretation of the standard geologic parameter states and do not fully comply with the method.
contractors argue that this is precisely the feature that makes tunneling such an entrepreneurial undertaking and provides experienced contractors with an edge over newcomers in the field.

In addition, this is also evidenced by the statement that a contractor may use different classification criteria for determining the advance rate, the excavation method or the initial support requirements. The decision on which approach is the most applicable varies depending on the nature and size of the project, the regional geology and the dominance that some extreme parameter states may have over the others.

Finally, a very interesting comment made by all the respondents is that the greatest uncertainty does not lie in the prediction of the ground class per se, but rather in the extent over which this ground class persists. It is interesting to notice that a similar statement was not made with respect to the individual parameter extents. If the association of parameter states with construction methods (i.e. the definition of ground classes) was completely deterministic, then the determination of the ground class extents should present the same degree of estimating difficulty. In practice, however, this is not the case. The definition of ground classes and their correspondence to construction methods involves a certain amount of conservatism, especially when a certain geologic parameter combination (geologic vector) lies in the "gray" area between two different classes. Obviously, the "safe" approach is to include such vectors in the more conservative ground class. This is clearly expressed in the following statement concerning the support of the Porter Square Station:
"Although subjectivity seems to be largely excluded from support predictions, one has to be aware that this is mostly due to the dampening of parameter differences, when relating parameters (rock classes) to supports. Where the effect of subjectivity did not disappear is in the spatial fluctuation of rock class predictions. These fluctuations, which indicate the length over which a construction procedure would be used, are important in longer tunnels." (Einstein et al., 1983).

If one considers the association of geologic conditions with construction methods as a variation of a regression problem, then the definition of ground classes becomes the transformation mechanism for relating the states of the geologic parameters chosen as the explanatory variables and the adequacy of the construction methods. It is obvious then, that the accuracy in predicting whether a certain construction method is adequate depends on which parameters are used as explanatory variables, as well as on the adopted transformation model (i.e. the relative weighting of parameter importance and the association of ground classes with construction methods). In simpler terms, the transformation from a state of information on the geology to a state of information on the adequacy of potential construction methods is in itself uncertain. This uncertainty is the cause of the aforementioned difficulty in establishing ground class extents, because it is not clear when a more conservative construction method can safely be replaced by a less conservative one (i.e. the problem is to estimate the (least conservative) absolute location of the interface between segments that require different construction methods). It is in this spirit that the
following comment was made:

"The greatest uncertainty is not in establishing the ground class states (since this is just a function of the likelihood of geologic parameter states and the ground class definitions) but rather in determining how a particular ground class will behave (in response to the associated construction method)".

This observation is fundamental in understanding the contractors' behavior with respect to making construction planning and estimating decisions. The most widely used methodology is a variation of hypothesis testing, whereby, on the basis of some supporting evidence, a conservative assumption is initially made - the null hypothesis. The null hypothesis is usually proposed by an experienced individual (from within the contractor's organization) based on this person's perception and interpretation of the geologic information available and drawing on past construction experience in a subjective manner. As such the development of the null hypothesis is contingent on the geologic and construction related information on which it is based, as well as on the subjective judgement involved. The null hypothesis is subsequently tested by either the same person or other people within the contractor's organization, on exactly the grounds on which it was based:

- Other persons may have additional information that was not originally considered (or equivalently the contractor acquires additional information after the development of the original assessment).

- Different people drawing on their own background and experience may propose a different interpretation of the information available.

- New "what if" scenarios (with respect to effect of the decision at hand on the overall construction of the project) may change the acceptable likelihood of the null hypothesis being wrong (i.e. the significance level).
Quoting one of the contractors interviewed:

"Decisions with respect to the assessment of the project's geology and the optimality of the construction approach to be adopted are made collectively. All personnel involved in a particular project assemble in "the war room" where all the assumptions, interpretations and strategies are put to the test: a certain (conservative) position is usually proposed and scrutinized; if somebody has sufficient evidence that a certain position is overly conservative (and can convince the others to this effect) then the former position is rejected and the cycle is repeated until everybody agrees."

5.7 Initial Support.

The prediction of the initial support is directly related to the previous section on establishing the project's ground class profile. Ground classes were indeed defined as a means of predicting the required support and as a result the observations made above still apply.

The relative\textsuperscript{27} importance of geologic parameters with respect to determining the initial support are shown in Table 5-III. Overall the 7 most important parameters are:

1. Joint density (RQD).
2. Rock type.
3. Fault characteristics.
4. Joint appearance.
5. Degree of weathering.

\textsuperscript{27}The given ranking of geologic parameters is not absolute. As explained earlier, the importance of each of these parameters depends on the regional geology, the type of the project, the states of the parameters themselves, etc.
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<tr>
<th>GEOLOGIC PARAMETERS</th>
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<th>CR3</th>
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<td>1. Rock type (hardness, compressive strength)</td>
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<td>2. Joint Density (RQD)</td>
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<td>4. Joint appearance</td>
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<td>9. Joint orientation</td>
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</table>

Ranking convention: 1 signifies the most useful parameter.

- : parameter is not required.

Table 5-III: Ranking of Geologic Parameters
Used for Initial Support Prediction.

7. Water pressure.

With respect to determining the initial support requirements, most contractors agree that in general a pilot tunnel can provide a reliable estimate for the needs of the main opening. The reliability of this prediction is again dependent on the regional geology, the pilot tunnel size, length and location in reference to the main opening, the size and length of the main cavern (tunnel) and the perceived ability of the pilot tunnel to represent the geologic conditions within the total volume of the project. Some contractors also expressed the opinion that a pilot tunnel can be a better predictor of the type and the extent of the support required (as opposed to other exploration methods) mainly because it allows visual inspection (i.e. an integrated picture of the geologic conditions) and instrumentation and monitoring of the rock behavior (over space and time):

"If a pilot tunnel requires steel, you know that a much bigger chamber will require steel; if a pilot tunnel is bald, from the rock type and the characteristics of that rock, a fairly good determination or the the required rock support can be made."

"One must be very careful in his observation of the pilot tunnel. Critical areas requiring support may not be evident due to the use of temporary supports, i.e. shotcrete and rockbolts. Rock movement cannot be easily determined with a naked eye. Instrument data must also be provided. Case in point would be the pilot tunnel in the DuPont Circle Station for WMATA in Washington, D.C."

The decision concerning the choice of initial support, however, is not based solely on geologic considerations. The contractors interviewed suggested several other technical, institutional and contractual factors that are equally important, such as:
- Tunnel use, location, size and length.
- Type of final lining and specification requirements.
- Contractor-crew familiarity.
- Safety of labor and equipment.
- Equipment, labor and material cost and availability.
- Excavation method.
- Bid prices versus "owner plugged" bid prices (more generally, the type of contract, the intent of the contract clauses, the procedure for justifying the "necessary" support and the wording of the changed conditions clauses).
- Predicted quantities of different types of support (i.e. economies of scale).
- Consequences of support inadequacy (with respect to the project and to other adjacent structures).

As a result, the configuration of the initial support (i.e. the types of temporary support to be actually used and the extents over which each type will be necessary) depends on the degree of uncertainty with respect to geologic conditions and the expected performance of each support type, as well as on the economic, contractual and institutional factors presented above. With respect to the latter and depending on the contract adopted by the owner, some contractors noted that the actual choice of the support during construction may also be based on a bid-unbalancing strategy. This strategy is sometimes adopted if the contractor believes that the engineer has underestimated the initial support requirements, or equivalently that the contractor will be relatively unconstrained in using large quantities of excess support. The contractor can unbalance (and lower) his bid by overpricing the (underestimated) excess support items and underpricing the
(overestimated) "expected" support quantities. Not only does this strategy increase the probability of the contractor being the low bidder, but also increases his expected profit margin. To avoid this potential problem, some owners do not let the contractors set their own prices for "excess quantity items"; instead the owner provides his own "plugged prices" for these items, an approach that if done equitably, is also supported by most of the contractors. In addition, owners also have the right to disqualify any tender if there is sufficient reason to believe that prices are unbalanced. In reality, however, such a claim is quite difficult to prove and enforce, even though it represents a desirable course of action:

"The contractor can use the amount of support placed as a means of making money by unbalancing his bid. High unit prices for support items induce the heavy use of support during construction (in the name of safety). Such unit prices (e.g. $/lb of steel) should be within a reasonable limit; otherwise, the bid should not be accepted. In other words, owners should control unbalancing as much as possible."

5.8 Estimation of the Advance Rate.

Progress in tunneling is measured by the advance rate (feet/shift). There is unanimous agreement among contractors that the construction advance rate (given a particular excavation and support sequence) is indeed the most important factor with respect to the determination of the time dependent variable cost of a project. The estimation of the advance rate can be conceptually considered as a two-step process. The contractor has to estimate:

- The likelihood of encountering different geologic conditions, a
task that is underlying construction planning and estimating in
general,
- The productivity of labor and equipment, given certain possible
geologic profiles.

The value and reliability of a pilot tunnel as a means of
determining the geologic conditions of a project has already been
discussed in the context of geologic inference. The most important
geologic parameters with respect to the estimation of the advance rate
are shown in Table 5-IV In particular, the 7 most important parameters
are:

1. Rock type.
2. Joint density (RQD).
3. Fault characteristics.
5. Joint appearance.
7. Degree of weathering.

In contrast to every other exploration method, however, a pilot
tunnel provides the contractor with information concerning both the state
and the behavior of the geology and the performance of different
excavation and support processes. The latter is a direct consequence of
the fact that the data concerning the construction of a pilot tunnel is
made available to all prospective bidders and as such can provide a basis
for estimating the advance rate for the construction of the main opening.
A list of such construction related information (contained in the
contractor questionnaire) includes the following:
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<tr>
<th>GEOLOGIC PARAMETERS</th>
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Ranking convention: 1 signifies the most useful parameter.

Table 5-IV: Ranking of Geologic Parameters
Used for Advance Rate Prediction.
1. Rock drillability data (force penetration rates for a certain drill).

2. Performance of different drilling and blasting patterns.

3. Average excavation and support rates (feet/shift).

4. Average cycle times (shifts/round).

5. Rock breaking and muck swelling characteristics.

6. Blasting vibrations for different blasting schemes.

7. Overbreak characteristics.

8. Rock stand-up time characteristics.

9. Dewatering requirements.

The usefulness of this information in estimating the advance rate has been the object of considerable disagreement among contractors. As explained earlier, this is probably due to the fact that the value of the above information is contingent on the representativeness of the pilot tunnel conditions as compared to the conditions in the final opening. In almost all cases, the equipment used to drive the pilot tunnel will be different from those used in the main project. As a result, some contractors discount most of the equipment-dependent data as meaningless, while others feel that a considerable amount of correlation still exists. This phenomenon is clearly evidenced in Table 5-V.

In spite of the above disagreement, the respondents indicated that:

- The pilot tunnel information is mainly used for determining, rather than verifying production rates.

- If there is a large discrepancy between the production estimated, and the one reported for the pilot tunnel, then the estimate is repeated to identify the cause of disagreement. In such cases, most contractors tend to place higher credibility to the pilot tunnel construction information (provided they believe in the applicability of the information to the main
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<th>Pilot Tunnel Construction Information</th>
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<td>2. Performance of different drilling and blasting patterns.</td>
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<td>3. Average excavation and support rates (feet/shift).</td>
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<td>5. Rock breaking and muck swelling characteristics.</td>
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<td>6. Blasting vibrations for different blasting schemes.</td>
<td>R</td>
<td>-</td>
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<td>7. Overbreak characteristics.</td>
<td>R</td>
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<td>8. Rock stand-up time characteristics.</td>
<td>R</td>
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<td>9. Dewatering requirements.</td>
<td>R</td>
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Key:  
R = required  
s = supplementary  
- = not needed

Table 5-V: The Value of Construction Related Information Provided by a Pilot Tunnel.
opening).

In addition to the issue of representativeness discussed above, the credibility of the pilot tunnel construction information is also dependent on who has undertaken its construction. Most contractors feel that the reliability of this information is much higher if the work was done by a reputable contractor and even more so if it was done by their own firm: "first-hand information is better than second-hand information".

5.9 The Excavation Round Length.

From a contractor's point of view, the most important decisions in tunneling deal with the determination of the optimum excavation-support sequence. An optimum sequence would enable the contractor to construct the project at a minimum cost, while observing all the prevailing constraints concerning safety, performance and functionality. Even though contractors do not use any formal optimization techniques for determining their optimal policy, they do experiment with different scenarios in order to arrive at an approximate solution.

A central issue in establishing the advance rate and hence the cost of each possible strategy is the determination of the round length, i.e. the basic length of progress along the alignment of the tunnel that can be achieved in each construction cycle\(^{28}\). The round length is primarily

\(^{28}\)A construction cycle involves excavation (drill-shoot-muck), support and the extension of necessary tunneling services.
based on the length of tunnel that can remain unsupported (from blasting the rock to installing the support), the required distance from the support to the face and the equipment limitations. As such, the basic variables influencing the round length are:

- the prevailing geologic conditions,
- the shape and size of the project,
- the excavation method and its impact on the stability of the rock,
- the desired rock movement before the installation of the support (to invoke the rock arch effect),
- the type and spacing of support and
- the speed of support placement.

The determination of the above variables is not only of interest to the contractor but also to the designer. The reason is that the round length and the distance of the support to the face are central in estimating the load that the initial support (and/or the final lining, depending on the situation) has to withstand. As a result, the designer often prescribes maximum values for both these variables in order to assure that the final load will not exceed the one assumed during the design. An interesting alternative, however, would be to specify the maximum allowable rock deformation (a measure of performance) and leave the decisions concerning the round length and support placement (logistics) up to the contractor. This arrangement would allow experienced contractors to take full advantage of their expertise and resources in determining what they consider as a more efficient excavation-support procedure. In addition, the contractor would be
forced to instrument and monitor the support's performance (in order to prove that the support conforms to the specifications), a fact that will inevitably lead to some form of construction adaptation based on feedback. As a matter of fact this may be a good first step in making US contractors more comfortable with the adaptable tunneling approach.

The contractors participating in this research had mixed reactions towards this suggestion. On the positive side, some contractors would prefer to be given performance measures rather than to be constrained on exactly how they operate. Their basic argument was that it would be more efficient to leave construction related decisions to the contractor's discretion. On the other hand, some contractors felt that such an arrangement would not necessarily be better because it places too much responsibility on the contractor. Instead, they proposed that rock deformation should be analyzed by the designer (the one most familiar with the project conditions) and its impact should be reflected in the design and suggested construction staging. In addition, all contractors admitted that the maximum round length suggested by the designer (if at all) is usually on the high side and often applies to the project as a whole. As a result, the contractor rarely uses the designer's estimate as the basis for construction planning and estimating. Typically, the contractor undertakes his own analysis of the project's geologic conditions and stability and uses these results to estimate the round length as a function of location.
5.10 Pilot Tunnel Location and Size.

There are no set rules concerning the location, shape, size and length of a pilot tunnel. These decisions vary from project to project depending on:

- The regional geology.
- The size of the project (cross section and length).
- The primary use of the pilot tunnel (geologic exploration, experimentation with design and construction approaches, ground treatment or reinforcement, instrumentation and monitoring, etc.).

The contractors participating in this research agreed that in general the best location for a pilot tunnel is in the crown of the future opening. Some contractors admitted that they could not even think of situations where the pilot tunnel would serve its cause better if located at any other elevation. Others, however, pointed out that while the crown is probably the most advantageous location, there are cases where the specific conditions of the project may favor other pilot tunnel elevations. In particular, one of the respondents suggested the following:

Crown: Large openings requiring support, instrumentation.
Center: Medium openings; favorable geologic conditions.
Invert: Drainage; sidewall support; wall plate drifts.
Below Invert: Drainage; instrumentation.

Even though this list is not definitive, it nevertheless illustrates some of the conditions under which a particular elevation may be chosen. The consideration of all possible conditions favoring a particular
configuration is unfortunately quite impossible since each project has its own unique characteristics.

The minimum cross section for a pilot tunnel is basically dictated by the need to have labor and equipment functioning as efficiently as possible during its construction. A minimum of 6 ft x 6 ft would be reasonable, even though 8 ft x 8 ft would be just as economical.

In addition, the diameter of the main opening must be large enough to justify the separate excavation of a pilot tunnel before the construction of the project. The minimum main opening diameter suggested by the contractors is in the order of 30 ft. This general suggestion, however, is not absolute. Depending on the location, accessibility, length and use of the project the minimum acceptable diameter may be larger or smaller.

In the same context, the adoption of a pilot tunnel depends on the length of the project as well. The project must be large enough to justify the cost and time involved in administering the construction of a pilot tunnel, even though the influence of the project's length is weaker than that of its cross section size. The determination of the minimum length is very much contingent on:

- The project's geology.
- The project's cross-section size.
- The integration of the pilot tunnel with the construction and operation of the main project.

Because of this strong dependence, the contractors' opinions varied widely, depending on the specific assumptions that each of them made.
The minimum length for a cavern ranges from 50 ft. to 500 ft. with a mean value of 250 ft. The minimum length for a tunnel ranges from 200 ft. to 2000 ft. with a mean value around 1000 ft.\(^{29}\)

In conclusion, there are few rules of thumb that can be employed in determining whether a pilot tunnel makes economic sense without jointly considering all the specific characteristics of the project at hand. Even though the above suggestions provide some general guidelines concerning the location of the pilot tunnel and the minimum size of the project, the decision of adopting a pilot tunnel can only be made through a careful analysis of its economic value as a subsurface exploration method and an integral part of the project's design and construction.

5.11 Extrapolating from Pilot Tunnel Observations.

As mentioned earlier, there are no fixed rules with respect to the size of pilot tunnels. By definition, any opening that runs parallel to the main opening and which is constructed in order to gather information concerning the design and construction of the project can be considered a pilot tunnel. According to this definition, full scale test sections can be considered as a special case of pilot tunnels. The term "test section" is defined here as a (full cross-section) segment of the main project that is primarily used for the development and validation of design and construction approaches. Test sections can be adopted in cases

\(^{29}\)One of the contractors did not provide an answer in this case; in his opinion a pilot tunnel can be economically justified only if used in caverns with a cross section of at least 50-70 ft.
where a "conventional" full length pilot tunnel would not be justified, either because the cross section of the main project is too small or because the main project is extremely long. In addition, of course, test sections are adopted whenever there are serious (technical, functional or economic) doubts as to the performance of the design, making thus full scale testing a necessity.\(^{30}\) Most of the previous discussion concerning the informational value of pilot tunnels was based on the (implicit) assumption that a pilot tunnel has a smaller cross section than the main opening but runs the whole length of the project (or is at least as long as the portion of the project under consideration). Under this assumption, the two main directions of inference are perpendicular to the project's axis. If, however, one assumes that a full scale test section is undertaken prior to the construction of the main project, then the main direction of inference changes to that of the project's axis (even though it is still required to predict geologic conditions outside the volume of the test section itself). In other words, one needs to extrapolate away from the pilot tunnel's (test section's) observations in all three dimensions.

The contractors participating in this research were in disagreement as to the value of these observations. Some considered the method as too expensive (primarily due to separate contract administration), by arguing that generally this kind of exploration (by staging the construction process) creates more cost than it saves. On the other hand, some

\(^{30}\) A comprehensive discussion on the effectiveness of test sections can be found in Lane (1975).
contractors suggested that the value of this approach is directly related to the degree of correlation between what has been observed in the excavated portion of the project and the remainder of the work (such correlation can easily be established if there are borehole observations for both the constructed and the unexcavated project segments). If this correlation is high (i.e. the project's geology is either highly uniform or repeats itself in cycles) then the proposed staging of construction can be of considerable value as a means of predicting not only the geology but the required support and construction performance as well. In contrast, if there are few or no borehole observations in the unexcavated portion of the work (as may be the case in a transmountain tunnel where the overburden is prohibitively high) this correlation cannot be established, even if it exists. Under these conditions, a pilot tunnel that does not run the full extent of the project loses most of its value. In other words, the observations made in a "short" pilot tunnel have little value when extrapolating in the direction of the tunnel's axis, unless the geologic conditions are known to be highly variable in the vertical direction and homogeneous in the horizontal direction (i.e. the exact opposite of the situation required for small cross-section, full-length pilot tunnels).

5.12 Advantages and Disadvantages of Pilot Tunnels.

Beyond its usefulness as a subsurface exploration method, a pilot tunnel may have several other uses depending on the configuration and needs of the project at hand. In evaluating the decision to use a pilot
tunnel, one should explicitly take the resulting benefits (or problems) into account because in some cases they may even outweigh the pilot tunnel's value as a pure exploration method. In addition, the construction of a pilot tunnel may include some of the work that would have been undertaken anyway, and as such, must not be included in its cost.

It became apparent from the beginning of this research that in most situations it would be impossible (and even unfair) to evaluate and justify the decision to use a pilot tunnel by merely considering its value as an exploration method. To counteract this problem, a significant effort has been devoted to the task of identifying some of the "non exploration" advantages (or disadvantages) of pilot tunnels as viewed by today's tunneling industry. A similar attempt was made to identify some of the cost items that are not uniquely associated with the construction of a pilot tunnel and which can thus be discounted as being unavoidable portions of the main project. Even though the consideration of these issues cannot be integrated into a general-purpose decision framework (in contrast to the value of exploration), it is still useful to discuss some of the potential benefits and problems that may arise, so that they can be treated at the project-specific level.

5.13 Pilot Tunnels - Benefits.

The benefits resulting from the use of a pilot tunnel can be divided into two sets. The first set is informational in nature. Its value stems from the fact that the corresponding information is made available during
the design-construction planning phase (i.e. prior to the commencement of the project's construction) and it can thus help both the designer and the contractor in eliminating some of the uncertainty involved in their respective tasks. This set includes:

- The information on the project's geology.
- The effect of a pilot tunnel in dewatering the rock.
- The information on the behavior of the rock under different excavation and support methods (including monitoring and experimentation).
- The production rates achieved during the construction of the pilot tunnel.
- The identification of external constraints on underground construction in general.

Most of these benefits have already been discussed.

The second set includes benefits that are realized because of the physical existence of the pilot tunnel and the resulting opportunity to use the pilot tunnel as an integral part of the construction process. In this sense, a pilot tunnel can be used for:

- The installation of presupport in the main opening's crown.
- Treating the rock ahead of the face.
- Dewatering the rock during construction.
- Providing relief in blasting the rock.
- Ventilation.
- Accessing critical locations.

- Other uses: For example, the pilot tunnel's outline provides extra surfaces that make the excavation of the first drift by mechanized ripping of the rock much easier. In addition, the existence of the pilot tunnel allows the possibility of using a partial face tunnel boring machine that anchors itself within the pilot tunnel and pulls (rather than pushes) the cutter head
towards the rock face; this approach has the advantage that the newly excavated area behind the machine is free to be supported as quickly as required.

The main difference between the two sets, as defined above, has to do with the timing of realizing the corresponding benefit. For the first set, the benefit is realized before construction begins, whereas for the second set the benefit is realized afterwards. In considering the value of a pilot tunnel "as an exploration strategy" (i.e. before construction begins) one has to still take both sets of benefits into account. This is particularly important, because in some cases the second set may be of more value than the first, or the elimination of the second (and more tangible) set may make a pilot tunnel an unattractive option.

It must be noted here that some contractors are uncomfortable with this approach because they do not believe that a pilot tunnel can be legitimately considered as the only source of the second set of benefits. This view is not altogether unjustifiable since some of these benefits can be achieved through other means as well; especially, in the case where the excavation of the main opening is to be done in multiple drifts, with the first drift being equivalent, in some respect, to a pilot tunnel. Even in this case, however, one should still take into account the existence of the pilot tunnel during the construction phase and estimate the value of the potential benefits or problems thereof, by analyzing the expected costs of the options with and without a pilot tunnel. In other words, one needs to look at the marginal value of the pilot tunnel benefits in comparison to the other options available.

This section examines some of the most important potential benefits
of a pilot tunnel that have not been addressed yet.

5.13.1 Presupport.

In cases where the main opening is quite large, or where the rock is of inadequate quality, the designer can use a pilot tunnel to install rock bolts in the opening's crown, acting as presupport for the first stage of the main project excavation. The objective of the presupport is to:

- minimize rock movement,
- reinforce the natural rock arch,
- decrease the required support for the main opening, and
- decrease the subsequent overbreak.

Contractors have very diverse opinions as to the usefulness of presupport. Some feel that the above objectives can be achieved and that presupport can indeed be of major help in reinforcing the rock and speeding up subsequent construction. Others discount the above benefits by arguing that if the support is installed during the main project construction on the same basis (e.g. time between blasting and supporting the rock, distance of support to the face, type of support) as for the pilot tunnel, then there should be no difference.

The whole issue appears to revolve around the size of the pilot tunnel as compared to the size of the first drift in multiple drift excavation\(^{31}\) and the span of rock to be initially exposed at the crown.

\(^{31}\)Assuming that the first drift will be located at the crown.
If the size of the two drifts is approximately the same, then it is obvious that, by definition, the "presupport" enjoys no particular advantages if installed from a pilot tunnel. On the other hand, if the pilot tunnel is much smaller than the first drift and the rock is not of particularly good quality, then the pilot tunnel presupport should be beneficial since it minimizes rock movement and the disruption of the natural rock arch. In fact, it is also possible to argue that in the latter case the installation of the presupport may even allow a decrease in the number of required drifts and thus help reduce the cost and time required for the construction of the main project. Other contractors, however, reverse this argument by pointing out that the installation of the necessary presupport is much more time- and labor-consuming if done from a relatively small opening.\(^\text{32}\) Thus, the effectiveness of presupport (if installed from a pilot tunnel) is affected both positively (less damage to the rock) and negatively (more expensive) by the pilot tunnel's size. An alternative that bypasses some of the difficulties in installing the presupport from the pilot tunnel is the option to wait until the main contract gets under way; the rock can then be presupported by installing rock bolts from the first drift and prior to blasting each round. This way the presupport extends over the length of one round ahead of the enlarged face where it is most needed.

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\(^{32}\)For example, in the case of the Porter Square Station, the initial plans called for the installation of 30 ft. rock bolts from a 12x12 ft. pilot tunnel (as part of the main contract). This would have required that each drill and each rock bolt be spliced twice. The final configuration consisted of a presupport of 10 ft. rock bolts.
In conclusion, the benefit of installing the presupport from a pilot tunnel is an issue that is very much dependent on the project's geology and the set of available options for sequencing the excavation and support of the main opening. In general, most contractors do not believe that the existence of the presupport can decrease the amount of overbreak to be experienced during the main excavation, while the ones who do cited a decrease of 10% to 20% (an indication that the effect on overbreak is also a function of the geology and other project characteristics). With respect to the advance rate and given that the presupport has already been installed, most contractors feel that its existence does speed up the construction of the project. The increase in the advance rate can range from insignificant, to 5% or even 10% depending on the situation. In general, the value of the presupport must be estimated on an individual project basis.

5.13.2 Blasting Considerations.

A common practice in hard-rock conventional (drill and shoot) tunneling is to use large-diameter burn-cut holes to furnish relief for the explosion (excavation) of the rock. A burn-cut provides space for the rock to expand during blasting, and thus provides the following benefits:

- Eliminates the need for furnishing relief through the
employment of short diamond-cut\textsuperscript{33} or V-cut\textsuperscript{34} holes,

- Allows each hole to be drilled the full length of the round,

- Long feeds can be used on each drifter\textsuperscript{35}, and since the feed can be as long as the round, steel changes will not be required for individual holes (which reduces the labor requirements and decreases the actual drilling time but increases the consumption of drill steel due to breakage) (Parker, 1970).

Most contractors agreed that a pilot tunnel (when viewed as a hole in the tunnel face) can serve the same purpose as a large burn-cut. In this capacity, a pilot tunnel can:

- provide relief for the subsequent heading rounds,

- help in reducing the blasting vibration levels, and

- decrease the cycle time per round.

As a result, it makes blasting rounds easier to design and excavate. The resulting effect on the advance rate can range, depending upon circumstances, from none (possibly even a hindrance) to a very substantial improvement.

According to one of the contractors interviewed, the existence of a crown pilot tunnel can also present a problem in that it may cause the rock to break in a non-uniform, wedge shape. The contractor sited his own

\textsuperscript{33}Inclined short drill holes near the center of the tunnel face, so arranged that when the first shots are exploded in the round, a diamond-shaped wedge of rock is removed; this allows relief for the remaining rock when the delay exploders set off the charges in the other drill holes.

\textsuperscript{34}A technique similar to diamond-cut.

\textsuperscript{35}A drifter is a heavy drill for drilling nearly horizontal holes in the tunnel face; drifters require support from jumbo-mounted jibs.
experience from an actual project where the existence of a crown pilot tunnel distorted the rock's reaction to blasting and caused more material to be excavated from the tunnel's crown than from the invert. In other words, instead of the face being vertical, excavation (blasting) exposed too much of the tunnel's crown and too little of its invert. As a result, too much of the crown was left unsupported because there was not enough room in the invert to install the already available, full-height steel sets. It is not clear, however, whether this problem is solely due to the existence of the pilot tunnel, or whether it can be attributed to inappropriate planning by the contractor. The fact that other contractors did not identify this problem does not really support either case (because it may be that they never experienced a similar situation); instead, one can safely conclude that this problem is not general.

5.13.3 Ventilation.

Under certain conditions, a pilot tunnel may also be used as a ventilation duct for the construction of the main opening. The amount of necessary ventilation is almost proportional to the amount of diesel horsepower used underground. The larger the tunnel, the more haulage units are required and hence the more horsepower; therefore, as the tunnel length increases, larger pipes and fans are typically required.\textsuperscript{36} In tunnels that have connecting shafts it is possible to exhaust air through these shafts to save vent pipe. Typically, the end of the main

\textsuperscript{36}State requirements on the number of cubic feet of ventilation air per diesel horsepower used underground varies between 50 and 100 cu. ft. per minute; these rules should be reviewed for each job.
ventilation pipe is kept 200 ft. from the tunnel face to prevent the pipe from blasting damage. This results in a dead-air space between the end of the pipe and the tunnel face. To obtain proper ventilation at the face, small fans are set up on the jumbo with short sections of pipe which extend back past the end of the main vent pipe (secondary ventilation system).

A pilot tunnel that communicates with the open air at its end away from the construction face can serve as a (large) ventilation pipe and can thus substitute for both the main and the secondary ventilation system. Hence, it can reduce the cycle time for the excavation-support sequence by eliminating the need to extend a ventilation duct in each round and by decreasing the "smoking time" portion of the cycle (due to increased flow capacity). According to the contractors participating in this research, the resulting increase in the advance rate can vary from 0% to 12% depending on the project's characteristics. Similarly, the ventilation cost can be reduced by 0% to 8%.

5.13.4 External Constraints.

Underground construction, especially in highly congested urban areas, has a profound impact on the environment and on the interests of the people that live or work in the project's vicinity. It is not surprising to find that this impact also works in reverse. In order to minimize the effects of construction on property, services and operations, the affected public imposes constraints on the construction process in the form of rules and regulations to which the project must conform; otherwise, legal action may be taken against any of the
principal parties to the construction contract (an event that is clearly undesirable since in most cases it translates into bringing the construction process to a halt, at least temporarily). An example of this problem can be found in the construction of the Porter Square Station. In that particular case, the contractor was informed upon the completion of mobilization, that the City of Cambridge prohibited the storing of explosives on site. This resulted in the contractor's loss of three working days, for which he was fortunately compensated by the owner.

The construction of a pilot tunnel can alleviate some of these problems by identifying these constraints before the commencement of the main project, thus allowing the designer and the contractor to modify their plans accordingly. The existence of a pilot tunnel, however, is not a guarantee that all such problems will be identified and dealt with before the construction of the project gets under way. In the example cited above, the construction of a pilot tunnel had indeed been undertaken, but "failed" to identify the constraint on explosive materials' storage. As a matter of fact, a considerable amount of underground construction was also under way in the same area and one would reasonably expect that at least the designer should have been aware of this city regulation. This example serves to indicate not so much the inability of a pilot tunnel to identify the problem, but rather the unpredictability in the nature and timing of external constraints.

Most contractors agree that, in general, the construction of a pilot tunnel can help in identifying the environment within which they should plan to operate. Their only reservations were based on the fact that, since the construction of a pilot tunnel is a small-scale operation, some
of the problems may not surface early (as was the case above). In addition, the value of this information depends significantly on whether "the owner, engineer and contractor (for the main project) do their homework properly" (i.e. whether they have utilized other means to identify these problems). According to the contractors, the problem areas that could be identified through the construction of a pilot tunnel, include:

- Traffic routing and disruption.
- Acceptable noise levels.
- Acceptable blasting vibration levels.
- Haulage restrictions.
- Explosives handling and storage.
- Dust suppression.
- Water discharge and treatment.
- Safety laws and enforcement.

Any of the above problems and especially the ones directly affecting the tunnel driving operations, like the restrictions on acceptable blasting vibrations and noise levels, can have a major impact on production and cost. For example, the contractor may not be able to do any blasting at night. According to one of the contractors, these constraints may increase the cost of the project by 15-20% (an amount that exceeds the typical cost of a pilot tunnel!).
5.14 Pilot Tunnels - Cost Issues.

The decision on constructing a pilot tunnel is basically a function of two variables: its perceived value and its expected cost. The main thrust of this research has focused on the evaluation of a pilot tunnel's benefits, since this is by far the most difficult and controversial issue. The cost of constructing a pilot tunnel (a small underground project in itself) can generally be estimated fairly accurately. In some cases, however, the construction of a pilot tunnel involves some of the work that would have been necessary under the main contract and as a result, must be discounted in performing a cost-benefit analysis. Such an item, for example, is the cost of an access shaft that is necessary for the construction of the pilot tunnel and the main opening. Other items that may fall in the category of "unnecessary expenses" (suggested by the contractors) include:

- Dewatering.
- The provision of initial tunnel (cavern) support ("presupport").
- The provision of access to a critical location (e.g. access shafts).
- Instrumentation and monitoring.
- Rock treatment and reinforcement.
- Ventilation.
- Utility relocations.
- The preparation of dump roads and dumpsites.

Some of the above items are self explanatory while others have already been discussed. Only the issue of access shafts will be
considered here because of its impact on subsequent decision making.

In some cases, the construction of a pilot tunnel requires the excavation of an access shaft that would have been necessary for the construction of the main opening even if no pilot tunnel were undertaken. In general, the cost of this shaft is not expected to be dependent on whether it is constructed as part of a pilot tunnel contract or as part of the main project. Even though most contractors agreed that the early construction of the access shaft does not entail an increase in its cost of construction, they also pointed out that this is only true if the location and size of this shaft does not seriously constrain the options available to the main project contractor. In this respect, the size of the access shaft is a crucial decision which if not made properly, may subsequently preclude the use of (large) specialized construction and haulage equipment. "If such equipment is necessary for the construction of the main opening, then the access shaft used for the pilot tunnel may be virtually useless to the main project contractor" and its cost must, of course, not be discounted.

5.15 Pilot Tunnels - Potential Problems.

In addition to the benefits already mentioned, the construction of a pilot tunnel may also be the cause of several problems, the importance and extent of which is significantly influenced by the project's geology and configuration. Most of these problems deal with the support necessary for the stability of the pilot tunnel and its impact on the construction of the final opening.
In cases where the rock is of poor quality, the construction of a pilot tunnel may require the heavy use of support (rockbolts, steel sets, shotcrete). Some of this support may have to be removed during the excavation of the main opening, thus slowing down the advance rate and necessitating a more costly excavation procedure (especially if steel sets are used). In addition:

"supporting, unsupporting (allowing the rock to move) and then supporting the rock again, may have an adverse effect on arch stability, resulting in more overbreak and additional support requirements (as compared to a once-supported opening without a pilot tunnel)".

The use of steel in the pilot tunnel support can also have an adverse effect on the mucking cycle and cause damage to equipment. Finally, the use of shotcrete as part of the pilot tunnel support defeats one of its major purposes: i.e. to let the contractor have a look at the nature and the behavior of the rock. All contractors are on (remarkable) agreement on this issue.

Another potential problem is the effect of blasting on previously grouted rock and the possibility of sudden, excessive water inflow. Even though this problem would still be present if grouting was done from the main opening instead of the pilot tunnel, it is felt that because of the larger free surface exposed in the pilot tunnel the probability of this event increases.

Finally, the construction of a pilot tunnel requires the commitment of significant resources (time and money). This commitment may make it very difficult for the owner of the facility to justify a change in the project's location or configuration if the pilot tunnel proves that such
action is necessary. This is particularly true if the investment in a pilot tunnel is approved because some of its cost was discounted as being part of the main project. Strictly speaking, however, this possibility should have been explicitly considered before the pilot tunnel was adopted. Consequently, the investment in a pilot tunnel should be considered as a "sunk cost" in evaluating the option to change the project's location, even though few organizations would be willing to admit that this is indeed the case; especially if the (public) owner had to go through a lengthy process to secure the pilot tunnel approval in the first place.

5.16 Exploration, Risk Allocation and Bidding Behavior.

The marginal value of geologic exploration (irrespective of the method used) is highly dependent on two parameters:

1. The amount of geologic information that already exists.
2. The perceived consequences of geologic uncertainty.

Even though the existing amount of geologic uncertainty is certainly the first factor that comes to mind when (statistically) evaluating new information, the economic value of this information is largely dependent on the consequences of the risks' outcomes. In other words, the way the geologic risk is shared between the parties to a contract determines the risk premiums to be required by each party and thus influences the value of information on the likelihood of the risk's outcomes.

Under a reimbursable cost plus fixed-fee contract, for example, the
owner assumes complete responsibility for the risk of constructing the project. As a result, little value, if any, can be attributed to geologic exploration from a contractor's point of view. In this case, it is the owner that values exploration the most because it can help the designer and the contractor select the best possible construction alternatives and thus help decrease the project's cost.

On the other hand, a fixed-price lump-sum contract places all the construction risks on the contractor, who in return must protect himself from the unexpected by including contingencies in his bid. The amount of these contingencies is in direct relationship with the perceived level of uncertainty concerning the project's geology (and its subsequent behavior with respect to the adopted construction process). Most contractors place a high value on exploration in this case. The major reason for this is that the determination of the contingencies is a highly subjective process; contractors cannot inflate their bids to an absolutely secure level and at the same time remain competitive. As a result, there is always the risk that the included contingencies will be inadequate and the contractor always stands the chance of losing a significant amount of money.\footnote{According to one of the contractors, the probability of losing money on a job (given that the bid must be competitive) is around 10%. This means that, on the average, the contractor loses money on one out of every 10 jobs that he undertakes!}

Based on the above observations, it becomes evident that the value of a pilot tunnel (or any other exploration strategy) must always be considered as a function of the type of contract and the implied risk
liabilities of each party. Under the typical case of a unit price contract, the allocation of risk and the subsequent value of risk reduction is very much dependent on:

- the inclusion and interpretation of a changed conditions clause, and
- how the bidding schedule is defined (i.e., the association of excavation and support items with a specific set of geologic conditions).

5.16.1 The Changed Conditions Clause.

The changed conditions clause is of such importance in protecting the contractor from a major economic loss that many of the contractors participating in this research have adopted (as a company policy) never to bid a project if this clause is not part of the contract. Even though other contractors were less absolute on this issue, they nevertheless pointed out that if a bid were to be submitted, the absence of a changed conditions clause would certainly have a considerable impact on the amount of contingencies they would require. In discussing this point one of the contractors added:

"It is my opinion that changed conditions clauses are employed by owners as an attempt to reduce contingency costs that are added to responsible contractors' bids for geologic unknowns. For this benefit, they accept additional responsibility for increased costs due to geologic conditions that are different than what one may have expected from the available information. From the contractor's viewpoint, the clause provides insurance, or relief, if conditions different from those that could have
been anticipated develop and cause increased costs. The clause (simply) allows the contractor to recover these increased costs for those geologic conditions that were not reasonably anticipated.

The impact of this clause's absence (on the contractor's strategy) depends upon circumstances:

- Past history of work experience with the owner and/or the engineer.
- The reliability and completeness of geologic information.
- The project size and scope.
- The possible risks of differing site conditions.
- The desirability of the project.
- The availability of other work.
- The existence of current or back-log work.
- The availability of labor and equipment, etc.

All of the above play a factor in making this decision. The end result varies from weighing the addition of a contingency to the bid to not submitting a bid at all."

In order to attract a large number of bidders, most owners today include a changed conditions clause as part of the contract documents. More often than not, however, the intent of this clause is marred by the existence of exculpatory clauses in the contract. Considering current contractual practices and with reservations as to the interpretation and use of changed conditions clauses, a contractor added that:

"If the contractor encounters:
1. Subsurface or latent physical conditions at the site differing 'materially' from those indicated in the contract, or

2. Unknown physical conditions at the site, of an unusual nature, differing 'materially' from those ordinarily encountered and generally recognized as inherent in the work of the character 'provided for in the contract',

The contractor should be able to recover additional costs, plus markup and profit. This is not easily achieved, however, due to exculpatory clauses in many specifications (i.e. the accuracy of the geological data or its interpretation is disclaimed, thus nullifying any reference to 'conditions indicated in the contract') and the myth that contractors always make money."

With respect to changed conditions claims, one of the contractors suggested that, in some cases, one of the most important objectives behind the owner's decision to construct a pilot tunnel is to provide himself with insurance against any such claims. Since the wording of a changed conditions clause is quite ambiguous as to what constitutes "conditions not reasonably anticipated", the construction of a pilot tunnel may be advocated as a provisor of "perfect information" thus nullifying the basis of any "changed conditions" claims. This strategy was subsequently identified by other contractors, as well; even though they agreed that this interpretation (of a pilot tunnel's results) has indeed been attempted, they also pointed out that it was without any success. Even though a pilot tunnel can be an excellent exploration method, very rarely can the observations in a pilot tunnel be considered as complete (perfect) information on the rest of the project. The possibility for the unexpected still remains (a fact that is usually
recognized by most arbitration and legal authorities).

5.16.2 Unit Price Contracts - Advantages and Limitations.

Complementing the use of a changed conditions clause is the option to prepare a bidding schedule (a quantified breakdown of the anticipated work) that is explicitly based on geologic conditions. Under this scheme, the owner undertakes a comprehensive exploration program and provides the contractor with all the results (factual data and interpretation). The contract is based on a particular and well defined interpretation of the factual information available (similar to the "Reference Conditions"; CIRIA Report, 1979) and each item in the bidding schedule is priced under the assumption that the adopted interpretation is indeed true. To compensate for the unavoidable discrepancies that will eventually materialize, the schedule also includes additional work items that are priced based on other possible geologic conditions. The contractors' opinions on the effectiveness of this approach appear to be divided. It is generally felt that, by associating the cost of the work with the actual geologic conditions, most of the (uncontrollable) risk of geologic uncertainty is transferred away from the contractor. As a result, construction contingencies should be reduced considerably. On the other hand, some contractors questioned the feasibility of administering such a contract under current practices. A contract that reimburses the contractor based on the actual field conditions (encountered during construction), can be misused by both the owner and the contractor. The most obvious problems revolve around the following issues:
- The increasing need for authoritative decision making in the field (especially on the owner's side) for determining whether the contractor's plans and methods are justified.

- The methodology for measuring and associating (i.e. pricing) the work in place in conformance with the existing schedule breakdown.

- The possibility of deliberately unbalanced bid prices and the excessive use of overpriced items during construction (given that short-term safety and stability of the project are the contractor's responsibility).

The successful administration of "true unit price" contracts is heavily dependent on the equitable resolution of the above problems and the development of better contracting practices. In the meantime, this approach can certainly cause more problems than it solves because either party (i.e. the owner or the contractor) can violate the underlying principle.

5.16.3 Contingencies - The Magnitude of the Problem.

The amount of contingencies added to a contractor's bid is a function of many parameters, most of which have been quoted above. In general, the most prominent are:

- the amount of geologic uncertainty, and
- the contractual risk-sharing approach.

Since one of the most important objectives of exploration is to decrease these contingencies, it became apparent from the beginning of this research, that the methodology for evaluating exploration should be in conformance with:

- the order of magnitude of the quantity being affected (i.e. the contingency), and
the accurate estimation of this quantity by an expert. To this effect and in order to gain a better understanding of the amounts adopted in practice, the contractors participating in this research were asked to estimate upper and lower limits on the contingency amounts that a contractor may include as part of his bid (taking into account the best and worst conditions they could think of). Even though this assessment required the dissemination of classified information, most contractors supplied the necessary answers, as quoted below:

Contingency as a percentage of total cost.

- CR1: 10 - 20%
- CR2: 10 - 30%
- CR3: 10 - 50% or more. All a function of bottom-line risk. Not necessarily net profit.
- CR4: 50% - up. "Anybody that says (that it is) less is lying!"

Unfortunately, the answers do not define a narrow cluster. It is not clear why these answers are in such wide disagreement, even though one could think of many "arguments" for supporting either the "low" group (CR1 and CR2) or the "high" group (CR3 and CR4). Most probably, the reasons behind this disparity are that:

- The contractors use different estimating procedures (some may build contingencies into the bid as they estimate each unit cost, rather than adding a lump sum in the end).

- The above estimates do not correspond to the same quantity (some contractors may use a combination of the above procedures and hence they may be reporting only the final lump sum amount which is, of course, smaller).

- The "low" group contractors may have underestimated the contingency range by stating a confidence interval for the
average amount\textsuperscript{38} (as opposed to a range on extreme situations).

- Each contractor considered different contractual situations (a very plausible explanation given the stated importance of a changed conditions clause and the methodology for determining and pricing the work in place).

- Contractors exhibit a different degree of risk aversion.

In any event, it is reasonable to argue that the above responses are indicative of the fact that the process for determining the contingencies to be included in a bid is highly dependent on the specifics of the situation, as well as on the contractor's personal risk preference (risk aversion). In other words, it is impossible to forecast (with any degree of confidence) what each individual contractor's strategy (or behavior) will be. In addition, the amount of contingencies required (irrespective of whose stand one assumes) are quite large when compared to the cost of a pilot tunnel.

5.16.4 The Potential of Pilot Tunnels in Reducing Contingencies.

In conjunction with the above question, the contractors were also asked to estimate the reduction in contingencies that may be effected by the adoption of a pilot tunnel. Their responses are given below:

- CR1: 2 - 5\%, depending on the location of the pilot tunnel and the type of geology encountered.

- CR2: 0 - 10\%, if the pilot tunnel provides enough information (i.e. is expected to be representative of the project's

\textsuperscript{38}This problem is quite common in subjective estimation. Most individuals have considerable difficulty in distinguishing between the distribution of a parameter and the distribution of its average; as a result they may provide their estimates by focusing on the wrong quantity.
conditions) to warrant a reduction in contingency.

- CR3: 5 - 20%, by confirming difficulties that do or do not exist.

- CR4: 5 - 15%, depending on the situation.

Even though it is evident that the above estimation problems are still present, the contractors' responses seem to indicate that a pilot tunnel can indeed be an economically viable exploration method. This does not mean, however, that the adoption of a pilot tunnel is unquestionably a sound economic investment. As explained earlier, one has to examine all possible exploration strategies and choose the one with the highest profitability index. Several contractors alluded to this when taking a position against the use of pilot tunnels for exploration purposes. Even though such absolute approaches are questionable, the argument is certainly valid.

39 The cost of the Porter Square Station, for example, was about $20 million (considering only the tunneling portion of the project) whereas the cost of the pilot tunnel was about $1.2 million (including $.4 million for the construction of an access shaft that would have otherwise been part of the main contract), or approximately 4 - 6% of the project's cost. This percentage is certainly commensurable (if not lower) with the quoted reduction in contingencies that may effected by the pilot tunnel's construction (one of the bidders for this project actually attributed a 10% reduction in contingency to the comprehensive exploration program undertaken).
5.17 General Recommendations.

One of the major objectives of this research was the assessment of a sufficient set of conditions for the use of pilot tunnels as an economically justifiable exploration strategy. From the discussions in the previous sections, however, it becomes apparent that the construction of such a set of prerequisites is far from possible. Even though this conclusion is unfortunate, one can hardly argue that it comes as a surprise. The economic evaluation of a pilot tunnel is a function of too many parameters to be cast into a simplistic cause-effect rule. Furthermore, none of these parameters has a dominant effect over the others to allow the simplification of the decision rule. As an example, consider an extreme case where a pilot tunnel can be considered as a perfect descriptor of a project's geologic conditions (i.e. the geology is variable in the longitudinal direction but perfectly homogeneous in the lateral direction). Even though the pilot tunnel may provide complete information concerning the project's geology, the ground's behavior is still uncertain since it also depends on other variables such as the size of the project and and the construction methods to be used. The former (estimation of geologic states) is of use to the designer and the contractor only because it is a predictor of the latter (ground behavior). Perfect knowledge on the state of the geology does not automatically translate into perfect knowledge about the effectiveness of a particular design or construction approach. This can only be achieved through the comprehensive use of instrumentation and monitoring at full
On the other hand, one can argue that even though a functional approach may not be possible, there should at least be a set of scenarios (collective set of conditions) under which the adoption of a pilot tunnel would constitute a sound investment. Unfortunately, this approach would also be deceiving for the following two reasons:

1. Usually, a pilot tunnel is not a single contender for the exploration funds available. If other methods are also applicable (and this is usually a function of the project's accessibility from the surface), then the decision on which to use requires the evaluation and comparison of all the options available (including combinations of methods). Contractors, for example, propose this argument by contemplating the existence and cost of other methods that can be equally effective. To make their perspective clear, some contractors ask for the linear density of boreholes (and/or other exploration methods) that can provide all the information anybody would ever need. In answering their own question, they argue that (at least for shallow urban projects) this density can always be achieved at a cost that is far less than the typical cost of a pilot tunnel. As a matter of fact there is a group of contractors that rejects the idea of pilot tunnels based on this argument alone!

40 Herein lies the advantage of the observational approach to tunneling.
2. In addition, the development of scenarios can never be of wide practical acceptance since it cannot answer "what if" types of questions. Since no two underground projects are exactly the same, it becomes highly improbable that a real-life situation can fit a given scenario exactly. Given the tight interaction between all the parameters in tunneling, even a small deviation will necessitate individual consideration. As a result, the evaluation of a pilot tunnel can only be done on a project basis; any attempt to generalize is futile because it can never be universally applicable.

On a more practical level, the original problem can be recast into a more reasonable form by searching for the conditions that are most likely (or unlikely) to make the use of a pilot tunnel an attractive option. This has in fact been the objective of this section.

Complementing their responses in the previous sections of this discussion, the contractors participating in this research identified several situations that may favor the construction of a pilot tunnel:

- **Size of the main opening:** large projects impose more difficulties in the prediction of excavation and support performance; slight variations in parameters like overbreak, support type and density, the advance rate, etc., result in large changes in the expected cost because of the size effect and economies of scale.

- **Location of the project:** Limited surface access for the comprehensive use of other exploration methods, like in:

  * Congested urban areas.

  * Inaccessible rural locations.

- **Unfavorable geologic conditions:** Highly variable geology, high
water pressure and/or flow, faulted formations, etc. (provided that the rock conditions in the pilot tunnel can be expected to be representative of the conditions in the rest of the main opening).

On the other hand, the following conditions are indicative that a pilot tunnel may be of very little value:

- Medium (or small) main openings.
- Comprehensive boring program is possible.
- Uniform geology, favorable geologic conditions, project is above the water table, etc.
- Project is in mixed face conditions; pilot tunnel observations are not representative of the rest of the opening.

The above observations along with the overall discussion in this chapter can serve as indicators for the most likely conditions that may support the economically justifiable use of pilot tunnels in underground construction. The potential uses of pilot tunnels are so many, and the relative importance of each so dependent on the project's individual characteristics, that an attempt to "summarize" the main points here is not considered appropriate. Given a set of project characteristics and before a final decision on the method and extent of subsurface exploration can be made, owners and/or designers should first review all the possible advantages or limitations of a pilot tunnel that have been presented; this thorough screening is necessary in order to make the preliminary and sometimes crucial decision whether a pilot tunnel should be considered (as opposed to adopted) as a possible strategy. The final decision rests upon the value of all the exploration options available. The possible approaches to quantifying this decision problem will be addressed in the rest of this report.
THE ECONOMIC VALUE OF GEOLOGIC EXPLORATION
AS A RISK REDUCTION STRATEGY
IN UNDERGROUND CONSTRUCTION

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(1981)

SUBMITTED TO THE DEPARTMENT OF CIVIL
ENGINEERING IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 1984

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Chapter 6

A Case Study:

The Porter Square Station

Pilot Tunnel.

This research on the evaluation of pilot tunnels as an exploration strategy in underground construction was initially motivated by the construction of a pilot tunnel for the Porter Square Station (part of the Red Line NW Extension, MBTA). In fact, most of the engineers and contractors participating in this research were either actively involved with the design and/or the construction of this project, or had bid parts of the work.

Even though every effort has been made in the course of this research to address the value of pilot tunnels in a general sense, the discussion presented in the previous chapter would not be complete if some of the specific comments concerning the usefulness of the Porter Square pilot tunnel were not presented. These comments can serve as an example of the general concepts concerning the conditions under which a pilot tunnel is most useful and should be undertaken. Furthermore, the Porter Square case illustrates some of the design uses of a pilot tunnel, as well as some of the factors influencing design conservatism under current US practices.

The Porter Square Station is an underground rock chamber with a span of 70 ft., a height of 45 ft., and a length of 550 ft., located in Cambridge Argillite about 70 ft. below the ground surface. The pilot
tunnel had a square 12x12 ft. cross section and extended for the full length of the station. There was no separate initial support and final lining for this station, since the design called for a final lining consisting of rock bolts, steel sets, welded wiremesh and shotcrete which could be used for both purposes (figure 6-1).

Prior to the construction of the pilot tunnel, a comprehensive borehole program was undertaken consisting of 26 vertical and inclined borings with loggings of RQD, fracture spacing, lithology and water conditions. These borings were interspersed along the full length of the station. The largest distance between observations did not exceed 80 ft. In addition, a 3 ft. exploration shaft was excavated which allowed visual inspection and logging as above.

6.1 The Value of the Porter Square Pilot Tunnel. The Contractor's View.

Considering the particular setting of this project, the contractors interviewed expressed the opinion that since:

- the boreholes were spaced close to each other,
- multiple borings were conducted in potential problem areas,
- the rock was uniform and of good quality,

most of the uncertainty involved in predicting the project's geologic conditions was eliminated. Thus, the subsequent construction of the pilot tunnel did not offer much in decreasing the project's geologic uncertainty. It merely served to verify the conditions already expected. In fact, some of the contractors stated that the adoption of this pilot tunnel was more beneficial to the designer, than to the prospective
Figure 6-1: Cross Section of the Porter Square Station indicating the location and size of the Pilot Tunnel and the configuration of the lining.
bidders. In their opinion, the cost of constructing the pilot tunnel could not be justified by considering the reduction in contingencies that might have resulted because of the availability of the pilot tunnel observations. Most of these contractors also insisted that the employment of the pilot tunnel had no impact on the amount of contingencies included in their bids, or in planning the construction of the project. The argument was presented that, since the excavation sequence and the initial support were prescribed by the designer, the contractors were left with limited alternatives in establishing the construction process.

6.2 The Value of the Porter Square Pilot Tunnel. The Designer's View.

The designer's objectives in proposing the construction of the Porter Square pilot tunnel were the following:

1. To verify the rock mass conditions (rock type, joint density, fault conditions, water conditions, rock's response to blasting, etc.) and thus, to validate some design assumptions.

2. To verify the criteria specified in the construction contract with regard to excavation and support requirements (like the thickness of the liner, the distance of the support to the face, the timing of support installation, etc.).

It is interesting to notice that the decision to use the adopted lining (rockbolts, steel sets, wiremesh reinforced shotcrete) was made before the construction of the pilot tunnel. In this respect, the pilot tunnel was not designed, or used, as an experiment to determine the final
lining, but rather as a means for testing the already determined design against it being inadequate. If the pilot tunnel were not excavated, this particular liner would still have been adopted; however, the excavation and support requirements, including those regarding the liner thickness, may have been more stringent.

As a result, the fact that the pilot tunnel was used for verifying (as opposed to determining) the final design implies that:

- The geologic information available (through the extensive borehole program on site, and from observations in adjacent excavations) was adequate for design purposes.

- The construction of the pilot tunnel was too close to the end of the design phase to allow for its explicit consideration during the design formulation.

- The designer wanted to be absolutely certain that the specified design would prove to be adequate, irrespective of which contractor would be the low bidder.

These observations illustrate some of the general concepts presented earlier, concerning:

- the marginal value of exploration,
- the importance of the exploration timing, and
- the design conservatism resulting from excessive liability and the fact that the designer does not know beforehand who will bid the work and the experience and capabilities of the low bidder.
With respect to the latter observation, the design of this project has been criticized by many contractors as being excessively conservative. Most of the contractors felt that the specification of a 15 inch thick shotcrete liner was a clear misuse of the material and of the method's intent. Furthermore, during one of the interviews conducted in the course of this research, it was admitted that "had the designer known which contractors would bid the work and who the low bidder would eventually be, the liner could have been made considerably thinner".

Furthermore, the designer's decision to recommend a pilot tunnel for the Porter Square Station was influenced by the project's size and location. Since the project is located in a thickly populated area and is surrounded by historical buildings, every effort was deemed necessary to minimize potential claims from third parties and the resulting litigation and delays. For this purpose, the pilot tunnel was used to ensure the adequacy of the proposed design and construction methods, for constructing a large chamber in a very "sensitive" urban area such as Cambridge. For the same reason, the designer used the pilot tunnel to experiment with techniques like presplitting the drill holes used for blasting, and "smooth wall blasting", in order to minimize rock movement and subsidence. Even though the former technique proved to be effective, it was not efficient (due to the need for a special tool for notching the drill holes that did not exist) and was not used by the main project contractor.
6.3 Conclusion.

Some of the above factors serve to decrease the value of the Porter Square pilot tunnel as a risk reduction strategy. In general, the value of information is in direct proportion to the relative expected consequences of the optimal design and construction decisions, with and without the information. If the possible change in these decision is marginal (as it appears to be the case in this particular project) then the information value of any experiment is also very small.

Consequently, in order for the designer and the contractor to make full use of a pilot tunnel's potential, the decision on its adoption must be made as early in the design phase as possible (when the major design assumptions are made). Postponing the construction of a pilot tunnel not only reduces its value, but also puts the designer in the awkward position of reconsidering design assumptions, and decisions that may have already been made available, either to the public or to other private agencies. Furthermore, the adoption of a pilot tunnel in relatively large caverns does not necessarily imply a reduction in design conservatism and construction contingencies unless the owner assumes some of the geologic risk and provides for the fair settlement of the additional costs resulting from unanticipated geologic conditions.
Chapter 7

Subsurface Exploration - The Owner's Perspective.

When an owner enters into a contract for the design and construction of an underground project he accepts, knowingly or not, the risk that the duration and cost of the work may exceed those estimated for its completion. In addition he also accepts the more subtle risk that the project's cost may not be anywhere close to the minimum necessary. The extent of these risks depends primarily on:

- the amount of geotechnical information available prior to construction (on which the engineer and the contractor have to base the project's design, construction planning and estimating), and

- the way the project's risks are shared between the owner, the designer and the contractor.

The fact that a project's subsurface conditions are often quite different from those originally anticipated is by far the most common cause of time and cost overruns. As a result, the amount of preconstruction information available becomes the determining factor in the ability of each party to estimate the nature and the cost of the work. In this respect, exploration reduces the likelihood that the designer and/or the contractor will misjudge the project's geology and thus increases the reliability of their cost and time estimates. In addition, it provides these parties with the information necessary for sound decision making and thus helps insure the most economical design and construction possible.

On the other hand, the actual cost of the work is also dependent on
how the geologic risk is shared between the contracted parties. In other words, the level of each party's risk exposure determines its financial liability and thus its susceptibility to cost variations. This statement is so obvious, that many owners have adopted its corollary as their operating strategy; i.e., it is felt that the best way to ensure that the job will be completed on time and within the allotted budget, is to transfer all the risks to the other parties. However, this strategy is not always in the owner's best interest. Both the designer and the contractor react to the increased risk exposure by increasing the conservatism embedded in the project's design and by charging inflated construction contingencies. Thus the cost of the project is neither guaranteed (because of the possibility of changed conditions claims by the contractor and the fact that in a unit price contract the actual cost of the project depends on the quantities of the work in place) nor optimal (because of increased design conservatism and inflated contingencies).

If an owner is sincerely interested in optimizing the delivery process of underground construction then it is necessary that other risk reduction and risk sharing strategies be identified and evaluated. This research contributes to this cause by analyzing the merits of subsurface exploration as a risk reduction strategy. Even though exploration is probably the most important "active" means for the economic and

\[4^1\] The word "active" is used to stress the fact that exploration actually reduces the geologic risk. An excellent discussion of a "passive" strategy, the improvement of risk sharing through better contracts, can be found in Stasiewicz (1981).
technical optimization of underground construction, its effects have not yet been adequately quantified to promote sound decision making.

To this effect, this chapter will:

- assert the value of subsurface exploration by examining the cause and effect relationship between the importance of the geologic risk and the contractors' bidding behavior,

- identify the effects of exploration on the parameters of the low bid distribution,

- present a general model for the determination of the optimum exploration program and comment on its feasibility, and

- address the general methodological issues that must be resolved before a reasonable framework for the evaluation of different exploration programs can be implemented.

7.1 The Effect of Geologic Uncertainty on the Distribution of Bids.

The effect of geologic uncertainty on a general level can be discussed on the basis of its observed effects on the distribution of construction bids. Figure 7-1, shows the normalized bid distributions for four different types of heavy construction arranged in increasing order of sensitivity to geologic risk. In comparing these figures the most striking observation is that these histograms, from the one for pipelines to the one for tunnels, show a continuous increase in:

- The variance of the bid distribution (i.e. an increase in the probability of receiving bids that are significantly lower or higher than the engineer's estimate).

- The difference between the mean bid and the engineer's estimate (i.e. on the average, the required compensation for undertaking the work increases).

These qualitative observations can be explained by considering the
Figure 7-1: Bid Histograms For Different Types of Heavy Construction (Moavenzadeh and Markow, 1974).
impact of geologic uncertainty in each of the above construction categories. It is evident that as one moves from pipelines to canals, to dams, to tunnels, the impact of the geologic risk on project cost increases. One can reasonably argue then, that there exists a cause and effect relationship between the amount of geologic uncertainty inherent in the type of a project and the difference of the mean bid from the engineer's estimate and the variance of the bid distribution.\footnote{42}

This correlation can be explained on the basis of the geologic risk's impact on:

- planning and estimating the work, and
- assessing the required risk premiums (contingencies).

A contractor's assessment of the project's geology is a function of both the objective and subjective information available. The impact of these two kinds of information in estimating a project's cost depends on their "relative proportion", as well as on the degree that the unknown geology and its interpretation affects the choice of construction methods and influences the project's major cost items. As a result, the variables causing the increasing variance in the normalized bid distributions are:

- the amount of uncertainty in assessing the project's geology and determining the most appropriate construction methods.

\footnote{42}The validity of these observations is partly based on the fact that the contractors' bids have been normalized as percentages of the engineer's estimate. This reduces the effect of individual project characteristics (the latter are taken into account by both the engineer and the contractor), and permits the general comparison of project types.
the degree to which the geology dictates the construction approach,
the percentage of the total cost that is contingent on the actual geologic conditions and the ground's behavior during construction.

Tunneling, for example, is a more "entrepreneurial" undertaking than pipelines; i.e., the contractor's assessment of the geologic conditions in tunneling (given the same amount of "objective" information) is much more contingent on the contractor's subjective interpretation of the geologic data provided. In addition, the contractor's interpretation of the geology has a marked effect on the development of construction approaches and the estimation of the project's cost. Since subjective information and its interpretation (experience) vary considerably from one contractor to the next, they result in a distribution of bids that has a higher variance.

The above factors explain the difference in the estimated expected cost of the work between contractors. In addition, the strong influence of geologic uncertainty in planning and estimating the work implies that (other things being equal) each contractor should be less confident in his prediction of the project's cost. In other words, the importance of geologic uncertainty results in a larger variance within each contractor's estimate. Since the variance in the distribution of a contractor's estimate for the total cost is in direct proportion with the charged contingency (risk premium), the net effect is a bid distribution that is on average higher than the engineer's estimate because of the inclusion of large contingencies. This observation explains why the difference between the mean bid and the engineer's estimate increases (in
the positive direction) as the impact of uncertainty on the assessment of the project's geologic conditions and cost increases (figure 7-2).

These very important observations are some of the first factors that led researchers to examine the value of geologic information and to develop rational exploration strategies.

7.1.1 The Low Bid Distribution.

At an aggregate level, the cost of a project to the owner is largely determined at the bidding phase. Cost variations around the quoted bid price can only occur due to changed conditions claims, or to variations in the estimated quantities of work items (in true unit price contracts). Thus, the submitted low bid price can serve as a first order estimator for the project's final cost range.

Specifically, it can be assumed that all the bids submitted for a certain project represent realizations of a random variable with a unique probability density function (PDF). This PDF can be estimated from observations on bid prices in similar projects. Since the bid prices for any type of project are dependent on its individual characteristics, the collection of data (i.e. bid prices) is a difficult task because of:

- misrepresentation (another project's bid prices may not be representative of the situation at hand)
- the available sample size (i.e., number of bids).

These problems can be partly alleviated by normalizing the available bid prices based on the engineer's estimate. This reduces the effect of individual project characteristics, like size, use, location, etc., and
Figure 7-2: Normalized Bid PDF's for Pipelines and Tunnels.
increases the available sample size. As a result, one can use the histograms of figure 7-1 to estimate both the underlying probabilistic process and its corresponding parameters.

To this effect and in order to develop a model for the low bid distribution, some basic definitions are necessary:

\[ n \] = number of bidders

\[ E \] = the engineer's estimate

\[ B_i \] = the \( i \)th bid price \( \quad (i=1,...,n) \)

\[ X_i \] = the \( i \)th normalized bid price

\[ = \frac{B_i - E}{E} \] \( \quad (i=1,...,n) \)

\[ Y \] = the normalized low bid price

\[ = \min(B_i - E)/E \] \( \quad (i=1,...,n) \)

Based on the available histogram data for tunneling bids, the random variable \( X \) has been assumed to follow a normal distribution. This assumption has been tested using the \( X^2 \) and the Kolmogorov-Smirnov tests at the 10% level of significance and proved to be satisfactory. Subsequently, the maximum likelihood estimators of the parameters of the underlying distribution can be estimated to be:

Expected value: \( E[X] = 20\% \)

Standard Deviation: \( SD[X] = 28\% \)

This means that the average bid in tunneling projects is about 20% higher than the engineer's estimate and that the probability of a bid being less than the engineer's estimate is about 24%. Of more interest, however, is the low bid distribution. From the definition of the normalized low bid price \( Y \):
\[ Y = \min[X_1, X_2, \ldots, X_n] \quad (i=1, \ldots, n) \]

and the assumption that construction bids behave like independent random variables \(^43\), it can be shown that the cumulative distribution function (CDF) of \( Y \) is:

\[ F_Y(y) = 1 - [1 - F_X(y)]^n \]

and its probability density function, PDF, is:

\[ f_Y(y) = n [1 - F_X(y)]^{n-1} f_X(y) \]

where:

\[ F_X(x) = \text{the CDF of } X_i \quad (i=1, \ldots, n) \]

\[ f_X(x) = \text{the PDF of } X_i \quad (i=1, \ldots, n) \]

This model can serve as a basis in identifying and discussing some of the owner's possible strategies for optimizing the cost of underground construction.

7.1.2 Number of bidders.

In a competitive bid situation the number of bidders on any given project is a very important variable because it has a direct effect on the probability distribution of the low bid price and consequently on the project's cost. Generally speaking, and all other things being equal, the price of the winning bid should decrease as the number of bidders increases. Since the low bid price has a direct bearing on the project's total cost, the number of bids submitted can be one of the most important variables affecting the project's total cost and in certain cases it may

\(^43\) The independence of bids is a very common and realistic assumption (Howard, 1966)
even have a stronger influence on cost than any marginal change in the adopted exploration program.

The above relationships were used to investigate the impact of the number of bidders, \( n \), on the distribution of the normalized low bid price, \( Y \) (Figures 7-3 and 7-4).

From the PDF graphs it can be readily seen that, as the number of bidders increases, the low bid distribution undergoes the following changes:

- its mean shifts to the left
- its variance decreases
- the area under the left tail increases (the PDF becomes more skewed to the left)

These changes can be more easily visualized from the CDF graphs. For example, the probability of the low bid being less than the engineer's estimate is about 55% for 3 bidders, whereas it increases to about 93% for 10 bidders - even though the mean bid is about 20% above the engineer's estimate. This is as expected, since as the number of bidders (the sample size) increases, so does the chance of getting a bid in the extreme left tail of the bid distribution.

Even though an increase in the number of bidders appears to be favorable, an owner should be very cautious in accepting this as a general operating strategy. There are two possible reasons why the low bid decreases:

1. One of the contractors may make a mistake in estimating the true cost of the work. As the number of bidders increases, so does the chance of receiving a miscalculated low bid.
Figure 7-3: Effect of the Number of Bidders on the Low Bid PDF.

\[ Y = \frac{\text{Low Bid} - \text{Eng. Estimate}}{\text{Eng. Estimate}} \]

\[ Y = \min\{X_1, X_2, \ldots, X_n\} \]

\[ f_Y(y) = n f_X(y) (1 - F_X(y))^{n-1} \]

\( n = \) number of bidders

\( X \sim N(20\%, (28\%)^2) \)
Figure 7-4: Effect of the Number of Bidders on the Low Bid CDF.
2. One of the contractors is either more competent or has other advantages over the rest of the bidders, like:

- good knowledge of the regional geology,
- recent experience with projects having similar characteristics,
- specialized equipment or labor, etc.

This possibility also increases with the number of prospective bidders.

Of the two possibilities, the former is certainly undesirable because it may lead to a significant amount of disputes and litigation and/or to a bankrupt contractor, neither of which are to the owner's advantage. As a result, an owner should not only induce as many contractors as possible to bid the job; he must also make sure that each of the contractors understands exactly the nature of the work involved and that none of the bids are (deliberately or not) unrealistically low.\footnote{44}

7.1.3 The Effect of the Bid Distribution Parameters.

Until now it has been assumed that all the submitted bids represent realizations of a random variable with a fixed PDF. It is also interesting, however, to examine the effect of changing the parameters of this PDF on the distribution of the low bid. These parameters can be changed by risk reduction and/or risk allocation, and it would be useful

\footnote{44In Italy, for example, bids that are outside a minimum or a maximum percentage of the engineer's estimate are automatically disqualified. The selection of the successful bid varies from owner to owner; all the methods, however, are variations of the following typical approach: The contract is awarded to the contractor whose bid is lower than, and closest to the average price of all acceptable bids (NAS, 1974).}
to gain an insight as to their effect.

The bid distribution (Normal PDF) is characterized by two parameters, the mean, \( E[X] \), and the variance, \( \text{Var}[X] \) (or equivalently, the standard deviation, \( \text{SD}[X] \)).

Assuming that the mean bid is 20% above the engineer's estimate (i.e. \( E[X]=20\% \) as is the case for tunneling), and that the number of bidders is \( n=6 \), Figure 7-5 shows the effect of changing the standard deviation of \( X \) (the normalized bid price).

As the standard deviation, \( \text{SD}[X] \), increases:

- the average low bid decreases
- the variance of the low bid distribution increases
- the skewness to the left of the low bid distribution increases

In practical terms, the standard deviation, \( \text{SD}[X] \), is a measure of the dispersion of the submitted bids. As the standard deviation increases, the distribution of \( X \) becomes more "flat" and thus the probability of getting a significantly low bid increases. Thus, the mean low bid decreases (on the average the low bid lies further into the left tail of the bid distribution), the variance of the low bid increases (extremely low bids become more probable) and the low bid distribution becomes more skewed to the left (extremely high bids become less probable).

On the other hand, assuming a standard deviation \( \text{SD}[X]=28\% \) and that the number of submitted bids is \( n=6 \), figure 7-6 shows that a change in the mean, \( E[X] \), produces a lateral translation (shift) of the low bid
Figure 7-5: Effect of the Standard Deviation of the Bid PMF On the Low Bid CDF.
Figure 7-6: Effect of Changing the Mean Bid on the Low Bid PDF.
distribution. Decreasing the mean, \( E[X] \), by 10\%, for example, shifts the average low bid by 10\%.

The reason for this phenomenon is that the shape of the bid distribution is completely determined by \( SD[X] \) and not by \( E[X] \). Changing the mean leaves the shape of the distribution unaffected; the only effect is that the distribution is now shifted and centered over the new mean. As a result, the probability distribution of the low bid is only a function of the relative difference between the low and the mean bid price. In other words, the probability of getting a low bid that is \( k \) percentage points below the mean, is independent of the mean's magnitude; it is only a function of \( k \) (figure 7-6).

7.1.4 Competitive Bidding - Conclusions.

In a competitive bid situation the low bid distribution has a considerable impact on the project's final cost. There are several factors affecting the parameters of the low bid distribution that can be influenced by the owner in an attempt to lower the winning bid price.

In general, the probability of getting a lower bid increases, as:

- the number of bidders increases
- the mean bid submitted decreases
- the variance of the bids submitted increases.

The owner can influence the above three variables in many ways, ranging from advertising, to the wording of the construction contracts adopted.

Exploration, the main focus of this research, can also influence the
above parameters. As the exploration intensity increases and the uncertainty in the project's geologic conditions decreases:

- the number of bidders should increase; the chance of a contractor suffering major losses decreases and this should induce more firms to bid on the project in a competitive manner (small firms typically require a larger risk premium to assume a considerable risk than larger firms do; this is one of the reasons behind the formation of joint ventures, a usual phenomenon in large underground projects); in addition, exploration reduces the probability that the winning bid will be the result of a contractor's mistake or oversight that may lead to excessive dispute settlement and the creation of an adverse construction atmosphere.

- the mean bid submitted decreases; the risk premium required by a typical contractor decreases along with the uncertainty on the risk outcomes — thus, the whole bid distribution is shifted to the left.

- the variance of the submitted bids decreases, due to the increase in the proportion of the objective information available.

Even though exploration affects all three of the above factors, its main contribution is to decrease the mean bid submitted, through the reduction of the contingencies on the geologic risk. The magnitude of this reduction is still uncertain since there are no objective data to this effect. The effect of exploration in decreasing the average bid price is also a function of how this risk is shared among the parties to the contract. Risk reduction (exploration) and risk sharing decrease the

45 The following comments are predictions based on probabilistic concepts and common sense. These predictions cannot be verified unless a thorough analysis of bidding behavior is undertaken. This analysis requires the collection of bidding data for projects that can be considered "similar" in every respect except for the amount of geologic information available; this task is clearly quite difficult if not impossible.
perceived magnitude of geologic uncertainty and thus complement each other. As a result, any reasonable effort to decrease the excessive contingencies charged by contractors should utilize both methods in parallel.

It must be emphasized here that even though exploration may decrease the bid variance, this is not necessarily a bad effect. An extremely low bid may be the result of a contractor's misjudgment on the risk's consequences; thus it may backfire at the owner through excessive litigation or arbitration on changed condition claims. Since these claims are time-consuming and are not priced competitively, the final cost of the project may escalate considerably. In this respect, exploration reduces the chance of misjudging the geologic risk and at the same time reduces the probability that unwarranted changed conditions claims will be ratified.

Finally, exploration affects the low bid distribution through another variable, the engineer's estimate. The above discussion assumes that the engineer's estimate is a constant. In reality, however, both the design itself and its estimate are affected by the engineer's perception of the geologic risk. In absolute terms, the consideration of the impact of exploration on the engineer's estimate implies a bid distribution that may have less variance, but is centered around a smaller dollar price. Consequently, in assessing the value of information of a pilot tunnel or any other exploration method, one must examine its impact on both the designer and the contractor. In other words, exploration helps decrease the variance of the difference between the project's final cost and the contractor's bid and thus assures the owner with a better final cost
estimate (budget).

7.2 The Concept of Optimum Exploration Intensity.

The primary objective of most owner entities is to construct a project at minimum cost, while meeting constraints concerning the product's safety, functionality and operational efficiency. To this effect, several general strategies can be identified from the above discussion on bid distributions. In particular, the owner should:

- attempt to increase the number of contractors bidding the work, while ensuring that none of the bids is unrealistically low due to an oversight or miscalculation,

- allocate the risks between the parties to the contracts so that the required contingencies and design conservatism are minimized,

- decrease the impact of geologic uncertainty by conducting a comprehensive exploration program.

In particular, exploration as a risk reduction strategy can play a crucial role in achieving the owner's objectives. By providing the engineer and the contractor with additional information concerning the nature and the behavior of the project's geology, it can help both parties in the development of a better product; in addition, it helps in decreasing the defensive measures that the latter adopt against the unexpected. These measures can be collectively summed under the term "conservatism":

- Design conservatism is most clearly manifested by the use of the "design for the worst conceivable geologic conditions" rule and the sometimes conscious decision not to treat design and construction as a continuous process; an approach that, more often than not, results in the employment of two distinct
support systems, where each ignores the existence of the other.

- Contractors exhibit conservatism in their initial choice and cost of support and the assessment of the production rate, both resulting in high construction estimates. In addition, contractors add significant contingencies to their bids in case the actual ground conditions encountered during construction are even worse than what was assumed for construction planning and estimating purposes based on the exploration data available.

Exploration can be considered as a financial investment whose expected benefit is the reduction of the above defensive strategies, all of which translate into inflated costs. An interesting question at this point, concerns the optimum level of investment in exploration that an owner should undertake. Clearly, there is a tradeoff between the effectiveness of exploration in reducing the construction cost of the project and the amount worth spending to achieve this objective. The owner has to trade between the resources spent for the design and construction of the project and those expended on geologic exploration (experimentation). The sum of the two expenditures represents the project's total cost.

It has been suggested that this decision situation can be modelled by the graph of figure 7-7 (Baecher, 1978). According to this model the cost of construction is a declining function of the undertaken exploration intensity, whereas the cost of exploration is obviously an increasing function. Furthermore, the sum of these two costs (i.e., the total cost of the project) is assumed to be a convex function and as such it exhibits a minimum. In other words, it is assumed that at a certain level of exploration intensity, the marginal cost of additional information equals the marginal decrease in the cost of construction. It
Figure 7-7: The Optimum Exploration Intensity.
is postulated then, that the exploration program that corresponds to this minimum cost is the owner's best choice, since it minimizes the overall cost of the project.

Even though this simplified model is certainly appealing and illustrates a valid general concept with respect to the value of exploration, it also has several shortcomings.

The identification of the optimum exploration program cannot be achieved through the use of a single attribute function. The model utilizes the notion of "exploration intensity" as a measure of the amount of exploration undertaken. Typically, exploration programs make use of several different methods, so the first problem is how to quantify "exploration intensity". If, for example, the exploration program consisted only of borings, then the spacing between boreholes could be used as a measure of intensity. On the other hand, it is not so obvious how one could construct a meaningful measure of intensity for a program that utilizes borings, observation wells, several geophysical methods and a pilot tunnel. A possible suggestion, of course, is to quantify exploration intensity by using a multiattribute function that represents the extent of every different method.

Unfortunately, the specification of a multiattribute measure of intensity does not necessarily solve the problem. A careful examination of the proposed model reveals that "exploration intensity" is not only a measure of a program's extent; it is also a measure of its efficiency.

46 The Porter Square Station represents such a case.
This can be easily illustrated through a simple example. Assume that exploration can only be conducted through borings and that intensity is quantified as the total number of borings over the fixed length of a tunnel's alignment. Clearly, a fixed number of borings implies the same exploration intensity, no matter whether the borings are all bundled together in a certain region, or whether they are spread evenly over the whole alignment. The resulting benefit, however, may be quite different in each of the two configurations; situations may even arise where the concentration of borings around an area of particular interest (e.g. a fault) may be more beneficial than the more intuitive approach of spreading them out. The fact that every level of intensity corresponds to a specific construction cost implies that the determination of the latter is based on the most efficient borehole arrangement, and that in general, the construction cost curve represents the "efficient frontier" that can be achieved for each level of investment in exploration. In other words, for every dollar amount invested in exploration, the corresponding exploration intensity is actually the description of the exploration program that results in the largest savings in construction cost. The model is not really driven by the "exploration intensity" variable, but rather by the dollar amount invested.

Furthermore, exploration has typically accounted for a very small fraction of the overall cost of underground projects:

"The cost of carrying out site investigations for tunneling works has been found to range from 0.1 to 7.5% of the tunneling costs" (CIRIA Report, 1979).

If these historical levels of investment lie anywhere close to the
theoretical optimum\textsuperscript{47}, it can be safely deduced that the objective function, in the neighborhood of the optimal exploration program, must be quite flat. The reason for this is that, by definition, the slope of the total cost curve is the sum of the slopes of the construction cost curve and the exploration cost curve, the former being negative and the latter being positive; since the sum of these slopes must be zero at the optimal exploration intensity level, the marginal decrease in construction cost must be of the same order of magnitude as the cost of exploration itself (i.e., 0.1 to 7.5\% of the total cost). Even though this may not be necessarily true for exploration intensity levels that are considerably less than the optimum (because the marginal decrease in construction cost may be initially very high), it is certainly true for exploration intensity levels that are higher than the optimum, because the total cost curve cannot have a positive slope that is greater than the marginal increase of the exploration cost itself. This observation can have one of two possible explanations:

The major problem is not to identify the optimum amount of money to be invested in exploration, but rather the configuration of the site investigation program that produces the maximum benefits. This is supported by the robustness of the proposed model in the neighborhood of the optimum exploration intensity as explained above; assuming that the efficient frontier is known, then even relatively large variations around the optimal level of

\textsuperscript{47} Otherwise, the owner is "leaving money on the table" by not investing in additional exploration.
investment should result in very minor changes in the project's cost.

On the other hand, the amount of money historically spent on site investigation programs may be not be close to what they should have been. Owners either do not fully appreciate, or cannot reliably estimate the value of exploration and have thus kept exploration expenditures "on the safe side" (i.e. they try not to "overshoot" the optimal exploration level). In addition, even though they may realize the potential for savings, owners may also have reservations as to the prudent use of the exploration funds and have thus kept exploration budgets low, to force their engineers to make "good" use of the money available.

Either of the above explanations is quite possible. Most probably, the true situation is a combination of the two. Irrespective of which of the two explanations one wishes to adopt, the general conclusion that can be safely drawn is that:

- there is a need for a method that would make possible the economic evaluation of different exploration programs,
- the evaluation of exploration programs must be done along two directions:

1. an acceptable exploration program must be expected to produce more savings than any other program requiring the same level of expenditures.

2. The best choice is the acceptable program that minimizes the project's total cost.
7.3 Searching for the Optimum Exploration Program.

The initial concept of an exploration program often undergoes modifications as more detailed and reliable information about the ground is gained during the course of the survey. Under these conditions, it is not always possible, or even prudent, to anticipate the extent, cost and strategy for the optimum exploration program possible from the very beginning. For example, a common procedure for site investigation comprises of three phases (Dumbleton et al., 1976):

Phase 1: Preliminary appreciation of site – an examination of existing information to assess feasibility, select routes, make preliminary cost estimates and plan the next phase of the investigation.

Phase 2: Preliminary ground investigation – site work to confirm feasibility, and to enable plans for the next phase of the investigation to be formulated.

Phase 3: Main ground investigation – site work to obtain the information required for design and construction.

Since phases one and two are exploratory, aimed at establishing the feasibility of the project, they do not require a high level of sophistication. The main problem is the design of the third phase, since this is the one that provides the designer and the contractor with the necessary detailed information. Even though it may not be evident from the above description, the configuration of the main exploration program is not a static decision problem.

Exploration is almost always conducted in stages, whereby the decision where and how to explore next is based on all the information already available. As such, the determination of exploration programs resembles a "bootstrapping" dynamic procedure: the next best step depends
on the findings of all the previous steps. In theory, the decision on which exploration method to use and the extent of the program for each stage should be based on a comparison of all the options available. In addition, this decision should incorporate the findings of the exploration programs in all previous stages. As a result, the underlying problem is combinatorial in nature. In contemplating the next best decision, one has to consider all the possible exploration methods and their extents, and at the same time assume all the possible states of information (i.e. sets of observations available) that may prevail at a particular stage. Unfortunately, the cost of the available options and the set of available observations (i.e. the descriptors of the current state in each stage) are not independent of the exploration methods that may have already been used in prior stages\(^{48}\) and as a result the structure of this problem does not readily lend itself to a dynamic programming formulation.

In practice, only a few exploration alternatives can be considered and the number of stages is usually small. The decision on which alternatives to evaluate is made dynamically as the exploration program progresses, and is based on the investigation's results, the availability and cost of the necessary labor and equipment and the engineer's past experience and intuition. Even though a direct search for the optimum exploration strategy does not appear to be feasible, because of the number of alternatives that have to be considered, one should at least

\(^{48}\) This violates Bellman's principle of optimality, a necessary prerequisite for the efficient use of dynamic programming.
strive for the next best solution, i.e. a quantified limited search. In other words, the owner should let the designer choose a set of promising exploration alternatives that ought to be considered and make the decision on which one to use according to the alternatives' values. This approach can be modelled using standard decision analysis techniques. The decision analysis approach basically requires the determination of the "expected value of sampled information" (EVSI) resulting from each possible exploration alternative when compared against the null option of doing nothing. The best policy then, is to adopt the program with the highest EVSI.

Even though this approach provides a reasonable alternative to the stochastic dynamic programming formulation (eliminating also some of the latter's problems and limitations\textsuperscript{49}) its implementation is still not an easy task. The major problem is how to assess the value (EVSI) of each possible alternative.

7.4 The Designer and the Value of Exploration.

Up to now, most of the discussion concerning the exploration model of figure 7-7 has focused on two issues:

1. The definition of "exploration intensity", and

\textsuperscript{49}Stochastic dynamic programming cannot consider the effects of risk aversion since the decision rule is based on maximizing the expected value of an additive objective function; utility theory, however, does not allow the addition of the utility of the parts to find the utility of the whole.
2. The determination of the optimum exploration program.

For the sake of this discussion it was implicitly assumed that the owner can indeed establish the value (EVSI) of a well defined exploration alternative. This is not necessarily true however. The major difficulty in assessing the value of exploration lies in determining a quantitative measure of its benefit. Exploration in itself, is of no direct interest to the owner. It is the designer and the contractor that make first-hand use of exploration and its results. As mentioned earlier, both the designer and the contractor adopt defensive strategies to protect their organizations from uncontrollable risks - geologic uncertainty being one of the most prominent. It is expected that additional information on the nature and the behavior of the project's geology should have a positive effect in reducing the influence of the geologic risk and lead to less conservative design approaches and less inflated construction contingencies. As a result, exploration benefits the owner indirectly, by inducing a reduction in the designer's and the contractor's defensive measures. If additional exploration does not affect the designer's or the contractor's decisions, then it bears no value to the owner.

From this brief discussion it becomes evident that a necessary requirement for analyzing the owner's decision on exploration is the ability to predict the designer's and the contractor's decisions as functions of the geologic information available. It is also important to notice that, to a certain degree, the owner can influence these decisions in a variety of ways; the most important probably being the risk sharing arrangement between the three parties, as specified in the contract's compensation and liability clauses and accent by the owner's reputation.
for dealing with such issues in the past. Thus, the prediction of the
designer's and the contractor's reaction to new geologic information must
also incorporate how this information is used under the prevailing risk
sharing arrangements. This is by far the most crucial and difficult step
in establishing the value of any exploration program.

Unfortunately, the impact of exploration is very difficult to
quantify because it cannot be statistically estimated from past
observations. Probably the most obvious reason is lack of representative
data; past behavior does not guarantee that future decisions will be made
in the same manner. This is particularly true concerning the designer's
behavior, since the estimation of an engineer's reaction to new
information requires that the estimator should at least possess an equal
skill in design. Clearly, if the owner had the capability to anticipate
the designer's decisions, then there should be no need for the latter's
services; the design should be done in-house. Given also the large
number of technical and institutional variables incorporated in the
designer's decision framework, the owner has no true means of predicting
the changes in design that may (or may not) result in the light of
additional geologic exploration. The assessment of the value of
exploration is a task that cannot be undertaken by the owner alone. Only
the engineer himself can predict the effect of new information in
structuring his design philosophy. As a result, the evaluation of
exploration must be undertaken as a joint venture between the owner and
the designer.

The above comments apply to the prediction of the contractor's
behavior, as well. Given a particular design approach and a certain
contractual arrangement, the owner needs to estimate the actual construction cost of the work. This task is not equivalent to estimating the low bid price; rarely is the final cost of the work equal to the price quoted by the contractor, since there is always uncertainty as to the quantities of the different construction items and the possibility for changed conditions claims. As a result, the argument that the contractor's behavior can be statistically tackled at an aggregate level, by considering the low bid deviation from the engineer's estimate is not strictly correct; the data available reflect quoted bid prices and provide no evidence as to the amount of exploration conducted, or the particular contract clauses adopted in each case. The histogram data used in this chapter reflect the aggregate bidding behavior in different types of heavy construction and do not discriminate between projects within each category. As such, they can only be used for analyzing general trends within each construction category, or for the comparison of bidding trends between different types of construction. In tunneling, for example, the expected bid price was estimated to be 20% higher than the engineer's estimate; this is an estimate of the true mean of the marginal distribution of bid prices for tunneling projects in general, and does not provide any information on the conditional mean bid, given a certain level of uncertainty in the geologic conditions or a particular contractual arrangement. In other words, this estimate cannot provide any evidence as to the effectiveness of exploration in changing the bid
distribution parameters. In addition, the number of bidders is unknown a priori. The need for this parameter is the most typical problem in all bidding models.

The estimation of the true cost of the work to the owner depends also on the contract type. In a lump sum contract, the final cost consists of the base construction cost, the payments for claims under the differing site conditions clause (if one exists) and the contractor's contingency and profit. On the other hand, the contingency and profit for a unit price contract are included within the price of each bid item. As a result, the contingency cost is a function of the actual quantities of work in place. This means that in order to estimate the project's true cost one must not only estimate the true quantities for all the bid items but also the corresponding unit prices charged by the low bidder. Clearly, this estimation task, as stated, is beyond the capabilities of most owners and/or designers; a different estimation approach becomes necessary.

In general, most owner entities cannot estimate the cost of the work, because they simply do not have the necessary expertise, or data to do so. The most capable of producing a reasonable estimate is the engineer, since he is the one who knows and understands the details and implications of the work as designed. As a result, the best prediction

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On the other hand, this situation can be modelled as a multiple regression problem; this approach has been adopted by an ongoing study, sponsored by the National Science Foundation, the results of which are not yet available.
of a project's true cost that an owner can have in practice, is the "engineer's estimate". Furthermore, the engineer follows the same estimating procedure as any contractor would do in arriving at his own determination of the project's total cost. This means, that the engineer's estimate must be the best possible assessment of the project's true cost; to assume otherwise would be equivalent to asserting that designers estimate costs with a consistent and conscious bias. It is also important to notice that the proposed model for determining the value (EVSI) of exploration is fortunately more insensitive to the engineer's estimate than what appears at first glance. The quantity of interest is the change in the cost of construction to be effected by the adoption of a new exploration program and not the absolute cost of the project. Considering the engineer's estimates (for two separate exploration programs) as random variables and recalling that the variance of the difference of two random variables X and Y is:

$$\text{Var}[X-Y] = \text{Var}[X] + \text{Var}[Y] - 2 \text{Cov}[X,Y]$$

it is reasonable to argue that, in this case, the variance of the difference between the engineer's estimates should be smaller than the individual variances. The reason for this is that X and Y represent outcomes of the same estimating procedure and thus they should be highly correlated. If in fact the variances of X and Y are approximately equal, and the procedure for determining either one is basically the same, then the variance of the difference should be very close to zero. In other words, any bias that may exist in the engineer's estimate will tend to cancel out when comparing the relative value of the available exploration alternatives.
In conclusion, the designer's services in predicting the effects and benefits of exploration are indispensable. Very few, if any, owner entities have the necessary in-house expertise to safely predict the effect of exploration on the decision frameworks of the other participants. Even though the accurate assessment of the value of exploration requires the contractor's input as well, in most situations the contractor does not join the team early enough to participate in this effort. Given these observations, it becomes evident that even though the exploration decision must be made by the owner (the entity controlling the financial resources), it is the designer who must provide the necessary input data for the quantitative analysis of this investment.
Chapter 8
The Value of Exploration - General Considerations.

8.1 Research Scope.

The primary objective of this research is to analyze the potential usefulness and the economic value of pilot tunnels as an exploration strategy in underground construction. From the interview and questionnaire results already presented, it becomes apparent that the value of a pilot tunnel is not only a function of its ability to provide the designer and the contractor with observations on the project's geology. More often than not, pilot tunnels have other important uses that set them apart from all other exploration methods. In addition to providing geologic information, a pilot tunnel can be used for:

- validating design assumptions,
- experimenting with new design approaches,
- field testing of new or untried construction methods,
- estimating production rates and support requirements,
- selecting excavation and support methods,
- identifying and mitigating externally imposed risks and constraints,
- providing benchmark information for the determination of "reasonably anticipated geologic conditions" in the event of litigation or arbitration over changed conditions claims,
- contributing as an integral part of design and construction (e.g., for ventilation, dewatering the rock before and during construction, installation of presupport, providing access to critical locations, etc.).
As a result, the value of a pilot tunnel is determined by two factors:

1. The geologic information it provides, which can be compared to the effectiveness of other exploration methods, and

2. Its cost saving contributions listed above, which do not have a counterpart in other exploration methods.

In general, the determination of the economic value of a pilot tunnel is extremely dependent on its cost saving contributions in addition to geologic information. While this statement was supported by most of the engineers and contractors participating in this research, it was also pointed out that the value of these contributions cannot be estimated without the explicit consideration of the individual characteristics of the work. In certain cases, for example, the use of a pilot tunnel may be absolutely necessary because of questions of construction feasibility, the technical need to use a pilot tunnel as an integral part of construction, or the potential for major construction cost savings that cannot be achieved otherwise. Under these conditions the decision to construct a pilot tunnel is quite obvious and no elaborate evaluation is necessary. In other cases, a pilot tunnel may have little to offer besides allowing the prospective bidders to have a look at the rock and how it behaves in response to the pilot tunnel's construction methods. If in addition, the project is small and in uniform geology then the pilot tunnel option may be safely rejected. These decisions, however, cannot be generalized.

Based on the above observations, this research has focused on the value of exploration, an issue that is common to all site investigation
methods. As explained in the previous chapter, the determination of an exploration program's "expected value of sampled information" (EVSI), is by far the most important and difficult step in determining the owner's optimal investment policy. To this effect, this chapter will present the general framework for the analysis of the exploration decision.

8.2 The Value of Exploration - A Systems Approach.

The decision to use a particular exploration program is basically a three-step iterative procedure. The first two steps deal with the determination of each program's expected value of information, which is the difference between:

- The reduction in the project's cost that can be achieved, i.e. the program's benefit.
- The cost of the program.

Once the EVSI of a program is determined, the third step is to compare this value to the expected value of other alternatives until all possibilities are exhausted and the best alternative is identified.

In this sense, the exploration program's information represents the input to a decision system whose output is the total cost of the work. The underlying problem is to devise a model that quantifies the sensitivity of the output (i.e. cost) to the decision variables, or input (spatial configuration and reliability of the program's observations). Even though this transformation mechanism has an additional set of decision variables, i.e., the contractual arrangement for risk sharing, it will be assumed here that these variables are known and will be
treated as constants (figure 8-1).

In general, the implementation of this transformation model, given a particular risk sharing arrangement, requires the following steps:

1. A quantified description of what is known about the project's geology prior to the adoption of the exploration program ("the prior").

2. A similar ("posterior") description of the state of information after the observations from the exploration program are made available.\textsuperscript{51}

3. The prediction of the design configuration given the posterior description of the geology.

4. The prediction of the construction excavation-support processes that are deemed necessary given the posterior geologic description and the subsequent design configuration.

5. The prediction of the project's final cost given all the above.

Several comments are necessary regarding these steps:

- At first, this procedure has to be executed once for the null option of not undertaking any more exploration. This is the base case against which each program should be compared in order to compute its EVSI.

- Second, the transformation from the prior to the posterior state of information on the project's geology is a process that in practice has to be undertaken independently by the designer

\textsuperscript{51} The prior probabilistic description of the geology is updated either through direct subjective encoding, or through the likelihood function which expresses the probabilities of the observations actually encountered given each of the possible true geologic states.
Figure 8-1: The Value of Exploration – A Systems Approach.
and the contractor. Given that the contractor is not known
during the design phase (i.e. when the decision on exploration
has to be made) the next best alternative is to use the same
posterior probabilistic geologic description for both purposes.

-Third, the prediction of the design and construction
configurations given a certain state of geologic information is
actually a prediction of behavior under uncertainty, and as
such must be made by explicitly taking into account the letter
and spirit of the design and construction contracts.

-Finally, the cost of the work depends on several other factors
that have not yet been considered explicitly. Even if the
project's geology and the design and construction decisions
were deterministically known, the cost of the project would
still be uncertain depending on issues like:

* The productivity of labor and equipment.
* The actual amount of permanent materials needed.
* The escalation of labor, materials and equipment cost.
* The contractor's contingencies.

As a result, another level of uncertainty is introduced; these
variations in the project's cost, that are not direct
consequences of geologic uncertainty, should generally be taken
into account in the engineer's estimate whenever possible.

In conclusion, it must be stressed here that the development of a
realistic decision model for the evaluation of exploration has to make considerable use of expert judgement. All the above steps, from the description of the project's geology to the establishment of design and construction policies, to the estimation of the final cost involve a great deal of subjectivity. As a result, it can be safely assumed that since the owner (i.e. the decision maker controlling the exploration funds) cannot generally make the required assessments, the required input will be provided by the designer. 52 The level at which the designer will be required to make subjective assessments (e.g., concerning the project's geologic conditions), however, is also an important issue and will be discussed next.

8.3 Geologic Inference - Sources of Information.

The choice of a particular model to represent the project's geology is one of the most crucial steps in evaluating exploration strategies. The capabilities of the adopted model can influence the perceived effectiveness of any exploration program. A good model must be able to make complete use of all the available objective data as well as the decision maker's subjective information (experience). If it cannot fully accommodate the latter, or if it cannot be readily updated in the light of new objective observations, then the conclusions on the value of

52 As mentioned earlier, the use of the designer as an "expert" is of particular importance because it eliminates the need for another party to predict the effect of geologic information on design decisions; thus, a potential source of uncertainty is removed.
exploration will be biased.\textsuperscript{53}

Information about the geology can be classified as "specific" or "general":

The observations made during a site exploration program can be considered to be specific information, because they typically associate states of nature with particular locations along the project's alignment. Even if it is weak, in the sense that the geologic state of a particular location may not be known exactly due to potential errors in the exploration procedure, the association of geologic states with project locations, is what basically distinguishes between specific and general information. Because of this association, specific information can also be called, in simple terms, as "ready to use" information. Boreholes, for example, provide observations for determining the type of the rock at particular elevations and locations along the project's vertical and horizontal alignment. Specific information can also be loosely termed "objective". It contains a certain amount of subjectivity but certainly not enough to lead to major discrepancies between different experts' assessments.

On the other hand, general information comes from a variety of sources:

\textsuperscript{53}This argument is similar to the notion of sufficiency in statistical estimation. Given a set of statistical data, one should attempt to identify estimators that collectively capture all the information contained in the data (be it direct or indirect). The same holds true in modelling what is known about the geology.
- an overall description of the geology in the project's geographical area,
- geologic observations made in other nearby projects, and
- the analyst's own experience from facing similar conditions in other projects (either near the project at hand, or at other locations).

As such, general information is not associated with particular locations along the project's alignment but rather describes how the geology behaves within certain "homogeneous regions". By definition the use of this information is quite subjective and can be subject to biases and "superstitious learning". Factors like availability, anchoring, representativeness, coherence, unstated assumptions and the volume of experience play a dramatic role in how relevant knowledge from indirect sources is applied to the situation at hand (Spetzler, Stael von Holstein, 1972).

Even though the assessment of general information is a difficult task, this information must not be discarded because of its subjectivity, because in some cases it may be the only information available due to limitations in the site investigation program. In any case, even if a considerable amount of site specific information does exist, general information and expert judgement play a crucial role in assessing the geologic conditions between or away from direct exploration observations. This is one of the main reasons requiring that a good geologic model should make formal use of subjective judgment.
8.4 Modelling versus Encoding.

Since specific information refers to explicit locations, the main problem of geologic inference is to assess the geologic conditions in project locations that are away, or between direct observations, so that a complete description of the project's geology is developed. In assessing the geologic conditions away from direct observations, the decision maker\textsuperscript{54} is faced with the choice of modelling versus encoding (Spetzler, Stael von Holstein, 1975). A simple (extreme) example concerning the problem of geologic prediction can serve to illustrate the difference between the two approaches.

Using a one-step encoding approach, the decision maker can make a direct assessment (using methods like the probability wheel, or betting cloth) on the likelihood of encountering different geologic conditions (i.e., ground classes) at each point along the project's alignment. In achieving this task, all the available geologic information (i.e., specific and general) is processed subjectively by the decision maker, without an explicit statement of the underlying assumptions and the methodology used to arrive at the final assessment. In other words, the decision maker acts like a "black box", accepting specific and general information as input, and producing a geologic assessment as output.

On the other hand, the modelling approach utilizes a formal

\textsuperscript{54}The term "decision maker" primarily refers to the designer, the entity responsible for providing the required expertise for the analysis of the exploration problem.
mathematical construct (the model) that transforms the "raw information" provided by the exploration program into an explicit mathematical representation of the spatial variability of ground characteristics, taking into account how these characteristics interact with each other and how they influence design and construction. Thus the final description of the geology depends on the model formulation as well as on the information available. This approach is characterized by the requirement to specify the transformation mechanism and the underlying assumptions in an explicit manner (i.e. there is no "black box").

The direct encoding of geologic conditions can be very cumbersome if done in a general sense and is usually simplified by assessing only the most likely and/or the extreme conditions in any segment. A conservative approach typically adopted for design, or construction planning purposes is to assess directly the "worst possible" geologic profile. Additional observations, through further exploration, are then used to test the hypothesis that the original worst conditions assumed still remain plausible. If the new information presents strong evidence against the original assessment, the decision maker can reevaluate his original prediction by repeating the direct encoding process. It is worth noting that, under this approach, it is much easier for new information to push the original assessment towards a more conservative one, rather than in the opposite direction. Needless to say that the direct encoding approach, though frequently used in practice, can lead to extreme cases
of bias and anchoring.55

The modelling approach can employ subjective information as well, but does so at a lower level. Rather than encoding the geologic profile directly, the decision maker assumes that the project's geologic conditions can be described by a particular probabilistic model. The assumed model substitutes for part of the expert's direct geologic assessment. Subjectivity is still present in the choice of the model itself and in the determination of a prior distribution for the model's parameters which have to be subjectively encoded. If the parameters of the assumed model were deterministically known and the model was indeed accurate in describing the project's geology, then subjectivity would be completely eliminated. Once the model is specified and the prior distributions of its parameters have been encoded, the model substitutes for the expert's opinion and can directly be used to provide a probabilistic assessment of the geology. It must also be pointed out that location-specific observations can be directly incorporated in the model according to the rules of probability theory. Additional

55Anchoring typically leads to overoptimism or overpessimism. Anchoring is sometimes used deliberately in order to prove a point, usually with regard to disputes over "differing site conditions" and the question of "the conditions reasonably expected". The formulation of "plausible" hypotheses tends to be dependent on the sequence with which the preconstruction information is presented, because of the tendency to place more weight on the information made available at the very beginning. The latter phases of exploration usually serve as a test of the original hypothesis. Given that null hypotheses are generally quite difficult to reject, a very dismal picture can be painted if one deliberately considers all the unfavorable observations first (the designer/owner approach) as opposed to the more optimistic approach of considering them last (the contractor's approach).
exploration can then be used to update the parameters of the adopted model according to Bayes' theorem, and to check the model's validity through goodness-of-fit tests.

It is important to observe that there is no clear-cut point at which modelling should stop and encoding should begin. Generally, this point depends on the problem at hand, the information available to the decision maker and the risk of either misrepresenting the objective data available, through excessive use of encoding, or oversimplifying the situation so that a particular probabilistic model can be adopted. In general, modelling should stop and encoding should be performed at the level of detail for which the decision maker feels the most comfortable in:

- prescribing subjective probability distributions, and

- accepting the validity of the proposed model. (Spetzler, Stael von Holstein, 1975).

Encoding at more detailed, or aggregate levels will produce less accurate results either because the decision maker (or his expert) cannot provide accurate probabilistic assessments (encoding problems) or because the resulting model does not encompass all the important variables (oversimplification). Since encoding is obviously unavoidable, the main focus must be on the accurate representation of the problem and the minimization of the previously mentioned probability encoding problems.

Furthermore, one might also add that the use of well structured model offers the additional advantage of forcing the decision maker to consider and state explicitly all the important variables and necessary assumptions, and thus induces a more rational approach in attacking the
problem. If things do not turn out as expected, the choice of a good model can also help in defending the decision maker's actions by allowing other parties to distinguish between a bad decision and a bad outcome.

Even though the above discussion on modelling versus encoding focuses on the representation of geologic conditions, the general principles presented apply to all other situations involving the transformation of information from a specific input set to a specific output set. The most pertinent example is the transformation from a given set of geologic conditions and the corresponding design and construction decisions to an estimate of the project's cost. This transformation can be done either through direct encoding, or through the adoption of a number of models, depending on the required degree of detail.

This research will present two possible approaches for the evaluation of subsurface exploration alternatives, the first of which relies more on subjective encoding, whereas the second makes extensive use of modelling. These models will be presented in the next two chapters. Before these models are presented, however, it is important to discuss some methodological issues concerning the submodels necessary for determining the expected value of sampled information (EVSI).

8.5 Required Submodels.

In general, the evaluation of exploration programs requires the development of two basic transformation mechanisms. The first is either a "Type I or a Type II model" (Benjamin and Cornell, 1970) where the problem is to determine the conditional distribution of a "dependent" set
of random variables given a particular realization of the "explanatory" set of (decision or random) variables. The second transformation deals with a different problem, where one has to predict a decision maker's actions given the outcomes of a set of decision and/or random variables.

More simply, the first problem deals with the quantitative description of variables that can be adequately treated as "states of nature". Examples are:

- The determination of a probabilistic description of a project's geology given a set of observations.

- The productivity of labor and equipment given a description of the geology and the adopted design and construction decisions.

- The future price of materials, given past trends and the current state of the economy, etc.

The general considerations for the estimation of these parameters have been presented above under the issue of modeling versus encoding. The common characteristic of these variables is the absence of a single controlling entity that can severely influence their outcome or state; for example, labor productivity cannot be controlled exclusively by the contractor, except maybe on the negative side.\(^{56}\)

In contrast, the second problem deals with the prediction of decisions, since some of the most important variables in determining the value of exploration are definitely decision variables and must be

\(^{56}\)Most contractors, however, have every reason to keep productivity high and no conscious attempt to decrease productivity is ever expected to be made. As a result labor productivity can be treated as a random variable (under the assumption of normal contractual practices) and not as a decision variable.
considered as such. Examples are the determination of the design configuration by the engineer, and the construction processes (e.g. excavation, support and dewatering methods) that a contractor plans to use and on which his bid will be based. As explained earlier these decisions cannot be predicted through past observations. Instead the prediction of these actions must be based on a "decision rule" that captures how these entities actually make their decisions in practice.

There are two approaches to this problem:

1. The prescriptive approach, and
2. The descriptive approach.

The "normative" or "prescriptive" approach is based on the idea that the decision maker behaves (or would like to behave) according to the rules of some rational theory. Following this approach, for example, one can assume that people behave either according to the "expected value criterion" or the "maximization of the expected utility" principle (both of which have been partly adopted in this research). Some of the decisions involved in the design and construction of underground projects can indeed be modelled using the normative approach. This is especially true when using a disaggregate model that only considers high-level policy decisions (such as the determination of contingencies, or the establishment of a bidding strategy). With respect to lower-level, operational decisions, however, these assumptions are typically far from being true. The evidence gathered in the course of this research does not support the argument that either the designer or the contractor behave in "a consistent, theoretically sound manner".
The "descriptive" approach does not try to predict behavior based on the principles of a "rational" theory but rather tries to simulate the decision rules adopted by the decision maker. To this effect, one can either examine how the decision making process is typically implemented in practice, or use observations on past behavior concerning cause and effect. The objective is to construct simple rules (heuristics) that simulate the subject's decision framework and observed behavior as accurately as possible. Neither the designer, nor the contractor operate at a high level of sophistication. Instead, most of the operational decisions in tunneling are based on simple heuristics that have proven to be effective in the course of actual practice. The analyst's problem is to identify and formalize these decision rules (heuristics) so that they can be incorporated within the general exploration model.

For the sake of coherence, however, this issue will be examined in more detail later, in conjunction with the model proposed for the evaluation of exploration programs.

8.6 The Definition of Design-Construction Ground Classes.

Before considering the above issues of decision making under uncertainty, it is necessary to present some of the basic ideas of optimum decision making in a deterministic environment. The main issues to be presented here are:

- the definition of ground classes, and
- the extension of this definition to encompass design and construction decisions.
For the purposes of this research, the association of a given set of
ageologic conditions with a particular design or construction approach
will be based on the definition of "ground classes", a concept that has
been extensively used in tunneling for describing the ground
characteristics pertinent to the design and construction of underground
structures. The underlying assumptions behind this concept are:

1. The ground at a particular location can be adequately
described by a set of geologic parameter states (a "geologic
vector") where the number of parameters and the number of
(discrete) states for each parameter can be arbitrarily large,
depending on the geology and the desired modelling accuracy.

2. There exists a finite set of construction methods (excavation
and support combinations) $CM_i$ ($i=1,...,n$) of which at least
one (i.e., $CM_n$) is adequate for the construction of every
possible set of geologic conditions within the extent of the
project at hand. These methods can be arranged according to
their cost in such a way that a more expensive method can be
used in all the geologic conditions for which a less expensive
method is adequate. In other words, the least expensive
construction method $CM_1$ can always be substituted by
$CM_2,...,CM_n$, whereas $CM_n$ cannot be substituted by any other
method.

3. A ground class $GC_i$ ($i=1,...,n$) is defined as a collection, or
set, of geologic vectors that describe all the possible
geologic conditions for which the adoption of construction method \( CM_i \) is the most economical alternative.

A construction method, as defined above, refers to a combination of excavation and (initial) support methods and does not explicitly include design decisions. In conventional, non-adaptable tunneling as commonly practiced in the US, however, the designer's decisions not only precede the contractor's decision making, they also impose constraints on the available excavation and initial support alternatives. As a result, the prediction of the contractor's actions is conditional on the designer's decisions.

For the purpose of determining the value of exploration, however, this problem can be bypassed quite easily. As mentioned earlier, most of the required input for the comparison of exploration alternatives must be provided by the designer, who can thus not only asses his own attitude in the presence of additional geologic exploration, but can also predict the construction methods to be used by the contractor given the construction specification requirements. In other words, the designer can at first define his own "design methods":

\[
dm_j \ (j=1,\ldots,m)
\]

for each of which he can subsequently predict the possible construction methods:

\[
cm_{jk} \ (j=1,\ldots,m; \ k=1,\ldots,s)
\]

that a contractor may use. The problem can now be cast in a form that is equivalent to the original definition of ground classes and construction methods by defining:

\[
CM_i := (dm_j, \ cm_{jk}) \ (i=1..n; \ n = m*s)
\]
Obviously, the association of the "artificial" design-construction methods $CM_i$ is made in such a way so that the original assumptions concerning the possibility of substituting a less expensive alternative with a more expensive one are still valid. The definition of ground classes remains the same as presented above; i.e., ground classes are now defined so that they correspond to each particular design and construction combination.

This transformation is used throughout the rest of this research for the following reasons:

1. It eliminates the necessity to predict the designer's decisions without considering the latter's reaction to contractual and financial liability by allocating this task to the most appropriate party (i.e., the designer).

2. It models the conditionality between design and construction decisions, which cannot be predicted a priori without considering the specific characteristics of the project, both technical and contractual.

3. It creates the necessary framework for the development of a decision support system that does not force the designer or the owner to accept an "optimum" exploration program that does not reflect all the characteristics of the project at hand. Instead, it can be used to evaluate exploration according to the personal preferences of the entities involved, taking into
account the adopte risk sharing approach as implemented in both the design and construction contracts, the behavioral effects of which cannot be predicted by a general purpose "prescriptive" model.
Chapter 9

The Value of Perfect Information

on

Ground Class Extents.

The first model presented in this research is an example of a high-level encoding approach, addressing the value of perfect information on ground class extents. The motivations for the development of this simple model are the following:

1. The contractors participating in this research expressed the opinion that the prediction of ground class extents is the most difficult task in construction planning and estimating.

2. The value of perfect information on ground class extents can, under certain conditions, be very useful in evaluating the option to construct a pilot tunnel. The construction of a pilot tunnel provides the designer and the contractor with continuous observations on the project's geology. Assuming that the variability of geologic conditions within the project's cross section is expected to be small, the observations made in the pilot tunnel can be approximately considered as perfect information on the ground class extents. As a result, the value of perfect information on extents provides an upper limit on a pilot tunnel's value as an
exploration method.\textsuperscript{57} Irrespective of the exploration program used, the preconstruction information on extents has a direct bearing on the optimal selection of excavation and support methods. In addition, the anticipated extents over which each of the chosen construction methods will be actually used influence directly the duration and cost of the work and as a result the contractor's contingencies.

9.1 Model Formulation and Assumptions.

A tunnel can be considered as a sequence of homogeneous geologic segments, where each segment is completely defined by its geologic state and extent along the main tunnel axis. In this context, the geologic state of a segment can be defined in exactly the same way as a ground class; i.e. as the collection of geologic vectors for which a particular design-construction (excavation-support) method is applicable. The elements of a geologic vector represent all the possible states of the important geologic parameters.

If the number of homogeneous segments is known to be \( n \), and the geologic state of of the \( i^{th} \) segment is known to be \( s_i \) then the cost of the tunnel can be modelled as a linear function of the form:

\[ \text{Cost} = \sum_{i=1}^{n} \text{Cost}_i \]

\textsuperscript{57} The actual value of a pilot tunnel depends on the variability of geologic conditions within the project's cross section. The higher this variability the lower the pilot tunnel's value. It must also be kept in mind that pilot tunnels have other uses beyond exploration, the value of which must be assessed separately.
\[ C = a + \sum_{j=1}^{m} b_j + \sum_{j=1}^{m} \sum_{k=1}^{m} c_{jk} f_{jk} + \sum_{i=1}^{n} d_{ij} W_i + \sum_{i=1}^{n} \frac{e_{ij}}{r_{ij}} W_i \]

Where:

- \( n \): the number of segments.
- \( m \): the number of construction methods \( CM_j \) considered.
- \( a \): fixed cost, independent of the construction methods used.
- \( b_j \): fixed cost uniquely associated with the use of \( CM_j \).
- \( c_{jk} \): cost of change from \( CM_j \) to \( CM_k \).
- \( f_{jk} \): the number of times \( CM_k \) follows \( CM_j \).
- \( d_{ij} \): the cost per foot of using \( CM_j \) in the \( i \)th segment.
- \( e_{ij} \): the time dependent cost of using \( CM_j \) in the \( i \)th segment.
- \( r_{ij} \): the advance rates when using \( CM_j \) in the \( i \)th segment.
- \( W_i \): the extent of the \( i \)th segment.

For the purposes of an approximate analysis it will be assumed that all the above variables are known and as such can be treated as constants with the exception of the extents \( W_i \) (\( i=1,\ldots,n \)) which will be treated as random variables. On the basis of this assumption the cost of the tunnel can be simplified to:

\[ C = g + \sum_{i=1}^{n} h_i W_i \]

where,

\[ g = a + \sum_{j=1}^{m} b_j + \sum_{j=1}^{m} \sum_{k=1}^{m} c_{jk} f_{jk} \]

\[ h_i = d_{ij} + \frac{e_{ij}}{r_{ij}} \]

which is a simple linear function of the unknown extents. The resulting model is shown in the figure below:
Even though the resulting model appears to be quite elementary, a little reflection on the above figure will inevitably reveal that the direct estimation of extents is a formidable problem because any such estimation must be done in a conditional space due to the strong correlation between extents. This correlation is caused by the following:

- The sum of all the extents equals L, the total length of the tunnel.

- The existence of location-specific observations indicating the existence of a certain ground class at a particular location constrains the sum of the extents of the segments on either side of the observation to an absolute maximum.

- By the same argument the sum of the extents between observations are also constrained to be less than the distance between the observations. This implies that long extents tend to be surrounded by short ones and vice versa.

To avoid the problem of these correlations it is expedient at this point to introduce more convenient random variables. To this effect, let:

\[ X_i = \text{the distance from the left end of the tunnel to the interface between the } i \text{ and the } i+1 \text{ segment (} i=0, \ldots, n) \]
Notice that $X_0 = 0$ (the left end of the tunnel) and $X_n = L$ (the right end of the tunnel) are not random variables.

As descriptors of the tunnel's topology, these absolute distances enjoy two important advantages over the relative extent lengths:

1. Since exploration is mostly location specific, it is much easier to estimate the probability density functions of the locations of the interfaces between segments rather than the length of the segments themselves. By properly choosing the variance of the PDF of each interface location, the engineer can be guaranteed that this location will never exceed its allowable bounds.\(^{58}\) In contrast, the direct estimation of extents disregards the constraint that a particular segment has to exist at every location where it has already been observed.

2. The locations $X_i$ of the interfaces between segments can be

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\(^{58}\)This can be accomplished by specifying the variance of the Normal PDF such that the interval of three standard deviations around the expected value of the interface location does not contain observations that do not correspond to the assumed neighboring segments.
considered to be mutually independent provided that their pdf's are chosen so that they do not violate the existing observations on segment states. In other words, since the inferences on extents are primarily made on the basis of location-specific observations, if one uses the observations on segments as the main source of information (as opposed to actually having direct observations on extents too) there is no reason to consider dependence between the interface locations.

For the purposes of this discussion the $X_i$'s will be assumed to be independent and normally distributed. The independence assumption implies that:

$$\text{Var}[W_i] = \text{Var}[X_i - X_{i-1}] = \text{Var}[X_i] + \text{Var}[X_{i-1}]$$

$$\text{Cov}[W_i, W_{i+1}] =$$

$$= \text{E}[W_i W_{i+1}] - \text{E}[W_i] \text{E}[W_{i+1}] =$$

$$= \text{E}[(X_i - X_{i-1})(X_{i+1} - X_1)] - \text{E}[(X_i - X_{i-1})] \text{E}[(X_{i+1} - X_1)] =$$

$$= \text{E}[X_i X_{i+1}] - \text{E}[X_i^2] - \text{E}[X_{i-1} X_{i+1}] + \text{E}[X_{i-1} X_1] - \text{E}[X_i] \text{E}[X_{i+1}]$$

$$+ \text{E}[X_i] \text{E}[X_1] + \text{E}[X_{i-1}] \text{E}[X_{i+1}] - \text{E}[X_{i-1}] \text{E}[X_i] =$$

$$= - (\text{E}[X_i^2] - \text{E}^2[X_i]) = - \text{Var}[X_i]$$

and finally:

$$\text{Cov}[W_i, W_{i+k}] = \begin{cases} - \text{Var}[X_i] & \text{for } k=1 \\ 0 & \text{otherwise} \end{cases} \quad i=1, \ldots, n-1$$

Using the substitution: $W_i = X_i - X_{i-1}$ the cost function can now be
written as:

\[ C = g + \sum_{i=1}^{n} h_i W_i \]

\[ C = q + \sum_{i=1}^{n-1} (h_i - h_{i+1}) X_i \]

where

\[ q = g + h_n L \]

Based on the above assumptions the cost of the tunnel \( C \) is normally distributed with parameters:

\[ E[C] = q + \sum_{i=1}^{n-1} (h_i - h_{i+1}) E[X_i] \]

\[ \text{Var}[C] = \sum_{i=1}^{n-1} (h_i - h_{i+1})^2 \text{Var}[X_i] \]

At this point, the situation can be summarized as follows: A contractor is faced with a lottery \( C \) which depends on the realization of the random variables \( X_i \). The problem is to estimate the minimum amount which a contractor will require as compensation for accepting participation in this lottery (i.e., the contractor's bid).

To proceed with this problem, one needs to make assumptions about the contractor's behavior. To minimize the computational effort one can assume that:
a) The contractor's utility curve is exponential:

\[ U(Z) = 1 - \exp(-z/b) \]

where \( b \) is the contractor's "coefficient of risk aversion". The smaller \( b \) is, the more risk averse the contractor is supposed to be.

b) The contractor's required profit is a fixed percentage \( p \) of the expected cost of the project.

Based on these assumptions, the contractor's bid is (Howard, 1970):

\[ B = E(C) + \frac{1}{2b} \text{Var}(C) + p E(C) \]

where the middle term represents the contingency required by the contractor due to the uncertainty in the segment extents. If this uncertainty were completely eliminated, then the contractor would not include any contingency and the bid would be:

\[ B^* = E(C) + p E(C) \]

The owner is thus faced with two options:

- he can do nothing, in which case the bid is expected to be \( B \),

or

- he can provide the contractor with perfect information on extents in which case the bid is expected to be \( B^* \).

As a result, the expected value of perfect information (EVPI) is

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59 The choice of the exponential utility curve permits the direct assessment of the certain equivalent in closed form and the use of the convenient "delta" property (Howard, 1970).
simply:

\[ B - B^* = \frac{1}{2b} \text{Var}[C] = \frac{1}{2b} \sum_{i=1}^{n} \left( d_i + \frac{e_i}{r_i} - d_{i+1} - \frac{e_{i+1}}{r_{i+1}} \right)^2 \text{Var}[X_i] \]

which represents an upper bound on the amount that the owner should spend on an exploration program that yields less than perfect information.

9.2 Input Considerations.

This model is very easy to implement, since most of the required input, with the exception of the probability distributions on the ground class interface locations, is also needed for preparing the engineer's estimate. Given a certain amount of geologic information the designer must first estimate the necessary cost parameters \( q \) and \( h_1 \) that correspond to the anticipated geologic profile and the construction methods expected to be used. These parameters, however, can be readily computed as functions of other cost parameters that are typically required for the preparation of a standard construction estimate.

This model makes use of a high-level encoding approach in that all the geologic information available, be it specific or general, is subjectively processed by the designer to arrive at a probabilistic assessment of the interface locations between different geologic segments. Thus, no specific model describing the spatial variability of the geology needs to be assumed; in this respect, the proposed process does not differ much from the usual practice of preparing a geologic
profile for the project's alignment. The only additional aspect is that
the engineer must also quantify his uncertainty concerning the exact
location of the interfaces between geologic segments by estimating:

1. **Their mean distance from a reference point** (like the beginning
   of the tunnel), and

2. **Their respective variance about the mean.**

The estimation of these two parameters is sufficient because the
interface locations have been assumed to be normally distributed. This
observation simplifies the assessment process even further. Since the
PDF's are assumed to be Normal, the assessment of the mean can be done
through equiprobable lotteries concerning the median, which are much
easier to visualize. Similarly, the assessment of the variance can be
done through lotteries that utilize the probability of the interface
being k standard deviations around the mean. For example the engineer can
assess the interval around the mean that has a 50% chance of containing
the interface; in this case the width of the assessed interval is equal
to \(2 \times 0.6745\) standard deviations.\(^{60}\)

The only other parameter needed is the coefficient of the
contractor's risk aversion. As explained earlier, this parameter cannot
be statistically estimated, with any degree of confidence, simply because
there are not enough data for its prediction. The only possible

---

\(^{60}\)The direct encoding of these parameters should be based on the
geologic information already available and must be performed in a manner
that minimizes the problems of misrepresentation, bias, anchoring, etc.,
that have already been mentioned in the discussion of modeling vs.
encoding. This can be achieved by following the procedures suggested by
Spetzler and Stael von Holstein (1972).
alternative is to subjectively assess a range of possible values by considering the resulting behavior under risk that these parameters would imply. In other words, the designer can construct lotteries involving monetary outcomes of the same order of magnitude as the cost of constructing the work, and by using his own risk behavior as a guide, establish a region for the contractor's risk aversion coefficient. Furthermore, the designer can be assisted in the assessment of this parameter by considering the contingency percentages quoted by the contractors in the course of this research.61

9.3 Conclusions.

Even though the development of this model required the adoption of some crucial assumptions, the final result can be extremely convenient for the approximate analysis of the value of a pilot tunnel as a near perfect predictor of ground class extents. The usefulness of this model basically depends on the variability of geologic conditions within the cross section of the main opening and thus on the reliability of the pilot tunnel observations. If the pilot tunnel observations are not representative of the conditions within the main opening, then its value is much smaller than the computed value of perfect information. In this case, or similarly if a different, less reliable, exploration method is actually being considered, the proposed model must be slightly modified

61I.e., by equating the model's contingency factor to the expected cost times the specified contingency percentage, and solving for the risk aversion coefficient, b.
so that it can accommodate a partial reduction\(^{62}\) in the variance of the interface locations. The variance of the project's cost is reduced as a function of the decrease in the variances of the segment interface locations.\(^{63}\)

In any case, the usefulness of this (simplified) model stems from the fact that it provides the designer and the owner with an easy-to-use sensitivity analysis tool that can answer "what if" type of questions without necessitating a considerable amount of input, or the heavy use of computer-based modelling. Since the model assumes that the geologic states within each homogeneous segment are known, different scenarios can be constructed based on alternative interpretations of the available geologic observations to test the sensitivity of the result to the geologic input, or to the design and construction approaches to be adopted for the project's construction.

In addition, sensitivity analysis must be also be used to test the impact of the contractor's risk aversion coefficient on the value of further exploration. This parameter can have a crucial effect in estimating the value of exploration and since it cannot be assessed directly, it is imperative to assess its importance by considering its extreme upper and lower values. This task can be simplified by inverting

\(^{62}\)In contrast to the complete reduction in variance on which the value of perfect information is based.

\(^{63}\)This approach is not pursued here because a more powerful model has already been developed for this purpose. This model will be presented in the remainder of this report.
the problem, i.e. by directly computing the risk aversion coefficient that corresponds to the "break even" point; i.e. where the cost and benefit of exploration are equal. If the coefficient corresponding to the break even point is "very large", then the benefit of exploration probably exceeds its cost because any smaller coefficient of risk aversion implies a more conservative contractor requiring thus larger contingencies (the reduction of which is the exploration's benefit). On the other hand, if the coefficient of risk aversion corresponding to the break even point is "very small", then exploration can only be beneficial if the contractor is extremely risk averse. Thus the decision on whether exploration is profitable depends on the designer's perception of the contractor's behavior under risk.
Chapter 10

The Expected Value of Geologic Exploration

A Markovian Model.

10.1 Introduction.

The rest of this report discusses the general model developed as a decision support tool in evaluating geologic exploration. Before this model is presented in detail, it is expedient at this point to provide an overview of the adopted methodology.

In order to develop this model, the following two assumptions have been made:

The first assumption is that, for design, construction planning and estimating purposes, the geologic conditions of a project can be sufficiently modelled by a set of geologic parameters, each following an independent Markov process along the project axis.

The second assumption is that the sequence of design-construction methods corresponding to a particular state of information about the geology, can be predicted through the application of the "threshold probability rule".

Based on the above assumptions the proposed model uses probabilistic concepts to update the decision maker's state of information concerning the project's geologic conditions, based on the already available observations through past exploration. Once the project's geologic description is updated, the model uses the threshold probability rule to
determine the corresponding sequence of design-construction methods. By calculating the cost associated with these methods, the model produces the mean and variance of the project's total cost.

Finally, the above process is repeated by simulating the future observations to be provided by the contemplated exploration program. The output of this simulation is the expected value and the variance of the project's cost, under the assumption that this exploration program is actually undertaken. By comparing the total cost distribution with, and without the proposed program, the decision maker can determine the expected value of additional exploration.

10.2 Geologic Model Requirements.

Some of the general requirements for a geologic model have already been presented as examples in discussing the issues of modelling versus encoding. These requirements are also presented here in order to discuss the advantages and limitations of the model adopted for this research.

As mentioned earlier, geologic information can be classified as "location-specific" or "general". This is to stress that in addition to the exploration of the site in question, a knowledge of the regional geology, the geologic history of the area, and thorough appreciation and understanding of the way in which rocks respond to changing geological environments, may be equally important (Robinson, 1972). Therefore the first requirement on the prediction model is that both location-specific and general geologic information about the site should be utilized to yield geologic predictions.
The general information about the tunnel's geology essentially remains unchanged as exploration proceeds, while the particular information from location-specific observations increases. It is therefore desirable that the predictions concerning the project's geologic conditions can be updated based on new observations. Furthermore, since subjective judgment is often necessary in geological predictions, the prediction and updating processes should be capable of incorporating subjective assessments. However, care should also be taken to minimize the potential encoding problems (see section 8.4).

A complete model should include all the geologic parameters that have a strong influence on design and construction decisions. A typical list of such parameters has been identified by the contractors participating in this research. This list may be expanded or contracted depending on the situation. The prediction model should therefore have the flexibility of including unexpected but important parameters that may have originally been considered unnecessary but whose influence increases due to additional exploration.

Most importantly, the model should be capable of simulating possible geologic profiles to facilitate overall construction planning. The profiles thus generated should not contradict the general expectations about the profile, which means that:

1. Each generated profile should not contradict observations on the parameters known before construction.

2. Most of the generated profiles should not deviate considerably from the general geologic conditions in the vicinity of the project.
In conclusion, the requirements for a good geologic model can be summarized as follows:

1. Tunnel profiles generated by the model should be compatible with general expectations on the actual profile.

2. The model should make full use of all the available information be it general or specific.

3. Geologic predictions can be updated as exploration proceeds and more information is gathered.

4. The prediction and updating processes should be capable of including subjective judgment when necessary.

5. The prediction model should include all relevant parameters and the entire ranges of their possible states. However, when unexpected important parameters are encountered, the model should be capable of including them also.

10.3 Geology as a Random Process.

Most physical quantities, like temperature or density, are generally functions of the three-dimensional space, as well as time. If the values of a quantity are deterministically known for every point in space and time, then the states of this quantity can be adequately described by a four-dimensional deterministic function. On the other hand, if the states of a quantity are uncertain, either in space or in time, a more complex representation becomes necessary. In this case, the description of the existing knowledge about the physical quantity's states can be modelled as a random process. A random process is the logical extension of a deterministic mathematical function: a deterministic function associates each point in space and/or time with a particular value (state), whereas a random process goes a step beyond by associating each point with a
probability distribution over all the possible values (states) of the quantity under consideration (i.e. the random variable). As a result, a series of process outcomes over which the decision maker has no control (e.g. geologic conditions) can be considered as the specific realization of an underlying random process.

Random processes are typically classified according to the domain of states of the underlying quantity, and the domain in space and/or time for which the process is defined. The probability distributions that a random process associates with each point in space and/or time can be:

1. **Discrete**: The quantity under consideration can only assume an enumerable set of values (states); in this case each point is associated with a probability mass function (PMF) leading to a discrete state random process.

2. **Continuous**: The quantity can assume any value over a continuous domain of possible states; each point in space and/or time is thus associated with a probability density function (PDF) leading to a continuous state random process.

In addition, a random process may be defined for:

1. An enumerable set of points in space and/or time: discrete space random process.

2. A continuous set of points in space and/or time: continuous space random process.

Given these definitions, random processes can be classified as:

1. Discrete state, discrete space.

2. Discrete state, continuous space.

3. Continuous state, discrete space.

4. Continuous state, continuous space.

The concept of random processes can be readily applied to the
description of geology, since the subsurface geologic conditions in the neighborhood of a project's site vary in three-dimensional space. Each point is associated with its own set of geologic conditions, which, of course, change from one point to the next. Even though the geologic conditions at every point are predetermined by nature, these conditions are not perfectly known before the construction of the project. As a result, one can adopt the Bayesian "degree of belief" interpretation of probability, and model the project's geology as a random process in space.

Random (or stochastic) processes have been extensively used to describe many physical and economic phenomena involving random variables which are functions of "space" or "time" parameters. For example, the number of people \( N \) in a queue can be regarded as a random variable which depends on time. Thus at a given time \( t \), the number of people in a queue is a random function \( N(t) \) which has a certain probability distribution \( P_N(n,t) \). This example is shown in figure 10-1, where \( P_N(n,t) \) is the PMF (probability mass function) of \( N(t) \). \( P_N(n,t_1) \) and \( P_N(n,t_2) \) are shown as PMF's of \( N \) at times \( t_1 \) and \( t_2 \) respectively. Thus, for example, at \( t=t_1 \), \( P[N=2] = 0.25 \) while at \( t=t_2 \), \( P[N=2] = 0.5 \).

In particular, the Markov process is one of the best known stochastic processes and is sophisticated enough to deal with complex systems, like the geologic environment (Howard, 1960, 1971; Cox and Miller, 1965; Chan 1981). The main characteristic of the Markov process is that of a single-step memory: past history apart from the most recent event is neglected in forming predictions about the future. Even though this can be a very restrictive assumption, the use of a Markov process is
Figure 10-1: An Example of a Discrete State, Continuous Space Random Process.
usually a good approximation to situations where the most recent step is
the most significant factor influencing the process's future states. The
most significant advantage in assuming a single-step memory (instead of a
multiple-step memory) is that probability calculations become
considerably simpler, often leading to closed form results.

The necessary condition for a stochastic process \( P_X(x,t) \) to be
classified as a Markov process, is that:

\[
P_X(x,t_{i+1}|x(t_i), x(t_{i-1}), \ldots) = P_X(x,t_{i+1}|x(t_i))
\]

(10.1)

where \( x(t_i), x(t_{i-1}), \ldots \) are the outcomes of the random variables \( X(t_i), \)
\( X(t_{i-1}), \ldots \) respectively and \( t_{i+1} > t_i > t_{i-1} > \ldots \). Thus the history
of past events, with the exception of the most recent one, has no effect
on the probability distribution of the random variable at a later time.

Considering the previous example on the number of people in a queue,
if \( P_N(n,t) \) obeys the Markov process, then the prediction on \( N(t^*) \) (i.e.,
\( P_N(n,t^*) \)) depends only on the number of people known to be in the queue
at a time most recent to \( t^* \) and not on the number any other time before.

Typically, the notion of a Markov process is associated with a
random variable which assumes different states at different points in
time. In this report "time" is equivalent to a position along the tunnel
axis, the location of which is identified by the distance \( t \) from a
certain fixed point (e.g. the portal, or the beginning of the tunnel.).
The situation is shown in figure 10-2 where the direction of the
construction advance is the positive direction of \( t \).
Figure 10-2: Definition of "space" for the Markov Process.

The geologic description model proposed in this research\textsuperscript{64} is based on the following assumptions:

- It is possible to define a set of geologic parameters which, for all practical design and construction purposes, provide a complete description of a project's geologic conditions. An example of such a set has been presented in the discussion of the "Contractor Questionnaire".

- Each of the parameters necessary for the description of geology is associated with an enumerable (as opposed to continuous) domain of feasible values. Since any number of discrete states can be assigned to each parameter, the decision maker can approximate continuous state parameters to any degree of accuracy.

- In the absence of location-specific information linking certain parameter states with particular locations (along the alignment of the project) each of the parameters describing the geology undergoes state transitions (i.e. changes in value in the direction of the project's axis) according to the probability laws of a discrete state, continuous space Markov process.

- The Markov processes followed by each of the geologic parameters are mutually independent.

- When location-specific observations are made available in the course of subsurface exploration, this information is used to update the individual Markov processes for each parameter according to Bayes theorem.

\textsuperscript{64} The Markovian geologic model presented in this report, is partly based on the the geologic prediction model for adaptable tunneling developed by Chan (1981). This model has been modified and extended to accommodate the preposterior analysis of imperfect information on the process's states, a step necessary for assessing the expected value of sampled geologic information.
10.4 Basic Elements of the Markov Process.

Central to the Markov process are the concepts of state, state transition, and extent. These three basic elements are introduced in the following sub-sections.

10.4.1 State.

The states of a random variable are the possible values that it can take. For example, the parameter states r for the discrete ground parameter "Rock Type" can be defined as follows:

\[
\begin{array}{c|c}
 r & \text{Schist} \\
 1 & \text{Metaquartzite} \\
 2 & \text{Diorite} \\
 3 & \text{Quartzite} \\
 4 \\
\end{array}
\]

such that "r=3" means that the state of rock type is Diorite.

10.4.2 State Transition.

A geologic parameter X at a certain position t can be regarded as a random variable X(t). As t increases from 0, X(t) changes its value (figure 10-3). Each of these changes is called a state transition. If at a certain position t the prevailing state is i (i.e., x(t)=i), the probability that the next state is j is \( P_{X_{i j}} \): "the transition probability from state i to state j". For example, if at a certain position x(t_0)=1, then the probability that the next state is 2 is \( P_{X_{12}} \). In a continuous space process, transitions occur only when there is an actual change of state (as opposed to virtual transitions occurring in fixed increments of length or time where the next state may be the same as the previous state.
Thus, since the next state is by definition different from the present state, $P_{x_{i_{i}i}} = 0$.

<table>
<thead>
<tr>
<th>$x=1$</th>
<th>$x=4$</th>
<th>$x=2$</th>
<th>$x=1$</th>
<th>$x=5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>o-----</td>
<td>t$_{1}$----</td>
<td>t$_{2}$----</td>
<td>t$_{3}$----</td>
<td>t$_{4}$------</td>
</tr>
</tbody>
</table>

**Figure 10-3: State Transitions.**

10.4.3 Extent.

After a parameter $X(t)$ has entered a certain state $i$ at $t_{i}$, the interval for which $X$ will remain in state $i$ is called the extent $HX_{i}$ of state $i$ at $t_{i}$. $HX_{i}$ can be thought of as the "horizontal thickness" of state $i$ and is depicted in figure 10-4 ($k \neq i \neq j$).

<p>| $&lt;$----------------- $HX_{i}$ --------------------$&gt;$ |
|------|------|------|------|</p>
<table>
<thead>
<tr>
<th>$k$</th>
<th>$i$</th>
<th>$j$</th>
<th>------</th>
</tr>
</thead>
<tbody>
<tr>
<td>------</td>
<td>$t_{i}$-----------------</td>
<td>$t_{j}$------</td>
<td>$t_{m}$------</td>
</tr>
</tbody>
</table>

**Figure 10-4: Definition of Extent.**

For the continuous space Markov process (where space (i.e., position) is measured on a continuous scale) the transition intensity coefficient $c_{x_{i}}$ of state $i$ of parameter $X$ is defined such that $c_{x_{i}}dt$ is the probability that a state transition occurs (i.e. the extent terminates) within the infinitesimal interval $dt$, given that state $i$ exists at the beginning of the interval (figure 10-5). Thus the probability that a transition occurs within the interval from $t=t_{k}$ to $t=t_{k}+dt$ is $c_{x_{i}}dt$. 
\[ X = i \quad X = j \neq i \]

\[ t_k \quad t_k + dt \longrightarrow \rightarrow t \]

**Figure 10-5: Probability of Making a Transition.**

Neglecting the small probability that there is more than one transition within \( dt \), the PDF of \( HX_i \) can be derived by first considering the CDF (cumulative density function) of \( HX_i \):

\[ F_{HX_i}(h) = P[HX_i \leq h] \quad (10.2) \]

If \( h \) is divided into \( m \) equal segments of infinitesimal length \( dt \) each, then:

\[ P[HX_i > h] = P[\text{no transition occurs within } h] \]

\[ = P[\text{no transition occurs within each of the } m \text{ segments}] \]

\[ = \lim_{m \to \infty} (1 - c_{X_i} dt)^m \]

\[ = \lim_{m \to \infty} (1 - c_{X_i} h/m)^m \]

\[ = e^{-c_{X_i} h} \]

From (10.2),

\[ P[HX_i > h] = 1 - F_{HX_i}(h) \]

Hence,

\[ F_{HX_i}(h) = 1 - e^{-c_{X_i} h} \quad (10.3) \]

By differentiating both sides of (10.3), the PDF of extent \( HX_i \) is
given by:

\[ f_{H_{X_1}}(h) = c_{X_1} e^{-c_{X_1}h} \quad (10.4) \]

which is the familiar exponential distribution with mean \(1/c_{X_1}\) and standard deviation \(1/c_{X_1}\). In other words, the extent of a state is exponentially distributed under the single-step memory assumption of the Markov process.

10.5 State Prediction at a Future Point.

Based on the Markov process concept one can determine the closed form expression for the probability of a parameter \(X\) being in a certain state at any future point. This probability is of great interest for the prediction of geologic conditions away or between the available observations at any point along the alignment of the project. The situation is depicted in figure 10-6 in which one needs to compute the probability of \(X\) being in state \(j\) at an interval \(u\) from the section at \(t_0\) given \(x(t_0) = i\). This probability cannot be found easily since within the interval \(u\) any number of transitions (including no transitions) can take place. It is therefore expedient to introduce matrix notation to express calculations in a compact form.

\[
\begin{array}{c|c|c}
X=i & & X=\
\hline
& & \\
\hline
& t_k & t_k^+ u \\
\hline
\end{array}
\]

Figure 10-6: State Prediction.
A Markov process $P_X(x,t)$ is completely defined by the transition intensity matrix $A_X$, such that:

$$A_X = [a_{Xij}]$$

where:

$$a_{Xij} = \begin{cases} -c_{X_i} & (i=j) \\ c_{X_i}P_{Xij} & (i\neq j) \end{cases}$$

Hence,

$$A_X = \begin{bmatrix} -c_{X_1} & c_{X_1}P_{X12} & c_{X_1}P_{X13} & \cdots & c_{X_1}P_{X1n} \\ c_{X_2}P_{X21} & -c_{X_2} & c_{X_2}P_{X23} & \cdots & c_{X_2}P_{X2n} \\ & \ddots & \ddots & \ddots & \ddots \\ & & \ddots & \ddots & \ddots \\ c_{X_n}P_{Xn1} & \cdots & \cdots & -c_{X_n} \end{bmatrix}$$

(10.5)

$A_X$ contains $c_{X_i}$ and $P_{Xij}$ and hence defines the Markov process completely.\(^{65}\) $A_X$ is especially useful in making state probability predictions which are discussed in the following sections.

10.5.1 Interval Transition Probabilities.

The problem of computing the interval transition probabilities can be stated as follows: "Given that the parameter $X$ is currently in state

\(^{65}\)In addition, since the transition intensity coefficients and the transition probabilities mentioned so far are regarded as constants (independent of location, $t$), the Markov process is said to be "homogeneous".
1, determine the probability that \( X \) is in state \( j \) at a distance \( u \) ahead of the current location. This problem of state prediction can be solved by introducing the interval transition probability matrix:

\[
V_X(u) = [v_{Xij}(u)]
\]

where,

\[
v_{Xij}(u) = P[X \text{ will be in state } j \text{ after an interval } u \text{ given the present state is } i]
\]

Generally, \( v_X(u) \) satisfies the forward Kolmogorov differential equation:

\[
\frac{dV_X(u)}{du} = V_X(u) A_X \tag{10.6}
\]

To prove (10.6), let \( du \) be a small interval:

\[
v_{Xij}(u+du) = v_{Xij}(u) v_{Xjj}(du) + \sum_{k \neq j} v_{Xik}(u) v_{Xkj}(du)
\]

\[
= v_{Xij}(u) (1-c_{Xj}du) + \sum_{k \neq j} v_{Xik}(u) a_{Xkj}du
\]

Thus,

\[
v_{Xij}(u+du) - v_{Xij}(u) = -v_{Xij}(u) c_{Xj}du + \sum_{k \neq j} v_{Xik}(u) a_{Xkj}du
\]

Dividing both sides by \( du \) and taking the limit as \( du \) approaches zero:

\[
\frac{d}{du} v_{Xij}(u) = -v_{Xij}(u) c_{Xj} + \sum_{k \neq j} v_{Xik}(u) a_{Xkj} \tag{10.7}
\]
Equation (10.7) is identical to (10.6) which is in matrix form.

The solution of (10.6) can be written as:

\[ V_X(u) = \exp [u A_X] \]
\[ = I + u A_X + 1/2 \ u^2 A_X^2 + \ldots + 1/m! \ u^m A_X^m \]  
(10.8)

In practical cases this series may converge very quickly and one can use only a few terms to get satisfactory accuracy. If convergence is not quick or high accuracy is needed, a closed form solution can be constructed by using the spectral resolution of \( A_X \) (Cox and Miller, 1965, pp. 183-284):

\[ A_X = B \ \text{diag} (z_1, z_2, \ldots, z_n) \ C^T \]

where \( z_1, z_2, \ldots, z_n \) are the eigenvalues of \( A_X \) and \( z_1 = 0 \). The matrices \( B \) and \( C^T \) are formed from the left and right eigenvectors of \( A_X \) with the condition:

\[ B \ C^T = I \]

Hence,

\[ V_X(u) = \exp [A_X u] \]
\[ V_X(u) = B \ \text{diag} (e^{z_1 u}, \ldots, e^{z_n u}) \ C^T \]

Another way to find a closed-form expression for \( V_X(u) \) is by using exponential transforms (Howard, 1971, p. 710). Howard also showed that \( V_{Xij}(u) \) is equal to the sum of a constant (the limiting state probability) and \( (n-1) \) terms such that:
\[ v_{Xij}(u) = v_{Xj} + k_2 e^{z_2 u} + \ldots + k_n e^{z_n u} \] (10.9)

where: \( v_{Xj} \) = limiting state probability of state \( j \),

\( k_2, k_3, \ldots, k_n \) = constants,

and \( z_2, z_3, \ldots, z_n \) = eigenvalues with negative real parts.

10.5.2 State Probabilities.

According to the results of the previous section, if a parameter \( X \) is in state \( i \) at \( t_0 \) the probability that \( X \) will be in state \( j \) at \((t_0 + u)\) is \( v_{Xij}(u) \). When the state of \( X \) at \( t_0 \) is not known deterministically but only a PMF \( P_X(x) \) at \( t_0 \) is given, the probability of finding state \( j \) at an interval \( u \) later can still be found. Let \( S_{Xj}(u) \) be the probability of having state \( j \) at \((t_0 + u)\):

\[
S_{Xj}(u) = P[X \text{ is in state } j \text{ after an interval } u]
= \sum_{i=1}^{n} P_X(i) P[X \text{ is in state } j \text{ after an interval } u \text{ given present state is } i]
= \sum_{i=1}^{n} P_X(i) v_{Xij}(u)
= \sum_{i=1}^{n} S_{Xi}(0) v_{Xij}(u) \tag{10.10}
\]

since \( S_{Xi}(0) = P_X(i) \) by definition of \( S_{Xj}(u) \) above.

To express equation (10.10) in a more compact form, let \( S_X(u) \) be the
row vector of state probabilities such that:

\[ \vec{s}_X(u) = (s_{X1}(u), s_{X2}(u), \ldots, s_{Xn}(u)) \]

Then (10.10) can be expressed as:

\[ \vec{s}_X(u) = \vec{s}_X(0) \vec{v}_X(u) \]
\[ = \vec{s}_X(0) \exp[\vec{A}_X u] \quad (10.11) \]

10.5.3 Limiting State Probabilities.

As the interval \( u \) increases, the effect of the present state on the probabilities of future states at an interval \( u \) later becomes smaller and smaller. When \( u \) approaches infinity, the probability of finding a certain state \( j \) at an interval \( u \) later becomes a limiting constant and is independent of the present state \( i \). This limiting constant is called a limiting state probability \( v_{Xj} \) and is given by:

\[ v_{Xj} = \lim_{u \to \infty} v_{X1j}(u) \]

Furthermore, let \( \vec{s}_X = (v_{X1}, v_{X2}, \ldots, v_{Xn}) \) be the limiting state probability vector. When the transition intensity matrix \( \vec{A}_X \) is given, \( v_{Xj} \) can be found by differentiating (10.11) with respect to \( u \):

\[ \frac{d \vec{s}_X(u)}{du} = \frac{d \exp[\vec{A}_X u]}{du} \]
\[ = \vec{s}_X(0) \exp[\vec{A}_X u] \vec{A}_X \]
\[ = \vec{s}_X(u) \vec{A}_X \quad (10.12) \]
As \( u \) approaches infinity \( \frac{dS_x(u)}{du} \) approaches \( S_x \) and (10.12) becomes \( \frac{d(S_x)}{du} = S_x \ A_x \). Since \( \frac{d(S_x)}{du} = 0 \) (\( S_x \) is constant):

\[
S_x \ A_x = 0
\]

i.e.

\[
\begin{align*}
v_{x_1}(-c_{x_1}) + v_{x_2}(c_{x_2}P_{x_21}) + \ldots + v_{x_n}(c_{x_n}P_{x_n1}) &= 0 \\
v_{x_1}(c_{x_1}P_{x_12}) + v_{x_2}(-c_{x_2}) + \ldots + v_{x_n}(c_{x_n}P_{x_2n}) &= 0 \\
&\vdots \\
v_{x_1}(c_{x_1}P_{x_1n}) + v_{x_2}(c_{x_2}P_{x_2n}) + \ldots + v_{x_n}(-c_{x_n}) &= 0
\end{align*}
\]

(10.13)

Equations (10.13) represent a homogenous system of simultaneous linear equations. Hence, the necessary and sufficient condition for a solution to exist is that the equations must be linearly dependent. This is in fact true since when all the equations are added together, the left-hand side vanishes (the coefficients of \( v_{x_1} \) vanish) becoming identically equal to the right-hand side. One more equation is thus needed which is:

\[
v_{x_1} + v_{x_2} + \ldots + v_{x_n} = 1
\]

(10.14)

since the parameter can occupy one and only one state at a time.

Thus solving \((n-1)\) equations from (10.13) simultaneously with (10.14) will give the values of \( v_{x_1} \). On the other hand, if \( v_x(u) \) is already found in a closed form (see previous section), then \( v_{x_1} \) can
easily be found by taking the limit as \( u \) approaches infinity.

The physical significance of \( v_{Xj} \) is that it is the relative percentage of the occurrence of state \( j \). If in a certain region state \( j \) (e.g. Granite) of a parameter \( X \) (e.g. Rock Type) occurs 70% of the time, \( v_{Xj} = 0.7 \). For a tunnel of length \( L \) in such a region, the expected total length of Granite is \( v_{Xj} L = 0.7 L \). Another use of the limiting state probabilities is to initialize the updating process: i.e., they provide the initial prior distribution to be used in updating the parameter state PMF's when observations are made available.

10.6 Reasons for Adopting the Markov Process.

The Markov process model conforms reasonably well to the five requirements stated at the beginning of this chapter. Specifically the Markov model satisfies these requirements in the following manner:

1. Tunnel profiles generated by the prediction model should be compatible with actual profile.

This requirement implies that the underlying concept of the geologic model should correspond to, or at least be compatible with, the actual situation. Whether geologic processes generally take place according to the Markov process is still an open question. However, observed thickness distributions of lithologic units show that they are either lognormally or exponentially distributed (identical to geometric PMF when a discrete space approach is used.) Exponential (or geometric) distributions on the other hand are characteristic of the Markov process. Krumbein and Dacey (1969) proposed a simple genetic process model of
sedimentation which leads to a geometric distribution of lithologic unit thicknesses. The derived geometric distribution is in fact the "discrete-time" analog of the exponential extent distribution implied by a continuous space Markov process.

Chan (1981) examined the form of extent distributions using the recorded extents of sections with various degrees of jointing in one of the Seabrook water tunnels. In order to record the lengths (extents) of different sections in each state, the degree of jointing was expressed as RQD, with states low, medium, and high. The recorded extent distributions of medium and high RQD sections were fitted with exponential distributions and then tested using the $X^2$ goodness-of-fit test. The results of the two tests confirm the possibility of an exponential extent distribution since this hypothesis could not be rejected for levels of significance below 15%. It should be noted that the appropriateness of using certain transition probabilities cannot be tested likewise. For a parameter with $n$ states, there are $(n^2 - 2n)$ independent transition probabilities. These $(n^2 - 2n)$ probabilities can always be chosen so that they fit any data set of actual transitions perfectly, since the data set also has $(n^2 - 2n)$ independent values (Chan, 1981).

Since geologic processes are not yet fully understood and since there are indications that some geologic processes (concerning lithologic unit thicknesses and RQD unit thicknesses) do show exponential extent distributions, the Markov model seems satisfactory. The proposed geologic model is thus compatible with several of the more important aspects of actual geology.
2. Both general and specific information about the geology of the project should be incorporated.

Assuming that a parameter $X$ in the tunnel region actually obeys the Markov process in the direction of the tunnel axis, the transition probabilities $P_{Xij}$ and transition intensity coefficients $c_{Xij}$ can be statistically assessed from recorded frequency data. In the absence of statistical data the transition parameters can be subjectively encoded based on a geologist's expert judgment. Thus, the general information concerning the regional geology is primarily incorporated in the transition intensity matrix of the Markov process.\textsuperscript{66}

Location-specific information is usually the result of subsurface exploration in the vicinity of the project. This information is derived from observations on parameter states at particular locations along the tunnel axis. If these observations can determine the state of a parameter, then a deterministic statement can be made at the point of observation (e.g. "the rock type at $t=1000$ ft. is Granite"). If the observation is not conclusive (i.e., non-deterministic), only probabilistic statements about the true parameter states at the place of observation can be made. This can be accomplished either by subjective judgment and direct encoding, or by updating the prior PMF at that point.

\textsuperscript{66}A comprehensive discussion of the data collection and encoding procedures can be found in Chan (1981).
given the outcome of the observation.  

Thus, general geologic information is incorporated when the values of $P_{X_{ij}}$ and $c_{X_i}$ are assessed, whereas specific geologic information, in the form of the observations made in the course of exploration, is used to update the parameter state predictions.

3. Predictions Can Be Updated as Exploration Proceeds and More Information is Gathered.

Suppose a parameter $X$ is in state $i$ at a particular location $t$. The probability of $X$ being in state $j$ at location $t+u$ is given by the interval transition probability $v_{X_{ij}}(u)$. As exploration proceeds this probability changes (is updated) because more information is gathered and the distance $u$ from the nearest observation may change. Thus parameter state predictions are continuously updated based on the exploration results.

Another level of updating concerns the parameters of the geologic model that have been assessed through direct encoding: If $P_{X_{ij}}$ and $c_{X_i}$ are originally established by subjective judgment, they can be updated using the concept of "competing hypotheses". For example, if different geologists are consulted, or a certain geologist expresses several different opinions about these parameters, several estimates ($c_{1X_i}, c_{2X_i}, \ldots c_{yX_i}$) of the transition intensity coefficients can be established.

---

67 The methodology for incorporating observations in the geologic prediction model and how "artificial" observations can be generated through simulation will be discussed in detail in later sections.
Each of these y values represents a "competing hypothesis" $H_m$ (m = 1, 2, ... y) which has a probability of being true $P_m$ (figure 10-7). Before any exploration is conducted each $P_m$ can be assigned a value $1/y$ (i.e. a vague prior is used). When the exploration program begins and observations are made available the probabilities of each competing hypothesis can be updated using Bayes theorem, depending on the likelihood of the obtained observations assuming in turn that each of the hypotheses is true. The same procedure can be used to update the probabilities associated with the $P_{xij}$.

4. The prediction and updating processes should be capable of including subjective judgment when necessary.

If the amount of existing data is not sufficient to form best estimates of the transition probabilities $P_{xij}$ and transition intensity coefficients $c_{xi}$ of a parameter X, these parameters can be directly encoded based on subjective judgment (Chan, 1981).

Another important use of subjective judgment is in encoding the probabilities of the true parameter states given a set of imperfect non-deterministic observations. In this case, the decision maker or an appointed expert is provided with location-specific observations on the project's geology, based on which he has to subjectively assess the state probability mass function for parameter X at that point. This PMF can be regarded as the posterior (final) probability distribution of X at that point (while the prior is the original prediction of the geologic model.)

Hence subjective judgment can be used to establish the transition probabilities and the transition intensity coefficients. It can also be
\[ H_1 : \ c_{X_1} \text{ equals } c_{1X_1} \]
\[ H_2 : \ c_{X_1} \text{ equals } c_{2X_1} \]
\[ H_3 : \ c_{X_1} \text{ equals } c_{3X_1} \]
\[ \vdots \]
\[ H_y : \ c_{X_1} \text{ equals } c_{yX_1} \]

The weighted mean:

\[ c_{X_1} = p_1 c_{1X_1} + p_2 c_{2X_1} + \ldots + p_y c_{yX_1} \]

is used in the geologic prediction model.

When \( p_m (m = 1, \ldots, y) \) is updated, \( c_{X_1} \) is updated.

Figure 10-7: Concept of Competing Hypotheses (Chan, 1981).
used to directly assess the parameter state PMF's at the locations of non-deterministic observations.

5. The prediction model should include all relevant parameters and the entire ranges of their possible states. However, when unexpected important parameters are encountered, the model should be capable of including them also.

When the importance of a parameter \( X \) is increased as a result of new observations made in the course of exploration, the model can be expanded to include this parameter as well. To this effect, the transition probabilities and transition intensity coefficients defining the Markov process for the new parameter can be established in exactly the same way as for the other parameters. Thus unexpected important parameters can be included in the original model by adding an additional Markov process.

10.7 Model Assumptions - Advantages and Limitations.

As shown above, a geologic model using the Markov process fulfills most of the desirable requirements. Beyond these requirements, however, there are several important assumptions associated with the adoption of the Markov process. These assumptions together with their respective advantages and disadvantages are discussed below.

10.7.1 Single-step Memory.

In order to adopt the Markov process concept, a single-step memory has to be assumed. This assumption implies that probabilistic predictions depend only on the most recent state, which is usually the
most important step in a process's history. In the case of a tunnel, this assumption means that the predictions concerning a parameter's states at a specific location depend only on the PMF of the parameter's states at the closest observations. The advantage of this assumption is that calculations become simpler and more manageable.

\[ X = \begin{array}{cccccccc}
1 & 2 & 3 & 4 & 3 & 2 & 1 & 2 & 3 & 4 \\
\end{array} \rightarrow t \]

**Figure 10-8: Example of a Cyclic Structure.**

The disadvantage is that in some cases past history that may also be important in forming predictions is not used (apart from the most recent step). A simple but extreme case is the cyclic structure shown in figure 10-8. Assuming a single-step memory, the best value that can be assessed for \( P_{X_{23}} \) is 0.5 which actually corresponds to the cyclic process because if the present state is 2, the next state will be 3 in 50 out of 100 times. But if one more step of past history (i.e. a double-step memory) is used, the prediction model obviously becomes superior to the previous one because by "remembering" the present and the preceding steps, the next state can be determined exactly. For example, if states 1 and 2 are encountered in succession, the probability that the next state is 3 is 1.0. This defect of the single-step memory can be lessened using

\[ \text{The latter, of course, depend on the reliability of the observation made at that point as well as on the nature and reliability of the already existing observations closest to them. This process continues until the "closest" observation becomes deterministic.} \]
subjective judgment (e.g. if state 1 and then state 2 are encountered, an "observation" is added subjectively which states that the next state is observed to be 3).

To summarize, the assumption of a single-step memory simplifies calculations considerably, but in doing so sacrifices some "predicting power" in cases where past history, apart from the most recent state, is also important in forming predictions.

10.7.2 Regional Homogeneity.

The Markov process used in the geologic prediction model is assumed to be homogeneous, i.e. $P_{Xij}$ and $c_{Xj}$ are constants independent of position $t$. There are two cases in which this simplifying assumption has to be modified. The first case is that of a tunnel crossing terrains of very different geologies. $P_{Xij}$ and $c_{Xj}$ for parameter $X$ may be significantly different in some of these regions. Each of these terrains should be treated as a "homogeneous region", within which $X$ is governed by a homogeneous Markov process. For example, if $X$ represents Rock Type and the tunnel goes through a sedimentary rock terrain and then an igneous rock terrain, different values of $P_{Xij}$ and $c_{Xj}$ (i.e., different transition intensity matrices) have to be used in these two terrains.

The second case is that if $P_{Xij}$ and $c_{Xj}$ at a certain position depend on the state of another parameter $Y$ at that position, then the Markov process for $X$ cannot be homogeneous throughout the entire tunnel (unless $Y$ is in the same state throughout the entire tunnel, which is unlikely). Therefore in regions where different states of $Y$ exist, different
transition intensity matrices for $X$ have to be used. An example is the case where $X$ represents "Degree of Jointing" and $Y$ "Rock Type". In a certain tunnel region the degree of jointing may vary strongly with rock types. Each of these regions is a "homogeneous region" for $X$. This case of parameter interdependence can be neglected if it is weak (e.g., the different transition intensity matrices for $X$ in regions where different states of $Y$ exist are approximately equal). The advantage is that only one transition intensity matrix needs to be established for each parameter and calculations to predict the ground classes at a certain point are greatly simplified.

If, however, there is a strong dependence between the states of different parameters, the situation can be modelled as follows:

1. An artificial parameter is created that substitutes for both the interdependent parameters and whose states correspond to every combination of states of the initial parameters; if Rock Type, for example, has 4 states and RQD has 3 states, then the artificial parameter "Rock-Type/RQD" has 12 states and can substitute for the other two. In this manner, the transition probabilities and the transition intensity coefficients can be estimated jointly, by explicitly taking into account all state combinations.

2. One of the two parameters (typically the one with the largest mean extents) is assumed to behave like an independent Markov process, while the other follows a conditional Markov process depending on the first parameter's states. In other words, each of the first parameter's extents is a "homogeneous" region for the latter. This approach is more computation-intensive than the one above, but can be simplified by considering the first parameter to be deterministic, in which case the model becomes identical to the situation where the tunnel can be divided into a known number of "homogeneous" segments.
10.7.3 Intercommunication of States.

For the sake simplicity and computational feasibility, it is also assumed in the proposed geologic model that there is intercommunication between every two states $i$ and $j$. This means that if $x(t_0) = i$, then there is a non-zero probability that $x(t_0 + u) = j$. This means that there are no "transient states" which have essentially no probability of occurring after a great distance from the present position. This assumption seems to be reasonable within the context of this research: there is no reason why a certain state cannot occur at a great distance from the present position. For example, if the degree of jointing at the tunnel face is high, there is no reason why it cannot be low at a great distance ahead.

10.8 The Treatment of Observations.

Based on the elementary concepts of the Markov process introduced so far, one can calculate probabilistic predictions concerning the state of a parameter $X$ at a distance $u$ away from an existing deterministic observation. Once the transition probabilities $P_{X_{ij}}$ and the transition intensity coefficients $c_{X_i}$ of a parameter $X$ are established, predictions on the states (in the form of the interval transition probabilities $v_{X_{ij}}(u)$ and the transition probabilities $P_{X_{ij}}$) and state extents (extent distributions) can be readily calculated provided that no information exists concerning the process's states at future locations. As the interval $u$ increases, the state probabilities are less dependent on the present situation. In particular, the interval transition probability
v_{X_{i,j}}(u) approaches a constant v_{X_{j}} (the limiting state probability) as u approaches infinity.

These probabilities, however, are primarily useful for predicting the geology away from already known geologic conditions. In most cases, exploration provides observations over the whole extent of a project's alignment, and as a result the typical inference problem is to estimate the geologic conditions between observations of varying reliability. In other words, s_{X_{i}}(t), v_{X_{i,j}}(t), P_{X_{i,j}} and the extent distributions will have to be modified (updated). These point observations are generally the results of geologic mapping, geophysical explorations, trenching, core drilling and subjective judgment.  

![Borehole Diagram]

**Figure 10-9:** Observations Using Borings.

An example of a single observation is shown in figure 10-9. A borehole was drilled to explore the ground conditions at a distance of 2500 ft. along the tunnel axis (i.e., at t=2500 from the beginning of the tunnel). At the intersection of the borehole and the tunnel axis it was found that the rock type was granite and that the rock was moist. Hence, at t=2500 there is a deterministic observation on the rock type and an

---

These point observations are different from the data (in the form of transition chains) from which $P_{X_{i,j}}$ and $C_{X_{i}}$ are originally established.
imperfect observation on water inflow. Since the latter observation is non-deterministic, the probability distribution concerning the possible water conditions at this location has to be estimated. This can be accomplished by using one of the following methods:

1. Direct encoding based on subjective judgment.

2. Bayesian updating based on the reliability of the observation.

1. According to the direct encoding approach,\textsuperscript{70} the decision maker (or his appointed expert geologist) observes the geologic environment around \( t=2500 \) and by considering other supporting information (general and specific), such as records from other borings, the regional geologic formations, the reliability of the sampling method, etc., makes a subjective probability assessment concerning the inflow of water at location \( t=2500 \). This assessment, for example, may yield the following PMF:

\[
\begin{align*}
P[\text{low water inflow}] &= P[w(2500)=1] = 0.15 \\
P[\text{medium water inflow}] &= P[w(2500)=2] = 0.75 \\
P[\text{high water inflow}] &= P[w(2500)=3] = 0.10
\end{align*}
\]

It is important to notice that the encoded probabilities represent the posterior (updated) PMF concerning the water inflow at \( t=2500 \). This assessment can now be used to update (or improve) the predictions on the

\textsuperscript{70}This is the approach adopted by Chan (1981) in developing a geologic prediction model for adaptable tunneling. Even though this method is theoretically correct, it can only be used after an observation is actually made and hence cannot be used for the evaluation of future exploration. This limitation has lead to the development of the likelihood method.
water states and state extents at other locations according to the rules of probability and the assumptions of the Markov process. Similarly, the same procedure can be used to update the predictions on rock type, given that granite was observed at t=2500.

2. According to the **likelihood (updating) approach** the decision maker does not make a direct prediction on the water conditions at the observation's location. Instead, he uses the reliability of the exploration method (as previously determined for geologic conditions similar to those present at location t=2500) to update the prior distribution on the water conditions at that location.

In other words, the decision maker establishes a prior PMF on the availability of water at location t=2500 by using the associated Markov process as updated by all other observations concerning the inflow of water at other locations.\(^\text{71}\) The prior distribution, for example, might be the following:

\[
\begin{align*}
P[\text{low water inflow}] &= P[w(2500)=1] = 0.3 \\
P[\text{medium water inflow}] &= P[w(2500)=2] = 0.5 \\
P[\text{high water inflow}] &= P[w(2500)=3] = 0.2
\end{align*}
\]

\(^{71}\) Obviously the likelihood approach is recursive. The described updating procedure, uses a "prior" state PMF that is actually "posterior" to all other existing observations. In other words, the effect of the previously made observations on the inflow of water at other locations is already included in the state PMF concerning the water conditions at location t=2500. Obviously, going backwards, one reaches the point where no observations are available. At that point, the prior PMF is given by the limiting state probabilities, which form the starting point for the updating process.
In order to update the prior PMF, the decision maker has to also assess the reliability matrix, or likelihood function, for the exploration method providing the observation, conditional on the true water inflow and the general geology of the region. For example the probability of observing moist rock given any of the three true states may be assessed as:

\[
P[\text{moist}|\text{water inflow} = \text{low}] = P[O(2500)=m|w(2500)=1] = 0.2
\]
\[
P[\text{moist}|\text{water inflow} = \text{medium}] = P[O(2500)=m|w(2500)=2] = 0.6
\]
\[
P[\text{moist}|\text{water inflow} = \text{high}] = P[O(2500)=m|w(2500)=3] = 0.2
\]

This information is sufficient for updating the prior PMF according to Bayes theorem, providing thus the posterior distribution on the water inflow at location \( t=2500 \):

\[
P[w(2500)=1|O(2500)=m] = k P[O(2500)=m|w(2500)=1] P[w(2500)=1] = 0.15
\]
\[
P[w(2500)=2|O(2500)=m] = k P[O(2500)=m|w(2500)=2] P[w(2500)=2] = 0.75
\]
\[
P[w(2500)=3|O(2500)=m] = k P[O(2500)=m|w(2500)=3] P[w(2500)=3] = 0.10
\]

Notice that the "likelihood" of the observation:

\[
P[O(2500)=m|w(2500)=1]
\]

is quite different from the posterior probability:

\[
P[w(2500)=1|O(2500)=m]
\]

The former does not depend on the findings of observations concerning the water conditions in the vicinity of the project that may be already available. Instead, the likelihood function depends primarily on the reliability of the method providing the observation and as such can be
considered a constant attribute of the method. In contrast the posterior probabilities not only depend on the observation being considered, but also on all the other observations available. As a result the likelihood (reliability) matrix can be established a priori; i.e. before the borehole is drilled and the observation is made. This is of particular importance in estimating the value of (future) exploration, since it is simply impossible to subjectively assess the posterior PMF for each parameter, and every observation location based on all the possible observation combinations. This problem can only be attacked through the use of Bayes theorem, since the number of the required operations (assessments) can very easily reach extremely high levels.

The methodology for updating the probability distributions on geologic parameter states is presented in the following sections. At this point it is important to note that the two approaches are not fundamentally different. In fact, the methodology for updating the probability distributions at other locations, between or away from observations, is exactly the same. This can be easily seen from the above example results. Both methods yielded the same posterior assessment (by construction) in order to illustrate the following fact:

The PMF's on parameter states away or between observations depend

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72 Strictly speaking this is not exactly true since the reliability of a method may depend on the states of other geologic parameters. This potential problem can be alleviated by assessing the method's reliability matrix as a function of location along the project axis in order to capture the effect of regional geology. This is the approach adopted in this research.
only on the PMF's for the same parameters at the closest observations available (in either direction). What enters the calculations are the parameter state PMF values only. Methodologically it makes absolutely no difference how the observation PMF's are assessed (as long as the method is theoretically correct).

10.9 Updating the Markov Process.

This section presents the mathematical expressions for updating the parameter state and interval transition probabilities for any point along the axis of a tunnel. This presentation is divided into two parts:

The first part focuses on updating state probabilities and interval transition probabilities for locations along the tunnel axis where no specific observations are available. In undertaking this task, it is assumed that the updated posterior state probability mass functions at the observation locations are already available. As mentioned earlier, the methodology for assessing the posterior parameter state PMF's at the location of observations does not affect the procedure for updating the state and interval probabilities for points between or away from direct observations. As a result the formulas presented are quite general and can be used no matter whether the posterior state PMF's at the observation locations are subjectively encoded, or computed through the likelihood function.

The second part addresses the methodology for updating the state probabilities at the observation locations based on likelihood or reliability functions. The methodology for subjectively encoding the
posterior PMF's at these locations (directly) is straightforward, and can be found in Chan (1981). Either of these methods can be used for providing the necessary input to the first part, as explained above, as long as one considers observations that actually exist; i.e., for geologic prediction based on specific observations made in the course of an already undertaken exploration program. If, however, the objective is to assess how possible, but currently unknown observations may affect geologic prediction, it is much more efficient (from a computational point of view) to use the likelihood method. The reason for this will become apparent when discussing the methodology for generating artificial observations through simulation.

10.9.1 Parameter State Prediction at Points Away or Between Observations.

Since the geologic parameter Markov processes are functions of a space variable, it is necessary to define the positive direction and the origin for assessing locations. As mentioned earlier, the origin for describing locations along the axis of the project can be any predefined point, such as the portal or the beginning of the tunnel. Similarly, one can adopt the convention that the positive direction of location is from left to right. This definition is superior to associating the positive direction of location with the direction of construction advance, since construction may proceed simultaneously in multiple headings.

To make the following presentation as clear as possible, the basic problem is presented in steps of increasing complexity. For this purpose, it is typically assumed that the Markov process is known to be at a certain state \( i \) at a particular location \( t_0 \) and that the problem is
to determine the parameter state probabilities based on observations "ahead" of this location. The fact that updating is only considered for locations "ahead" of the current position enhances the clarity of presentation, and does not affect the validity of the results, because the "current location" is itself an observation location that is ahead of its predecessors. As a result, the process is recursive, with its origin at the beginning of the tunnel.

10.9.1.1 No Observations.

This is the base case where no observations exist ahead of the current position. At the current location $t_0$ (figure 10-10) the state of parameter $X$ is $i$. The probability that at position $t$ ($t > t_0$) the state is $j$, is given by the interval transition probability:

$$ P[x(t) = j | x(t_0) = i] = v_{Xij}(t-t_0) $$

<table>
<thead>
<tr>
<th>$X=i$</th>
<th>$X=j$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

--------- $t_0$ ----------------- $t$ ---------------> $t$

Figure 10-10: State Prediction at Position $t$.

10.9.1.2 One Deterministic Observation.

There is a deterministic observation at $t_1$: $x(t_1) = k$ (figure 10-11). The probability that at $t$ ($t > t_0$) the state is $j$, is given by the updated interval transition probability:

$$ v_{Xij}^d(t-t_0) = P[x(t) = j | x(t_0) = i, x(t_1) = k] $$

(The superscript "d" stands for "deterministic".)
\[ X = i \quad X = j \quad X = k \]

\[ \begin{array}{c|c|c}
\hline
& t_0 & t_1 \\
\hline
X = i & \multicolumn{2}{c}{\text{---}} \\
X = j & \text{---} & \text{---} \\
X = k & \text{---} & \text{---} \\
\hline
\end{array} \rightarrow t \]

**Figure 10-11: One Deterministic Observation at \( t_1 \).**

For: \( t_0 \leq t < t_1 \)

\[ v_{Xij}(t-t_0) = \frac{P[x(t)=j|x(t_0)=i] \cdot P[x(t_1)=k|x(t_0)=i, x(t)=j]}{P[x(t_1)=k|x(t_0)=i]} \]  \hspace{1cm} (10.15)

Since,

\[ P[x(t)=j|x(t_0)=i] = v_{Xij}(t-t_0) \]

\[ P[x(t_1)=k|x(t_0)=i, x(t)=j] = P[x(t_1)=k|x(t)=j] \]

\[ P[x(t_1)=k|x(t_0)=i, x(t)=j] = v_{Xjk}(t_1-t) \]

and,

\[ P[x(t_1)=k|x(t_0)=i] = v_{Xik}(t_1-t_0) \]

Equation (10.15) becomes:

\[ v_{Xij}^d(t-t_0) = \frac{v_{Xij}(t-t_0) \cdot v_{Xjk}(t_1-t)}{v_{Xik}(t_1-t_0)} \]

For: \( t \geq t_1 \),

\[ v_{Xij}^d(t-t_0) = P[x(t)=j|x(t_0)=i, x(t_1)=k] \]

\[ = P[x(t)=j|x(t_1)=k] \]

\[ = v_{Xkj}(t-t_1) \]

Thus,

\[ v_{Xij}^d(t-t_0) = \begin{cases} 
\frac{v_{Xij}(t-t_0) \cdot v_{Xjk}(t_1-t)}{v_{Xik}(t_1-t_0)} & (t_0 < t < t_1) \\
\frac{v_{Xij}(t-t_0) \cdot v_{Xik}(t_1-t)}{v_{Xik}(t_1-t_0)} & (t > t_1)
\end{cases} \]  \hspace{1cm} (10.16)
10.9.1.3 One Non-Deterministic Observation.

If the observation at \( t_1 \) is non-deterministic (figure 10-12) but is expressed in a probabilistic form (\( n \) is the total number of states):

\[
P[x(t_1)=k] = P_{1k} \quad (k=1, 2, \ldots, n)
\]

\[
P[X=k] (k = 1, \ldots n)
\]

\[
\begin{array}{ccc}
X=1 & X=j & P[X=k] \\
\end{array}
\]

\[
--- t_0 ------- t ------- t_1 ---- \rightarrow t
\]

Figure 10-12: One Non-Deterministic Observation at \( t_1 \).

\( v_{Xij}(t-t_0) \) is updated to \( v_{Xij}^n(t-t_0) \) (the superscript "\( n \)" stands for "non-deterministic") where:

\[
v_{Xij}^n(t-t_0) = \sum_{k=1}^{n} P[x(t_1)=k] P[x(t)=j|x(t_0)=i, x(t_1)=k]
\]

\[
v_{Xij}^n(t-t_0) = \sum_{k=1}^{n} p_{1k} v_{Xij}^d(t-t_0)
\]

(10.18)

10.9.1.4 Several Deterministic Observations.

When there are several (\( q \)) deterministic observations at locations \( t_1, t_2, \ldots, t_q \) (figure 10-13) such that:

\[
x(t_r) = k_r \quad (r=1, 2, \ldots, q)
\]

(10.19)

\( v_{Xij}(t-t_0) \) is updated to \( v_{Xij}^{ds}(t-t_0) \) ("\( ds \)" stands for "deterministic-several").
\[ \begin{align*}
X = i & \quad X = k_1 \quad X = j \quad X = k_2 \quad \ldots \quad X = k_q \\
\vdots & \\
t_0 & \quad t_1 \quad t \quad t_2 \quad \ldots \quad t_q \quad \rightarrow t
\end{align*} \]

Figure 10-13: Several Deterministic Observations.

Due to the assumption of a single-step memory, \( v_{X_{1j}}^{ds}(t-t_0) \) is dependent on the known states immediately preceding and following the position \( t \).

Thus for: \( t_0 < t < t_1 \),

\[ v_{X_{1j}}^{ds}(t-t_0) = P[x(t)=j|x(t_0)=i, x(t_1)=k_1] \]

which is the same probability given by (10.15) with \( k = k_1 \). Again because of single-step memory:

For: \( t_{r-1} < t < t_r \) \hspace{1cm} (r = 2, 3, \ldots q)

\[ v_{X_{1j}}^{ds}(t-t_0) = P[x(t)=j|x(t_{r-1})=k_{r-1}, x(t_r)=k_r] \]

\[ \begin{align*}
&= \frac{P[x(t)=j|x(t_{r-1})=k_{r-1}] \cdot P[x(t_r)=k_r|x(t_{r-1})=k_{r-1}, x(t)=j]}{P[x(t_r)=k_r|x(t_{r-1})=k_{r-1}]} \\
&= \frac{v_{X_{kr-1j}}^{ds}(t-t_{r-1}) \cdot P[x(t_r)=k_r|x(t)=j]}{v_{X_{kr-1k}}^{ds}(t-t_{r-1})} \\
&= \frac{v_{X_{kr-1j}}^{ds}(t-t_{r-1}) \cdot v_{X_{jkr}}^{ds}(t-t_r)}{v_{X_{kr-1k}}^{ds}(t-t_{r-1})} \\
&= \frac{v_{X_{kr-1j}}^{ds}(t-t_{r-1}) \cdot v_{X_{jkr}}^{ds}(t-t_r)}{v_{X_{kr-1k}}^{ds}(t-t_{r-1})}
\end{align*} \]
For:\ \ t > t_q, 
\[ v_{Xij}^{dS}(t-t_0) = P[x(t) = j | x(t_q) = k_q] \]
\[ = v_{Xkqj}^{dS}(t-t_q) \]

Thus to sum up (\( k_0 \) is equal to 1, the state at the current location):
\[ v_{Xij}^{dS}(t-t_0) = \begin{cases} 
\frac{v_{Xkr-1j}^{dS}(t-t_{r-1}) v_{Xjkr}^{dS}(t_{r}-t)}{v_{Xkr-1kr}^{dS}(t_{r}-t_{r-1})} & (t_{r-1} < t < t_{r}) \\
v_{Xkj}^{dS}(t-t_q) & (r = 1, ..., q) \\
v_{Xkqj}^{dS}(t-t_q) & (t > t_q)
\end{cases} \quad (10.20) \]

10.9.1.5 Several Non-deterministic Observations.

There are \( q \) non-deterministic observations at \( t_1, t_2, ..., t_q \) (figure 10-14) which are given by the PMF's:
\[ P[X(t_r) = k] = p_{rk} \quad (k=1, 2, ..., n) \]
\[ (r=1, 2, ..., q) \quad (10.21) \]

\[
\begin{array}{cccccc}
X=1 & p_{1X}(x) & X=j & p_{2X}(x) & \cdots & p_{qX}(x) \\
\hline
& & & & & \\
\hline
\end{array}
\]

--- \( t_0 = \) --- \( t_1 = \) --- \( t = \) --- \( t_2 = \) --- \( t_q = \) --- \( t \)

Figure 10-14: Several Non-Deterministic Observations.

\( v_{Xij}^{dS}(t-t_0) \) is updated to \( v_{Xij}^{\text{nsS}}(t-t_0) \) ("ns" stands for "non-deterministic - several") which depends on the non-deterministic observations immediately preceding and following position \( t \).

For: \( t_{r-1} < t < t_r \ (r=1, 2 \ldots q) \),
\[ v_{Xij}^{NS}(t-t_0) = P[x(t)=j | \text{Observations at } t_{r-1} \text{ and } t_r] \]

\[ = \sum_{m=1}^{n} \ p_{r-1m} \ P[x(t)=j | x(t_{r-1})=m, \text{ observation at } t_r] \]

(let \( p_{01} = 1 \) and \( p_{0r} = 0 \) for \( r \neq 1 \))

\[ = \sum_{m=1}^{n} \ p_{r-1m} \ \sum_{k=1}^{n} \ p_{rk} \ P[x(t)=j | x(t_{r-1})=m, x(t_r)=k] \]

where:

\[ P[x(t)=j | x(t_{r-1})=m, x(t_r)=k] \]

\[ = \frac{P[x(t)=j | x(t_{r-1})=m] \ P[x(t_r)=k | x(t_{r-1})=m, x(t)=j]}{P[x(t_r)=k | x(t_{r-1})=m]} \]

\[ = \frac{v_{Xmj}(t-t_{r-1}) \ v_{Xjk}(t_r-t)}{v_{Xmk}(t_r-t_{r-1})} \]

For \( t > t_q \),

\[ v_{Xij}^{NS}(t-t_0) = P[x(t)=j | \text{Observation at } t_q] \]

\[ = \sum_{k=1}^{n} \ p_{qk} \ P[x(t)=j | x(t_q)=k] \]

\[ = \sum_{k=1}^{n} \ p_{qk} \ v_{Xkj}(t-t_q) \]
To sum up,

\[
v_{X\left(t-t_0\right)}^{n} = \begin{cases} 
\sum_{n=1}^{n} \sum_{k=1}^{n} p_{rk}v_{Xm_j(t-t_{r-1})}v_{Xj_k(t_r-t)} & (r=1,\ldots,q) \\
\sum_{k=1}^{n} p_{qk}v_{Xk_j(t-t_q)} & (t > t_q)
\end{cases}
\]

(10.22)

10.9.2 State Prediction at Observation Points.

In the previous section, the expressions for updating the geologic parameter states between direct observations, given the location-specific observations made in the course of an exploration program, were based on the assumption that the posterior state probabilities at the observation locations were available. This section presents the mathematical expressions for determining the posterior parameter state probability distributions at locations where exploration observations are made. As discussed earlier, the updating of these distributions will be based on the likelihood function corresponding to the method used to obtain the observation. The likelihood (or reliability) matrix of a particular exploration method is defined as:

\[
P[b(t_b)=k|s(t_b)=j] = L_{jk}(t_b)
\]

\[j = 1, \ldots, n\]

\[k = 1, \ldots, m\]

where,

\[n\]

is the number of states for the geologic parameter.

\[m\]

is the number of states for the observation of the geologic parameter.
\( t_b \) is the location of the observation. 
\( b(t_b) \) is the observation made at location \( t_b \). 
\( s(t_b) \) is the true state of the geologic parameter at location \( t_b \). 
\( L_{jk}(t_b) \) is the likelihood of observing state \( k \) at location \( t_b \) given that the true parameter state is \( j \).

It should be noted that the above definitions do not explicitly associate the likelihood matrix \( L_{jk}(t_b) \) with a particular geologic parameter or exploration method. This was deemed necessary for the ease of notation, even though it is understood that the likelihood matrix refers to a particular combination of an exploration method and a geologic parameter. Furthermore, it must also be pointed out that the likelihood matrix is assumed to be a function of location \( t_b \) as well. In certain cases the reliability of an observation method does not only depend on the geologic parameter being observed, but may also depend on the general geologic conditions at that point. This assumption is thus necessary in order to capture the effect that other parameters may have on the reliability of the observations and thus to model the problem in its generality.

10.9.2.1 Updating State Probabilities at the Observation Points.

The general updating problem can be stated as follows: "What is the probability that the true parameter state at the (existing, or intended) observation location \( t_b \) is state \( i \), given that an observation \( b(t_b) = k \) has been made at location \( t_b \)?". Using the already developed expressions for the interval transition probabilities and the definition of the likelihood matrix presented above:
\[ P(s(t_b) = i | b(t_b) = k) = \frac{P(b(t_b) = k | s(t_b) = i) \cdot P(s(t_b) = i)}{P(b(t_b) = k)} \]

\[ P(b(t_b) = k | s(t_s) = i) = \sum_{j=1}^{n} P(b(t_b) = k | s(t_b) = j) \cdot P(s(t_b) = j | s(t_s) = i) \]

If \( t_s < t_b \) then:
\[ P(s(t_b) = j | s(t_s) = i) = V_{ij}(t_s, t_b) \]

If \( t_s > t_b \) then:
\[ P(s(t_b) = j | s(t_s) = i) = \frac{P(s(t_s) = i | s(t_b) = j) \cdot P(s(t_b) = j)}{P(s(t_s) = i)} \]

\[ = \frac{V_{ji}(t_b, t_s) \cdot s_j(t_b)}{s_i(t_s)} \]

To sum up, define:
\[ L_{jk}(t_b) = P(b(t_b) = k | s(t_b) = j) \]

\[
\begin{cases}
\sum_{j=1}^{n} L_{jk}(t_b) \cdot V_{ij}(t_s, t_b) \cdot s_i(t_s) & \text{for } t_s < t_b \\
\sum_{j=1}^{n} L_{jk}(t_b) \cdot a_j(t_b) & \\
\sum_{j=1}^{n} L_{jk}(t_b) \cdot V_{ji}(t_b, t_s) \cdot s_j(t_b) & \text{for } t_s > t_b \\
\sum_{j=1}^{n} L_{jk}(t_b) \cdot s_j(t_b) & \text{for } t_s = t_b \\
\frac{L_{ik}(t_b) \cdot s_i(t_b)}{s_i(t_s)} & \\
\sum_{j=1}^{n} L_{jk}(t_b) \cdot s_j(t_b) & (10.23)
\end{cases}
\]

In this form, the expressions for updating the state probabilities
at the observation locations are "iterative", in the sense that the right hand side of the equations refers to "prior" probabilities that include the effect of all the observations made to this point but not the effect of the observation at hand. As a result, these probabilities are "posterior" with respect to all other observations. This means that it is also necessary to update the interval transition probabilities \( v_{ij}(t_s, t_b) \) because they will be needed for updating the parameter state probabilities based on the next observation to be made. It is also important to notice that the interval transition probabilities are now written as:

\[
v_{ij}(t_s, t_b)
\]

as opposed to:

\[
v_{ij}(t_b - t_s)
\]

The reason for this slight change in notation is that these are posterior probabilities, and as such they are not only dependent on the relative distance between the observation locations (as is the case for the original Markov process), but also on the absolute location of the observations as well.

10.9.2.2 Updating Interval Transition Probabilities.

The general problem addressed here is the following: Given that a geologic parameter is in state \( i \) at location \( t_s \), i.e. \( s(t_s) = i \), and that state \( k \) has been observed at location \( t_b \), i.e. \( b(t_b) = k \), what is the probability that the true parameter state at location \( t_o \) is state \( j \)?

Mathematically the following probability is needed:

\[
P[s(t_o) = j | s(t_s) = i, b(t_b) = k] \quad \text{ (for } t_s < t_o \text{)}
\]

The requirement that \( t_s < t_o \) follows from the assumed directionality of
the Markov process.

Case 1: \[ t_b < t_s < t_o \]

Due to the one-step memory of the process the posterior equals the prior:

\[
P[s(t_o) = j | s(t_s) = i, b(t_b) = k] = P[s(t_o) = j | s(t_s) = i] = \nu_{ij}(t_s, t_o)
\]

Case 2: \[ t_s < t_b < t_o \]

\[
P[s(t_o) = j | s(t_s) = i, b(t_b) = k] = \]

\[
\frac{P[s(t_o) = j, b(t_b) = k, s(t_s) = i]}{P[b(t_b) = k, s(t_s) = i]}
\]

\[
\sum_{j=1}^{n} P[s(t_o) = j, s(t_b) = h, s(t_s) = i, b(t_b) = k]
\]

\[
\sum_{i=1}^{n} P[b(t_b) = k, s(t_b) = h, s(t_s) = i]
\]

\[
\sum_{h=1}^{n} P[b(t_b) = k | s(t_b) = h] P[s(t_o) = j | s(t_b) = h] P[s(t_b) = h | s(t_s) = i] P[s(t_s) = i]
\]

\[
\sum_{i=1}^{n} P(b(t_b) = k | s(t_b) = h) P[s(t_b) = h | s(t_s) = i] P[s(t_s) = i]
\]

\[
\sum_{h=1}^{n} \sum_{i=1}^{n} L_{hk}(t_b) \nu_{ij}(t_b, t_o) \nu_{ih}(t_s, t_b)
\]

\[
\sum_{i=1}^{n} L_{hk}(t_b) \nu_{ih}(t_s, t_b)
\]

Case 3: \[ t_s < t_o < t_b \]

\[
P[s(t_o) = j | s(t_s) = i, b(t_b) = k] = \]
\[
\sum_{h=1}^{n} P[b(t_b)=k|s(t_b)=h] \sum_{j=1}^{n} P[s(t_o)=j|s(t_s)=i] \sum_{h=1}^{n} P[s(t_b)=h|s(t_s)=i]
\]

\[
\sum_{h=1}^{n} L_{hk}(t_b) \sum_{j=1}^{n} V_{jh}(t_o,t_b) V_{lj}(t_s,t_o)
\]

\[
\sum_{h=1}^{n} L_{hk}(t_s) V_{ih}(t_s,t_b)
\]

Finally:

\[
P[s(t_o)=j|s(t_s)=i,b(t_b)=k] = \begin{cases} 
V_{lj}(t_s,t_o) & t_b < t_s < t_o \\
\sum_{h=1}^{n} L_{hk}(t_b) V_{jh}(t_b,t_o) V_{ih}(t_s,t_b) & t_s < t_b < t_o \\
\sum_{h=1}^{n} L_{hk}(t_b) V_{ih}(t_s,t_b) & t_s < t_o < t_b \\
\sum_{h=1}^{n} L_{hk}(t_b) V_{jh}(t_o,t_b) V_{lj}(t_s,t_o) & t_s < t_o < t_b \\
\sum_{h=1}^{n} L_{hk}(t_b) V_{ih}(t_s,t_o) & t_s < t_o < t_b
\end{cases}
\]
10.10 Geologic Parameter and Ground Class Profiles.

The previous discussion on the Markov process along with the expressions developed for updating the prior parameter state and interval transition probabilities form the necessary foundation for the development of probabilistic geologic parameter profiles. A parameter profile is the posterior expression concerning the state probabilities of the associated Markov process along the domain of interest; i.e., along the axis of the tunnel. Each point along this axis is associated with a probability mass function that gives the probability that the associated geologic parameter will be in any one of its possible states. These PMF's differ from the original Markov process PMF's in that they reflect all the information provided by the exploration program.

Geologic parameter profiles, however, cannot be directly used in design and construction planning. For these purposes it is necessary to consider the joint impact of all the parameters, in order to establish a description of the project's geology that is directly related to design and construction decisions. This can be achieved by transforming the developed parameter profiles into ground class profiles according to the definitions presented in the previous chapter.

To this effect, a necessary intermediate step is to associate each point along the axis of the tunnel with a probability mass function over all possible geologic vectors. If the project's geologic conditions are described by m geologic parameters, each having $n_i$ possible states, then the number of geologic vectors $k$ is:

$$k = n_1 * n_2 * \ldots * n_m$$
This means that each location along the tunnel axis is associated with a PMF over all (i.e., \( k \)) possible geologic vectors. If the \( j^{th} \) geologic vector is defined as:

\[
\mathbf{v}_j = (s_{1j}, s_{2j}, \ldots, s_{mj}) \quad j = 1, 2, \ldots, k
\]

where \( s_{ij} \) is the state of the \( i^{th} \) geologic parameter corresponding to the \( j^{th} \) vector, then the probability that \( \mathbf{v}_j \) defines the true geologic conditions at location \( t \) is given by:

\[
P_{\mathbf{V}}(\mathbf{v}_j, t) = P[S_1(t) = s_{1j}] \cdot P[S_2(t) = s_{2j}] \ldots \cdot P[S_m(t) = s_{mj}] \quad j = 1, 2, \ldots, k
\]

where \( P[S_i(t) = s_{ij}] \) is the posterior probability that parameter \( i \) is at state \( s_{ij} \) at location \( t \). Thus the geologic vector distribution is simply the joint parameter state distribution under the assumption of parameter independence.

Since each ground class \( G \) is defined as a set of mutually exclusive geologic vectors, the probability that ground class \( g_h \) exists at location \( t \), is simply the sum of the probabilities of the corresponding vectors:

\[
P_{\mathbf{G}}(g_h, t) = \sum_j P_{\mathbf{V}}(\mathbf{v}_j, t)
\]

where in the above expression the summation extends over all the vectors \( \mathbf{v}_j \) that belong in ground class \( g_h \). As a result, the original geologic parameter profiles are transformed into ground class profiles quite easily, since the only operations involved are multiplication and addition of matrices.

The ground class profiles reflect all the geologic information necessary for design and construction purposes that has been provided by
the already undertaken exploration program. In order to associate the
amount and type of exploration conducted with the project's cost, the
next issue is to predict the design and construction policies that would
have been implemented (as well as the resulting cost of the work) under
the assumption that no more exploration will be conducted.

10.11 The Threshold Probability Rule.

A necessary prerequisite for determining the value of exploration is
the ability to predict the changes in design and construction policies,
and hence in cost, that are expected to be brought about by the
availability of additional geologic information. This need for
predicting the designer's and the contractor's reaction to new
information has probably been the most difficult problem in the
development of this research, because the methodology to be adopted would
probably have the strongest impact on the practical usefulness of the
proposed model.

The main issue is whether a "prescriptive", as opposed to a
"descriptive" approach should be used in modelling the designer's and/or
the contractor's decision frameworks. The former is quite easy since
several theories of rational behavior exist that can easily be applied to
the problem at hand. One such method, for example, is stochastic dynamic
programming, which assumes that the decision maker's objective is the
minimization of the expected cost of the work. 73

73A similar approach has been developed by Kim (1984).
On the other hand, the evidence collected in the course of this research does not support the assumption that cost minimization is an adequate descriptor of the behavior of these parties (under conditions of uncertainty), since it ignores some very important variables, like risk aversion and the contractual and organizational allocation of risk. In addition, a model that prescribes how a decision maker should behave is of little value in predicting his behavior, if the decision maker does not follow the model's assumption and uses his own method.74 This is of particular importance in modelling the designer's and the contractor's behavior; even though the owner can influence some of the factors affecting the designer's and the contractor's decisions, he cannot explicitly control their actions over matters for which these parties are responsible (like the choice of design and construction methods).

As a result, the only available alternative is to adopt a "descriptive" approach that simulates how decisions are actually made in practice. Based on the findings of this research, the proposed method is a variation on the principle of hypothesis testing that centers on the notion of the "threshold probability". The main advantage of this method is that it provides a very good approximation to how design and construction decisions are actually made under current US practices.

From the definition of ground classes and the above discussion on ground class probability profiles, it becomes apparent that there is some

74 "The trickiest problem in the rational preparation for action is, in the opinion of psychologists and economists, the conversion of objectives into criteria" (i.e., decision rules) (Kaufmann, 1968).
non-zero probability for any ground class to exist at any location along the alignment of a project. Using the numbering convention adopted in this research, and assuming that n ground classes, corresponding to n design-construction methods have been defined, ground class 1 (i.e., g₁) represents the most favorable geologic conditions that may be encountered, whereas ground class n (i.e., gₙ) represents the most adverse conditions. As a result, if a particular design-construction method CM₁ is chosen for a certain segment of a project, there is some finite probability that this method may in fact prove to be inadequate. The only exception to this rule is the most conservative and hence most expensive design-construction method CMₙ. Since the latter cannot always be specified for the whole length of the work, the choice of design-construction methods can be considered as a typical example of a "calculated risk".

To this effect, the designer (acting as the owner's expert representative) sets up the null hypothesis that method i is indeed adequate; the alternate hypothesis, of course, is that method i is inadequate and that a more conservative method has to be used:

Null Hypothesis \[ H₀ : \text{Method } i \text{ is adequate.} \]
Alternate Hypothesis \[ H₁ : \text{Method } i \text{ is inadequate.} \]

The typical decision rule used in hypothesis testing is the following:

**Decision Rule:** Reject the null hypothesis in favor of the alternate if, based on the information available (i.e., the observations provided from a subsurface exploration program), the probability of making a Type
I Error\(^{75}\) is more than "alpha", "the level of significance".

In this case, however, making a Type I Error merely implies excessive conservatism, because rejecting the null hypothesis automatically means that a more conservative method will be considered. Making a Type II Error\(^{76}\) is much more serious, because it defeats safety by accepting the null hypothesis that method \(i\) is adequate when in reality a more conservative method should be used. The probability of a Type II Error is commonly known as "beta": the "threshold probability".

As a result, the above decision rule should be modified to reflect the importance of the Type II Error:

**Decision Rule:** "At any point along the alignment of the tunnel, use the least conservative method whose probability of being inadequate, based on the available information, is less than the acceptable threshold probability."

To facilitate the use of this rule, let \(Z_i(t)\) be defined as a Bernoulli variable that takes on the value 1 (success) if \(CM_i\) is adequate for the geologic conditions at location \(t\) (i.e., that the true ground class is at least as favorable as class \(i\)).

\(^{75}\)Type I Error: To reject the null hypothesis when it is actually true.

\(^{76}\)Type II Error: To accept the null hypothesis when it is actually false.
Thus, the probabilities concerning the adequacy of design-construction method $CM_i$ at any location $t$ are given by the PMF of $Z_i$:

$$Z_i(t) = \begin{cases} 
1 & \text{if } CM_i \text{ is adequate at } t, \\
0 & \text{otherwise}
\end{cases} \quad i = 1, 2, \ldots, n$$

$$P_{Z_i}(z_i, t) = \begin{cases} 
\sum_{j=1}^{i} p_G(j, t) & \text{for } z_i = 1 \quad (CM_i \text{ is adequate}) \\
\sum_{j=i+1}^{n} p_G(j, t) & \text{for } z_i = 0 \quad (CM_i \text{ is inadequate})
\end{cases} \quad (i = 1, 2, \ldots, n)$$

where $p_G(j, t)$ is the probability that ground class $j$ exists at location $t$.

From an operational point of view, the application of the threshold probability rule can be best explained when one considers the cumulative form of the ground class probability profile (figure 10-15). At each point $t$ along the alignment of the project, this profile gives the probability that the actual ground class at that location is at least as favorable as ground class $i$ ($i=1, \ldots, n$). For example, at location $t$, the probability that the true ground class is at least as favorable as ground class 2 is approximately 0.88 (which simply equals the probability of ground class 1 and ground class 2 at that location). By definition, this figure also gives the probability that method $CM_i$ is adequate. For example, the probability that $CM_2$ is adequate at location $t_o$ is equal to 0.88, the probability of having either ground class 1 or 2. The complement of this CDF gives the probability that method $i$ is not
Figure 10-15: The Cumulative Form of the Ground Class Profile And the Application of the Threshold Probability Rule.
adequate. If a horizontal line is drawn below the top of the CDF profile at a distance equal to the threshold probability, one immediately gets the least conservative, acceptable sequence of design-construction methods as defined by the points of intersection of the threshold probability line and the CDF curves for each ground class. This sequence represents the expected design and construction decisions as a function of the threshold probability.

As a final comment, this model is intended to be used (in actual practice) by the designer, who also typically serves as the specifications writer for the owner-contractor contract. Since the designer often possesses information relevant to the contractual sharing of risk between the owner and the contractor, he should also specify the threshold probability in a way that captures the effect of geologic uncertainty and risk sharing on the contractor's behavior as well. In other words, the designer should subjectively assess the contractor's general construction planning strategy, given the available information on geologic conditions and the intent of the contract clauses, based on his prior experience. This process cannot be modelled since it involves the conditional prediction of behavior that cannot be easily quantified and on which there are no objective data.

10.12 Estimating the Cost of the Project.

Once a sequence of design-construction methods has been established by applying the threshold probability rule, the next step is to estimate the corresponding cost of the work in order to associate the given
exploration information with a dollar value. Since, however, the value of exploration is directly related with the cost savings that can be effected through additional exploration, only the affected portion of the cost need be considered.

The cost function used in the proposed model is very similar to the one presented in discussing the value of perfect information on ground class extents:

\[ C = a + \sum_{i=1}^{n} b_i + \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} f_{ij} + \sum_{i=1}^{n} \sum_{k=1}^{m_i} d_{ik} w_{ik} + \sum_{i=1}^{n} \sum_{k=1}^{m_i} \frac{e_{ik}}{r_{ik}} w_{ik} \]

Where:

\( n \) : the number of construction methods \( CM_i \) considered.
\( m_i \) : the number of segments in which \( CM_i \) is used.
\( w_{ik} \) : the extent of the \( k \)th segment in which \( CM_i \) is used.
\( a \) : fixed cost, independent of the construction methods used.
\( b_i \) : fixed cost uniquely associated with the use of \( CM_i \).
\( c_{ij} \) : cost of change from \( CM_i \) to \( CM_j \).
\( f_{ij} \) : the number of times \( CM_j \) follows \( CM_i \).
\( d_{ik} \) : the cost per foot of using \( CM_i \) in segment \( k \).
\( e_{ik} \) : the time dependent cost of using \( CM_i \) in segment \( k \).
\( r_{ik} \) : the advance rate when using \( CM_i \) in segment \( k \).

The model keeps track of the policy dependent variables \( f_{ij} \) and \( w_{ik} \) corresponding to the specified threshold probability and the current (posterior) ground class profile. The rest of the necessary input, i.e. the cost and performance parameters presented above, is provided by the designer. Little additional effort is required since most of these unit costs are also necessary for preparing the engineer's estimate.
In conclusion, it must also be mentioned that the model has the capability of accepting probabilistic cost data (in the form of expected value and variance) if such input is available either through subjective encoding or statistical estimation. If this is the case, the final output of the model provides both the expected value and the variance of the total cost.

10.13 Intermediate Summary.

This chapter has thus far presented the basic assumptions and the methodology incorporated in the first phase of the proposed model for the evaluation of exploration. Phase I focuses on assessing the cost of a project as a function of the amount and reliability of the observations made in the course of the exploration program already adopted. In this sense, this portion of the model is a complete estimating mechanism linking the information on geology with a sequence of design and construction methods and finally with cost.

The geologic prediction model is based on the assumption that each geologic parameter of interest follows an independent Markov process. The transition intensity matrix for each of these processes can either be based on available statistical data, or can be subjectively encoded to reflect the general geologic information concerning the project site.

Each of the exploration methods used to observe the states of the geologic parameters at specific locations is associated with a likelihood or reliability matrix. As a result, a reliability matrix has to be assessed (probably by a geotechnical expert) for each exploration method,
each parameter and if necessary for each observation location. The latter is only necessary if the reliability of the observation is also strongly affected by the regional geology (i.e. the states of other geologic parameters in the vicinity of the observation).

Based on the assessed reliability matrices and the observations made during exploration, the posterior parameter state distributions for each of the observation locations are determined. If the likelihood method is not used, then these posterior state probabilities can be subjectively encoded. The subjective assessment should reflect all the general and specific information available, since it bypasses the formal updating of the Markov process at these locations. If the likelihood method is used, it is also necessary to update the interval transition probabilities from each observation location to all others, since they are necessary for updating the state probabilities at these locations.

Given the updated state probabilities at each of the observation locations, the original state probabilities of the Markov process at points between or away from direct observations are updated next. The methodology for updating these PMF's is independent of the method used for assessing the posterior state PMF's at the observation locations. The final result is a series of probabilistic profiles that express the probability that each of the parameters considered will be in a particular state at a certain location along the project axis.

The individual parameter profiles are then merged into a geologic vector profile by considering all the possible combinations of parameter states that may exist. Thus the resulting vector profile is actually the
joint PMF over all the combinations of parameter states. To simplify the amount of calculations that have to be performed, the geologic parameters considered are assumed to be independent so that their marginal PMF's equal the conditional and thus the joint PMF equals the product of the marginals.

The geologic vector profile is subsequently merged according to the definition of ground classes to produce the ground class profile. This profile expresses the probability that a particular ground class will actually prevail (as a function of location). It is important to notice that even though the ground class profile is computed by merging individual Markov processes, it does not itself follow a Markov process. As a result the single-step memory assumption ceases to be valid. The development of the ground class profile concludes the geologic prediction part of the model.

Based on the cumulative ground class profile and the acceptable threshold probability specified by the designer, the least conservative sequence of design-construction methods is determined according to the threshold probability rule (heuristic). According to this rule the sequence of design and construction methods to be implemented is the least conservative one, whose probability of being inadequate at any point along the project axis is less than the threshold probability (i.e., the maximum probability acceptable for making a Type II Error). This sequence is principally characterized by the length of the segments in which each of the design-construction methods CM_i is used, and the number of times a transition has to be made from one method to another. The latter form the model's input to a total cost function which utilizes
the associated unit prices supplied by the designer (part of the
ingineer's estimate) to produce an estimate of the final cost of the work
as a function of the available geologic information and the designer's
choice of the threshold probability. Unit prices can also be provided in
a probabilistic form, in which case the model's output is the expected
value and the variance of the total cost.

The above sequence of procedures (Phase I) represents the necessary
foundation for conducting a preposterior analysis on the EVSI of an
exploration program by associating the final cost of the work with:

1. The amount and reliability of the observations made in the
course of exploration.

2. The influence of geologic uncertainty and the adopted
contractual risk sharing arrangement on the designer's
specification of the threshold probability.

The next step is to present how this methodology can be applied to
the case where the exploration program has not yet been adopted (and as a
result its observations are not yet known) in order to determine its
expected economic value.

10.14 Creating Artificial Observations - Simulation.

The analysis presented in the previous sections (Phase I) was based
on the assumption that an exploration program had already been adopted,
and as a result the observations used to update the geologic parameter
Markov processes were "real". When considering the decision to adopt a
new exploration program, however, the results of the observations to be
made in the future are obviously not known. As a result, it becomes
necessary to consider all the possible exploration results that might have been observed had the program been actually undertaken. This problem, however, cannot be always attacked through direct enumeration.

As an example, consider the simple case of a tunneling project where the designer is contemplating the decision to sink 10 new boreholes. If each one of these boreholes can provide 4 different observations for each geologic parameter, and the geologic prediction model includes 5 parameters, then the number of possibilities is exactly $5 \times 4^{10} = 5,242,880$. It is remarkable how a simple situation such as this one results in an incredibly large number of calculations. This problem is at its worst when the exploration method to be evaluated is a pilot tunnel which, of course, provides continuous observations (i.e., the exponent in the permutation formula becomes infinity!). As a result, the option to enumerate all the possible exploration results can be safely abandoned, unless the problem is quite trivial, in which case no analysis is probably necessary.

Given this observation the only option available for the analysis of future exploration (Phase II) is the use of Monte Carlo simulation. This is in fact the approach adopted in developing this model, the details of which are presented here.

The following discussion is based on the assumptions below:

1. There is no dependence between observations between different geologic parameters, and as a result the observations on each parameter can be generated independently. Thus, the following methodology need only focus on generating observations and updating the state PMF of one geologic parameter at a time.

2. The number, location and reliability matrices for the
contemplated observations are known. Only the observations themselves are not known. If these observations will be made in a pilot tunnel, then the problem can be discretized by assuming individual observations at fixed or variable intervals; the extents of these intervals can be arbitrarily small.

3. The parameter state PMF's at the existing and contemplated observation locations have already been updated to reflect all the available information from the already undertaken exploration program (Phase I).

Given the above assumptions, the basic problem is how to generate a single observation \( b(t_b) \) concerning the state of a certain parameter, at a particular location. The probability of observing state \( k \) at location \( t_b \) is given by:

\[
P[b(t_b)=k] = \sum_{j=1}^{n} P[b(t_b)=k|s(t_b)=j] \cdot P[s(t_b)=j]
\]

\[
= \sum_{j=1}^{n} L_{jk}(t_b) \cdot s_j(t_b)
\]

where,

\( n \) is the number of states for the geologic parameter.
\( m \) is the number of states for the new observation.
\( t_b \) is the location of the new observation.
\( b(t_b) \) is the new observation to be made at location \( t_b \).
\( s(t_b) \) is the true state of the geologic parameter at location \( t_b \).
\( s_j(t_b) \) is the posterior probability that the geologic parameter is in state \( j \) at location \( t_b \) given all other observations.
\( L_{jk}(t_b) \) is the likelihood of observing state \( k \) at location \( t_b \) given that the true parameter state is \( j \).

Using the above expressions one can compute the probabilities of observing any state \( k \) \((k=1,\ldots,m)\) at a particular location \( t_b \). Given this
PMF on the possible observation states at $t_b$, an artificial observation is generated at this location (through the inverse cumulative method) which in turn is added to the set of available observations (notice that all the other observations are "real" while the latter is "artificial"). Based on this newly created observation the parameter state PMF's and the interval transition probabilities from each observation location to all others (including the locations of the unknown future observations) are updated using the formulas presented in discussing the "likelihood method".

This procedure represents one iteration of the basic generation and updating process. Once an observation at a certain location has been generated and the necessary probabilities have been updated, the process is repeated by considering some other observation at another location (for the same geologic parameter). Continuing in this manner an artificial observation for a particular geologic parameter and for each of the "new" locations can be generated. The same process is repeated for all the other geologic parameters. This represents one simulation cycle.

Once this cycle is completed for all the geologic parameters, a complete set of new observations is available, based on which the state PMF's at locations between or away from observations can be updated. Repeating the procedures of Phase I, the final cost of the project corresponding to the enlarged set of available observations can be
finally be computed. Thus each simulation cycle associates the addition of a vector of artificial observations with a new cost estimate. If unit costs are provided in a probabilistic manner, then the final output includes both the expected value and the variance of the total cost.

This cycle can be repeated as many times as necessary in order to assess the full distribution of the "output" (i.e., the project's cost) as a function of the "input" (i.e., the number and reliability of the observations and the specified threshold probability). The artificial experiments of Monte Carlo simulation are equivalent to conducting "real life" experiments in much the same way as one might experiment with an actual roulette wheel, or dice. In other words, simulation offers the decision maker with statistical data concerning the economic consequences of a particular decision or policy. These data can thus be used to evaluate the policy according to a decision criterion.

An interesting question at this point concerns the number of simulations (experiments) that should be performed. The answer to this question depends on the desired accuracy. Considering the general case where the model provides an estimate of the expected value and the variance of the total cost, the decision maker has to at first assume a

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The need for a method predicting the designer's decisions should now become evident. It is simply impossible for the designer to assess the new design and construction policies corresponding to each possible artificial set of observations. This is a characteristic requirement of simulation. Had the original problem been the estimation of the cost of the work and not the determination of the EVSI of an exploration program, there would be no need for the threshold probability rule since the designer could have made the necessary assessment directly.
sampling distribution for the mean and variance (either on some theoretical basis or through a histogram). Once each of these distribution is assessed, the number of experiments necessary can be determined on the basis of the desired width of a y% confidence interval (Benjamin and Cornell, 1970). An example of this procedure is presented in section 11.8.1.

10.15 The Expected Value of Sampled Information.

Phases I and II have presented all the necessary steps for achieving the original objective of this research, i.e. the determination of the EVSI of an exploration program. The situation can now be summarized as follows:

On the basis of the already undertaken exploration program the total cost of the project has a determined expected value $E[C]$ and variance $\text{Var}[C]$ (Phase I). A new exploration program is being considered, which, if adopted, is expected to result in a final cost with expected value $E[C^*]$ and variance $\text{Var}[C^*]$ (Phase II). Both of these costs are dependent on the type and extent of the corresponding exploration programs as well as on the adopted threshold probability.

If the cost for conducting the contemplated exploration program is D, then the EVSI of the program is simply:

$$\text{EVSI} = E[C] - E[C^*] - D$$

If the resulting EVSI is positive, then the decision to adopt the exploration program is acceptable, since it is expected to result in cost savings that equal the program's EVSI. However, this does not mean that
this decision is optimal. If several new exploration programs are being considered the optimal decision is to select the alternative with the highest EVSI.

These conclusions, of course, are based on the assumption that the owner is willing to accept expected value as a valid criterion for financial decision making. If this is not the case, then a different decision rule has to be adopted. For example, the owner may base his decision on the maximization of expected utility, provided that a meaningful utility curve can indeed be encoded. If the owner is an organization, it is very doubtful whether such a utility curve does exist. Even if the decision on exploration can be made by a single individual within the owner organization, one must be very careful in assessing the behavior of this person under conditions of uncertainty; typically decision makers show a very different degree of risk aversion depending on whose money is at stake (i.e. the organization's, or theirs).

If despite these problems a meaningful utility curve can be assessed, the value of exploration can be determined as follows:

Since not all utility curves (with the exception of the linear and exponential) possess the "delta" property the value of exploration cannot be determined as the difference between the certain equivalent for

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78 The delta property is the phenomenon where increasing all the outcomes of a lottery by the same constant amount "delta" results in a similar increase in the certain equivalent of this lottery (Howard, 1970).
the case where no additional exploration is conducted and the case of adopting the new program. Instead, the value of exploration V is the amount of money that has to be added to C^* + D so that the resulting utility equals the utility of the no exploration option: 79

\[ E[U(C)] = E[U(C^* + D + V)] \]

Typically, the above equation is highly nonlinear and as a result, the value of an exploration program V cannot be computed in closed form but only through trial and error. The situation, however, is considerably simpler if the decision maker's utility curve is exponential:

\[ U(x) = 1 - \exp(-x/b) \quad b>0 \]

In this case, the "delta" property holds and the value of exploration V equals:

\[ V = U^{-1}(E[U(C)]) - U^{-1}(E[U(C^*)]) - D \]

or,

\[ V = CME(C) - CME(C^*) - D \]

where CME(C) is the "Certainty Monetary Equivalent of the lottery C".

Because of the computational simplicity of this expression, the exponential utility curve can also be used as an approximation of the decision maker's utility curve. This can be accomplished by calibrating the risk aversion coefficient b to get the best possible fit between the

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79 By the same token C and C^* must correspond to the total cost of the project including cost items that are not affected by exploration. This is necessary in order to capture the effect of risk aversion at the true monetary level. In other words, the attractiveness of a program that can save $100 depends on the whether the total cost of the work is $1,000 or $1,000,000.
decision maker's true utility curve and the exponential for amounts of money in the neighborhood of the project's cost. The sensitivity of the final result to this assumption can be tested by varying the risk aversion coefficient.

10.16 Sensitivity Analysis.

In order to use the proposed model for the evaluation of exploration programs, a considerable amount of subjective input is necessary. Most of this input comes from the designer, who in this case acts as the owner's expert. In particular, one of the most important assessments made by the designer in using this model, is the adopted threshold probability; in some cases, this assessment may have more impact on the project's cost than any of the exploration alternatives. This would be the case, for example, if the most conservative exploration method $CM_n$ is by far more expensive than $CM_{n-1}$, and a slight increase in the threshold probability results in a change of methods (i.e., from $CM_n$ to $CM_{n-1}$) even for a short tunnel segment. As a result, the analysis of exploration would not be complete if the sensitivity of the final decision is not tested against the choice of the threshold probability.

To this effect, the designer should run the model several times, assuming different threshold probabilities for each run and observe the changes in the project's total cost. More importantly the changes in total cost should be translated into changes in decisions concerning the value of further exploration (since this is the objective in using the
model). If the choice of the threshold probability results in radical changes in cost, or in the decision on exploration, the owner should probably review the risk sharing approach, and attempt to reduce the designer's and the contractor's conservatism in order to decrease the project's cost (by inducing the use of a larger threshold probability).

Another approach that may prove to be useful, is to plot the cost of the project as a function of different threshold probabilities and observe the point at which the proposed exploration program ceases to have a positive value. If this level is quite "high" then the exploration program should probably be acceptable, whereas if it is too "low" then this exploration option should probably be abandoned.

10.17 Summary.

This chapter has presented a model for determining the expected value of sampled geologic information. This model consists of two phases:

Phase I deals with the basic procedures for transforming a certain amount of general and location-specific geologic information into an

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80 If the objective of this model were to estimate the project's cost there would be no need to use the threshold probability rule.

81 This approach is similar to the Internal Rate of Return criterion for capital investments. By computing the IRR of a project the decision maker basically avoids the assessment of the appropriate discount rate, which usually is quite difficult to establish correctly. If the IRR is significantly higher or lower than the level at which the discount rate might be, then a decision can be made without assessing the exact discount rate. In fact, a little reflection shows that the ideas of the discount rate and that of the threshold probability are quite similar.
estimate of the project's cost.

Phase II deals with the evaluation of a proposed exploration program. The process begins by generating artificial observations at the contemplated exploration locations through Monte Carlo simulation. For each simulated set of observations, the model repeats the Phase I calculations and produces one data point: the associated "experimental" project cost. This process continues until enough data is generated to estimate the expected project cost and its variance to a specified degree of accuracy.

The EVSI of the evaluated exploration program is computed by comparing the cost of the project under the option to explore against the null option of undertaking no more exploration. An exploration program is considered acceptable if its EVSI is positive. Furthermore, it is considered optimal if it has the highest EVSI among all acceptable alternatives. An example application of this model is presented in the next chapter.
Chapter 11

EVGE: A Decision Support System
For the Evaluation of Exploration.
A Case Study.

11.1 Introduction.

The proposed model for the evaluation of exploration programs has been implemented as a computerized decision support system\textsuperscript{82}. This system is referred to here as EVGE\textsuperscript{83} (Expected Value of Geologic Exploration) and runs on a DEC VAX11-780.

This chapter presents an example application of this system in evaluating the option to use a pilot tunnel for the discharge water tunnel project of the Seabrook Power Station, N.H.\textsuperscript{84} The actual discharge tunnel is over 15,000 feet (2.8 miles) long. Only the western portion (7662 feet long) from borehole ADT-1 ($t=0$) to ADT-42 ($t=7662$) is used in this example (figure 11-1).

\textsuperscript{82}Decision Support System: A computer program that aids in decision making through man-machine interaction.

\textsuperscript{83}EVGE: Popular ancient Greek exclamation (like eureka!) meaning "bravo!" or "well done!".

\textsuperscript{84}This project has also been used as a case study by Chan (1981) in presenting the geologic prediction model for adaptable tunneling. In order to minimize duplication of effort, this research adopted the same case study, since the input required for Chan's model is a subset of the input required for EVGE.
Finally, the exploration program to be evaluated is a pilot tunnel that runs the full length of the tunnel segment under consideration (i.e., 7662 ft.).

11.1.1 General Geology.

The bedrock types in the region of this project include metamorphic rocks of the Kittery formation, igneous rocks of the Newburyport pluton and intrusive diabase dikes. Due to the complicated processes of formation, the spatial relationships between the rock types are sometimes very irregular. A detailed description of the regional geology and history can be found elsewhere (Rand, 1974).

11.1.2 Geologic Parameters.

A list of the most important geologic parameters in hard rock tunneling has already been presented in discussing the interview and questionnaire results. These include (but are not limited to) the following seven parameters:

1. Rock type.
2. Joint Density (RQD).
3. Fault characteristics.
4. Joint appearance.
5. Degree of weathering.
7. Water Pressure.

Since this example serves as a simplified demonstration, only the
Figure 11-1: Seabrook Power Station Discharge Water Tunnel (Chan, 1981).
four most important parameters are actually used. These are:

1. Rock Type (R).

Rock type is a very useful characteristic because it allows one to draw certain conclusions concerning other parameters such as joint orientation and foliation. The rock types considered include schist, metaquartzite, diorite and quartzite. Diabase dikes are neglected because they are thin and as a result have little effect on design and construction decisions. The states of rock type (as a random variable R) are defined in Table 11-I (a).

2. RQD (D).

RQD (Rock Quality Designation) is commonly used as a quantitative measure of the degree of jointing which directly affects tunneling performance. The states of this parameter are defined in Table 11-I (b).

3. Degree of Weathering (E).

Severe weathering is found in some zones in the tunnel region. It is detrimental to tunneling performance in a similar way as other major defects such as faults and clay seams. The states of this parameter are defined in Table 11-I (c).

4. Availability of Water (W).

This parameter is called "availability of water" in order to include the effect of both water inflow and water pressure. The availability of water is a geologic property that indicates the potential water inflow into the tunnel. The states of this parameter are defined in Table 11-I (d).
(a) Rock Type (R)

<table>
<thead>
<tr>
<th>R</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Schist</td>
</tr>
<tr>
<td>2</td>
<td>Metaquartzite</td>
</tr>
<tr>
<td>3</td>
<td>Diorite</td>
</tr>
<tr>
<td>4</td>
<td>Quartzite</td>
</tr>
</tbody>
</table>

(b) RQD (D)

<table>
<thead>
<tr>
<th>d</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>High 75–100%</td>
</tr>
<tr>
<td>2</td>
<td>Medium 25–75%</td>
</tr>
<tr>
<td>3</td>
<td>Low  0–25%</td>
</tr>
</tbody>
</table>

(c) Degree of Weathering (E)

<table>
<thead>
<tr>
<th>a</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Not Severe</td>
</tr>
<tr>
<td>2</td>
<td>Severe</td>
</tr>
</tbody>
</table>

(d) Availability of Water (W)

<table>
<thead>
<tr>
<th>w</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Low</td>
</tr>
<tr>
<td>2</td>
<td>Medium</td>
</tr>
<tr>
<td>3</td>
<td>High</td>
</tr>
</tbody>
</table>

**Table 11-I: Definition of Parameter States.**
11.1.3 Ground Classes.

From the definition of states for the four geologic parameters considered, it can be seen that a total of 72 (= 4x3x2x3) possible geologic vectors may exist at any location along the tunnel axis. For example, (2, 3, 2, 3) is a geologic vector meaning "metaquartzite, low RQD, severe weathering and high availability of water".

These vectors have subsequently been grouped into design-construction ground classes (i.e., sets of geologic vectors) corresponding to the chosen construction methods CM\(_1\). Five ground classes G\(_i\) have been established, corresponding to the construction methods CM\(_1\) listed in Table 11-II. The geologic vectors \(V_j\) for each ground class G\(_i\) are shown in Table 11-III. Table 11-III is in fact a simplified ground class classification table because only some of the 72 geological vectors are included. The corresponding ground classes of the remaining geologic vectors can be assigned through a conservative approach. For example, a geologic vector (not listed in Table 11-III) is assumed to be in G\(_3\) if the geologic conditions as indicated by this vector are "better" than those of the vectors listed in G\(_3\) but are "worse" than those listed in G\(_2\). Using this approach the remaining geologic vectors are assigned to the defined ground classes and the full ground class classification table is shown in Table 11-IV.
<table>
<thead>
<tr>
<th>CM</th>
<th>EXCAVATION-SUPPORT METHOD</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Full face drill and blast.</td>
</tr>
<tr>
<td></td>
<td>No support.</td>
</tr>
<tr>
<td>2</td>
<td>Full face drill and blast.</td>
</tr>
<tr>
<td></td>
<td>Conventional steel sets.</td>
</tr>
<tr>
<td></td>
<td>Amount of support: medium.</td>
</tr>
<tr>
<td>3</td>
<td>Heading and bench drill and blast.</td>
</tr>
<tr>
<td></td>
<td>Conventional steel sets.</td>
</tr>
<tr>
<td></td>
<td>Amount of support: medium.</td>
</tr>
<tr>
<td>4</td>
<td>Heading and bench drill and blast.</td>
</tr>
<tr>
<td></td>
<td>Conventional steel sets.</td>
</tr>
<tr>
<td></td>
<td>Amount of support: large.</td>
</tr>
<tr>
<td>5</td>
<td>Multiple drift drill and blast.</td>
</tr>
<tr>
<td></td>
<td>Conventional steel sets.</td>
</tr>
<tr>
<td></td>
<td>Amount of support: large.</td>
</tr>
</tbody>
</table>

*Table 11-II: Generalized Construction Methods Corresponding to Defined Ground Classes.*
<table>
<thead>
<tr>
<th>G</th>
<th>r</th>
<th>d</th>
<th>e</th>
<th>w</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1,2,3</td>
<td>1</td>
<td>1</td>
<td>1,2</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>1,2</td>
</tr>
<tr>
<td>3</td>
<td>1,2,3,4</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>1,2,3,4</td>
<td>3</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>5</td>
<td>1,2,3,4</td>
<td>3</td>
<td>2</td>
<td>1,2,3</td>
</tr>
</tbody>
</table>

Table 11-III: "Simplified" Ground Class Classification.
<table>
<thead>
<tr>
<th>G</th>
<th>r</th>
<th>d</th>
<th>e</th>
<th>w</th>
</tr>
</thead>
<tbody>
<tr>
<td>1:</td>
<td>1,2,3</td>
<td>1</td>
<td>1</td>
<td>1,2</td>
</tr>
<tr>
<td>2:</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>1,2</td>
</tr>
<tr>
<td>3:</td>
<td>1,2,3,4</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1,2,3,4</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>4:</td>
<td>1,2,3,4</td>
<td>3</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1,2,3,4</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1,2,3,4</td>
<td>1</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>1,2,3,4</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1,2,3,4</td>
<td>3</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>5:</td>
<td>1,2,3,4</td>
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<td>2</td>
<td>1,2,3</td>
</tr>
<tr>
<td></td>
<td>1,2,3,4</td>
<td>2</td>
<td>2</td>
<td>1,2,3</td>
</tr>
<tr>
<td></td>
<td>1,2,3,4</td>
<td>1</td>
<td>2</td>
<td>1,2,3</td>
</tr>
</tbody>
</table>

Table 11-IV: Ground Class Classification Table.
11.2 Estimating the Parameters of the Markov Processes.

Once the states for each of the four geologic parameters have been defined, the basic parameters for the corresponding Markov processes have to be estimated. These parameters are the transition intensity coefficients and the transition probabilities.

Since no frequency records on state transitions and extents were available, the required input was encoded subjectively.\textsuperscript{85} According to the expert consulted, parameter interdependencies were not significant and as a result the four parameters have been assumed to be independent. Since the geologies of the western portion of the discharge tunnel are believed to be similar (homogeneous) throughout, that portion is regarded as a homogeneous region for each of the four parameters. This implies that the values of the transition intensity coefficients and transition probabilities remain the same throughout that portion of the tunnel.

11.2.1 Transition Intensity Coefficients.

The transition intensity coefficient for each parameter state was subjectively encoded according to standard questioning procedures (Spetzler, Stael von Holstein, 1975; Chan, 1981). Since the expert was uncertain about the true value of these coefficients, 3 estimates were assessed for each $c_{X_1}$, corresponding to different "competing hypotheses" (i.e., a 3 point PMF was encoded). The detailed procedures can be made

\textsuperscript{85} This assessment process was conducted by Chan (1981) based on the judgment of H.H. Einstein.
clear by considering how estimates for $c_{R1}$ were derived:

The geologist was asked the following question:

"The tunnel goes through several lengths of schist. What could be the average length? Give a best estimate. Also give the upper and lower bounds on the average length."

To answer this question the geologist produced and used an estimated profile of rock types along the tunnel (figure 11-2). By taking in this profile the average of the lengths of schist existing at the tunnel axis the best estimate was determined. Then the upper and lower bounds were determined by considering how much the average length could deviate from the best estimate.\(^{86}\)

The three estimates were:

\[
\begin{align*}
H_1 & : \text{best estimate} = 750' \\
H_2 & : \text{upper bound} = 1000' \\
H_3 & : \text{lower bound} = 550'
\end{align*}
\]

Therefore:

\[
\begin{align*}
c_{1R1} & = 1/750 = .00133 \\
c_{2R1} & = 1/1000 = .00100 \\
c_{3R1} & = 1/550 = .00182
\end{align*}
\]

Similar questioning procedures were carried out for metaquartzite, diorite and quartzite. The other parameters were subsequently considered

---

\(^{86}\)This procedure of using an estimated profile is not mandatory and the geologist could derive directly the estimates through subjective judgment.
Figure 11-2: Seabrook Power Station Discharge Water Tunnel. Estimated Rock Type Profile (Chan, 1981).
and the results are summarized in Table 11-V.

11.2.2 Transition Probabilities.

The transition probabilities for each parameter were also estimated subjectively. In particular, the expert's uncertainty concerning the true value of these parameters lead to the establishment of three competing hypotheses for each row of transition probabilities. The detailed procedures can be made clear by considering how estimates for $P_{Rlj}$ ($j=1, 2, 3, 4$) were derived (Chan, 1981):

The geologist was asked the following question:

"If the tunnel runs into schist at some point, how many times out of a hundred will it run into (i) metaquartzite, (ii) diorite, (iii) quartzite next? At first give the best estimates of the three frequencies. Then assume different viewpoints and theories to give additional sets of estimates."

The geologist subsequently came up with three sets of estimates based on three hypotheses (one based on an estimated profile and the other two on different opinions). The estimates were divided by 100 to give the following probabilities:

<table>
<thead>
<tr>
<th></th>
<th>$m=1$</th>
<th>$m=2$</th>
<th>$m=3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{mR12}$</td>
<td>.05</td>
<td>.00</td>
<td>.00</td>
</tr>
<tr>
<td>$P_{mR13}$</td>
<td>.20</td>
<td>.50</td>
<td>.00</td>
</tr>
<tr>
<td>$P_{mR14}$</td>
<td>.75</td>
<td>.50</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Similar questioning procedures were carried out for the other three
\[
\begin{array}{cccc}
\text{m} & 1 & 2 & 3 \\
\hline
\text{c}_{mR1} & .00133 & .00100 & .00182 \\
\text{c}_{mR2} & .00800 & .00667 & .01000 \\
\text{c}_{mR3} & .00286 & .00167 & .00333 \\
\text{c}_{mR4} & .00250 & .00167 & .00333 \\
\text{c}_{mD1} & .00222 & .00143 & .00333 \\
\text{c}_{mD2} & .00333 & .00182 & .00667 \\
\text{c}_{mD3} & .00154 & .00125 & .00286 \\
\text{c}_{mE1} & .000444 & .000435 & .000465 \\
\text{c}_{mE2} & .00167 & .00200 & .00118 \\
\text{c}_{mW1} & .000833 & .000769 & .000870 \\
\text{c}_{mW2} & .00500 & .00400 & .00100 \\
\text{c}_{mW3} & .00167 & .00143 & .00200 \\
\end{array}
\]

Table 11-V: Transition Intensity Coefficients of all Parameters Based on Different Competing Hypotheses.
states of rock type. Then the other parameters were considered in a similar manner; the final results are summarized in Tables II-VI and II-VII. (There was no need to assess the transition probabilities of E which had only two states.)

11.2.3 Geologic Input.

The assessed transition intensity coefficients and transition probabilities can be input to the system either in the form in which they were encoded (i.e. using the competing hypotheses as a PMF) or by first computing the expected values of these PMF's and inputting a single estimate for each parameter. Theoretically it makes no difference which of the two methods is actually used, since the results are the same in either case. From a practical point of view, the former method of specifying all the possible values of each parameter along with their associated probabilities has the advantage of allowing the comparison of the ground class profiles under each of the competing hypotheses because they are computed independently. If this information is not needed, one should use the latter method since it requires much less computation time and is thus faster and cheaper. The former method is used for this example.

To prepare the necessary input, a vague prior is assumed for each of the competing hypotheses $H_m$ (i.e. $P_m = 1/3$).

A transition intensity coefficient to be input to the model is thus calculated by straightforward expectation. For example:

$$c_{R1} = P_1 c_{1R1} + P_2 c_{2R1} + P_3 c_{3R1}$$
<table>
<thead>
<tr>
<th>( m = )</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_{mR12} )</td>
<td>0.05</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>( P_{mR13} )</td>
<td>0.20</td>
<td>0.50</td>
<td>0.00</td>
</tr>
<tr>
<td>( P_{mR14} )</td>
<td>0.75</td>
<td>0.50</td>
<td>1.00</td>
</tr>
<tr>
<td>( P_{mR21} )</td>
<td>0.05</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>( P_{mR23} )</td>
<td>0.60</td>
<td>0.50</td>
<td>0.40</td>
</tr>
<tr>
<td>( P_{mR24} )</td>
<td>0.35</td>
<td>0.50</td>
<td>0.60</td>
</tr>
<tr>
<td>( P_{mR31} )</td>
<td>0.05</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>( P_{mR32} )</td>
<td>0.20</td>
<td>0.10</td>
<td>0.30</td>
</tr>
<tr>
<td>( P_{mR34} )</td>
<td>0.75</td>
<td>0.90</td>
<td>0.70</td>
</tr>
<tr>
<td>( P_{mR41} )</td>
<td>0.20</td>
<td>0.20</td>
<td>0.30</td>
</tr>
<tr>
<td>( P_{mR42} )</td>
<td>0.10</td>
<td>0.30</td>
<td>0.10</td>
</tr>
<tr>
<td>( P_{mR43} )</td>
<td>0.70</td>
<td>0.50</td>
<td>0.60</td>
</tr>
</tbody>
</table>

Table II-VI: Transition Probabilities of \( R \) Based on Different Hypotheses.
<table>
<thead>
<tr>
<th>m =</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_{mD12}</td>
<td>1.00</td>
<td>0.85</td>
<td>0.925</td>
</tr>
<tr>
<td>P_{mD13}</td>
<td>0.00</td>
<td>0.15</td>
<td>0.075</td>
</tr>
<tr>
<td>P_{mD21}</td>
<td>0.75</td>
<td>0.90</td>
<td>0.825</td>
</tr>
<tr>
<td>P_{mD23}</td>
<td>0.25</td>
<td>0.10</td>
<td>0.175</td>
</tr>
<tr>
<td>P_{mD31}</td>
<td>0.50</td>
<td>0.00</td>
<td>1.00</td>
</tr>
<tr>
<td>P_{mD32}</td>
<td>0.50</td>
<td>1.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>m =</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_{mW12}</td>
<td>0.50</td>
<td>0.75</td>
<td>0.40</td>
</tr>
<tr>
<td>P_{mW13}</td>
<td>0.50</td>
<td>0.25</td>
<td>0.60</td>
</tr>
<tr>
<td>P_{mW21}</td>
<td>1.00</td>
<td>0.80</td>
<td>0.90</td>
</tr>
<tr>
<td>P_{mW23}</td>
<td>0.00</td>
<td>0.20</td>
<td>0.10</td>
</tr>
<tr>
<td>P_{mW31}</td>
<td>1.00</td>
<td>0.80</td>
<td>0.90</td>
</tr>
<tr>
<td>P_{mW32}</td>
<td>0.00</td>
<td>0.20</td>
<td>0.10</td>
</tr>
</tbody>
</table>

Table 11-VII: Transition Probabilities of D and W Based on Different Hypotheses.
\[ = .333(.00133) + .333(.001) + .333(.00182) \]
\[ = .00138 \]

A row of transition probabilities to be used in the first stage is calculated in a similar manner. For example:

\[
\begin{pmatrix}
P_{D21} & P_{D22} & P_{D23}
\end{pmatrix} = P_1\begin{pmatrix}P_{1D21} & P_{1D22} & P_{1D23}\end{pmatrix}
\]
\[ + P_2\begin{pmatrix}P_{2D21} & P_{2D22} & P_{2D23}\end{pmatrix} \]
\[ + P_3\begin{pmatrix}P_{3D21} & P_{3D22} & P_{3D23}\end{pmatrix} \]
\[ = .333 (.75 .00 .25) \]
\[ +.333 (.90 .00 .10) \]
\[ +.333 (.82 .00 .18) \]
\[ = (.82 .00 .18) \]

The transition intensity coefficients and the transition probabilities to be used in this example are summarized in Tables 11-VIII to 11-XI.

11.3 Point Observations.

Although no frequency data were available for this project, on which to base the estimation of state transitions and state extents, there were many point observations in the form of boreholes along the tunnel axis. In the original application of the geologic prediction model for adaptable tunneling, the posterior geologic state probabilities at these locations were encoded subjectively. In other words, after the drilled cores from these boreholes were inspected, the posterior PMF's of the parameter states were assessed directly, taking into account all the specific and general geologic information that was available (Chan,
Table 11-VIII: Transition Probabilities (first 4 columns) and Transition Intensity Coefficients for R.

<table>
<thead>
<tr>
<th>i</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>( c_{RI} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.00</td>
<td>.02</td>
<td>.23</td>
<td>.75</td>
<td>.00138</td>
</tr>
<tr>
<td>2</td>
<td>.02</td>
<td>.00</td>
<td>.50</td>
<td>.48</td>
<td>.00822</td>
</tr>
<tr>
<td>3</td>
<td>.02</td>
<td>.20</td>
<td>.00</td>
<td>.78</td>
<td>.00262</td>
</tr>
<tr>
<td>4</td>
<td>.23</td>
<td>.17</td>
<td>.60</td>
<td>.00</td>
<td>.00250</td>
</tr>
</tbody>
</table>

Table 11-IX: Transition Probabilities and Transition Intensity Coefficients for D.

<table>
<thead>
<tr>
<th>i</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>( c_{PI} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.00</td>
<td>.93</td>
<td>.07</td>
<td>.00233</td>
</tr>
<tr>
<td>2</td>
<td>.83</td>
<td>.00</td>
<td>.17</td>
<td>.00394</td>
</tr>
<tr>
<td>3</td>
<td>.50</td>
<td>.50</td>
<td>.00</td>
<td>.00188</td>
</tr>
</tbody>
</table>
\[ \begin{array}{cccc}
   & 1 & 2 & c_{wi} \\
   i &   &   &   \\
   1 & .00 & 1.00 & .000448 \\
   2 & 1.00 & .00 & .00162 \\
\end{array} \]

**Table 11-X: Transition Probabilities and Transition Intensity Coefficients for E.**

\[ \begin{array}{cccc}
   & 1 & 2 & 3 & c_{wi} \\
   i &   &   &   &   \\
   1 & .00 & .55 & .45 & .000824 \\
   2 & .90 & .00 & .10 & .00633 \\
   3 & .90 & .10 & .00 & .00170 \\
\end{array} \]

**Table 11-XI: Transition Probabilities and Transition Intensity Coefficients for W.**
1981). For example, at borehole ADT-1 (t=0), the following PMF was designated for rock type:

\[
\begin{align*}
P[r=1] &= 0.00 \\
P[r=2] &= 0.00 \\
P[r=3] &= 1.00 \\
P[r=4] &= 0.00
\end{align*}
\]

In fact, this PMF denotes a deterministic observation, i.e., the rock type at t=0 is observed to be diorite. There were 13 boreholes along the western portion considered, and as a result there are 13 observations for each parameter. The subjectively assessed posterior state probabilities for each parameter and each observation location are shown in Tables II-XII to II-XV.

With respect to considering observations that have already been made (i.e. "real") the proposed system offers a choice of two methods: The first method is similar to the one used by Chan (1981) whereby observations are used to directly assess the posterior PMF's at the corresponding locations and thus no updating on these PMF's needs to be done by the system. The second method accepts the available observations as direct input (i.e., without any subjective preprocessing) and uses the reliability matrix corresponding to the method producing the observation to update the prior PMF's. The prior PMF's are computed by using the Markov process assumptions and the already incorporated observations. This is the method used in this example. The observed states are shown in Table II-XVI and the assumed likelihood matrices are shown in Table II-XVII.
<table>
<thead>
<tr>
<th>Borehole</th>
<th>Depth (feet)</th>
<th>State 1</th>
<th>State 2</th>
<th>State 3</th>
<th>State 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>33</td>
<td>341</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>717</td>
<td>0.0</td>
<td>0.2</td>
<td>0.8</td>
<td>0.0</td>
</tr>
<tr>
<td>34</td>
<td>1239</td>
<td>0.0</td>
<td>0.5</td>
<td>0.0</td>
<td>0.5</td>
</tr>
<tr>
<td>35A</td>
<td>1945</td>
<td>0.0</td>
<td>0.0</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>36</td>
<td>2788</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>37</td>
<td>3566</td>
<td>0.8</td>
<td>0.0</td>
<td>0.0</td>
<td>0.2</td>
</tr>
<tr>
<td>37B</td>
<td>4010</td>
<td>1.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>38</td>
<td>4659</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>39</td>
<td>5256</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
</tr>
<tr>
<td>43</td>
<td>5785</td>
<td>1.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>41</td>
<td>6604</td>
<td>0.0</td>
<td>0.0</td>
<td>0.9</td>
<td>0.1</td>
</tr>
<tr>
<td>42</td>
<td>7662</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 11-XII: Subjectively Encoded Posterior PMF's on R at the Observation Locations.
<table>
<thead>
<tr>
<th>Bore-hole</th>
<th>t (feet)</th>
<th>State Probabilities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0.5</td>
</tr>
<tr>
<td>33</td>
<td>341</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>717</td>
<td>1.0</td>
</tr>
<tr>
<td>34</td>
<td>1239</td>
<td>0.5</td>
</tr>
<tr>
<td>35A</td>
<td>1945</td>
<td>0.2</td>
</tr>
<tr>
<td>36</td>
<td>2788</td>
<td>0.2</td>
</tr>
<tr>
<td>37</td>
<td>3566</td>
<td>0.5</td>
</tr>
<tr>
<td>37B</td>
<td>4010</td>
<td>0.0</td>
</tr>
<tr>
<td>38</td>
<td>4659</td>
<td>0.0</td>
</tr>
<tr>
<td>39</td>
<td>5256</td>
<td>1.0</td>
</tr>
<tr>
<td>43</td>
<td>5785</td>
<td>0.8</td>
</tr>
<tr>
<td>41</td>
<td>6604</td>
<td>0.8</td>
</tr>
<tr>
<td>42</td>
<td>7662</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Table 11-XIII: Subjectively Encoded Posterior PMF's on D At the Observation Locations.
<table>
<thead>
<tr>
<th>Borehole</th>
<th>t (feet)</th>
<th>1</th>
<th>2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>33</td>
<td>341</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>2</td>
<td>717</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>34</td>
<td>1239</td>
<td>1.0</td>
<td>0.0</td>
</tr>
<tr>
<td>35A</td>
<td>1945</td>
<td>0.6</td>
<td>0.4</td>
</tr>
<tr>
<td>36</td>
<td>2788</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>37</td>
<td>3566</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>37B</td>
<td>4010</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>38</td>
<td>4659</td>
<td>0.2</td>
<td>0.8</td>
</tr>
<tr>
<td>39</td>
<td>5256</td>
<td>0.8</td>
<td>0.2</td>
</tr>
<tr>
<td>43</td>
<td>5785</td>
<td>0.6</td>
<td>0.4</td>
</tr>
<tr>
<td>41</td>
<td>6604</td>
<td>0.8</td>
<td>0.2</td>
</tr>
<tr>
<td>42</td>
<td>7662</td>
<td>1.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Table 11-XIV: Subjectively Encoded Posterior PMF's on E At the Observation Locations.
Table 11-XV: Subjectively Encoded Posterior PMF's on W At the Observation Locations.
<table>
<thead>
<tr>
<th>Borehole</th>
<th>t (feet)</th>
<th>State Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R</td>
<td>D</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>33</td>
<td>341</td>
<td>3</td>
</tr>
<tr>
<td>2</td>
<td>717</td>
<td>3</td>
</tr>
<tr>
<td>34</td>
<td>1239</td>
<td>2</td>
</tr>
<tr>
<td>35A</td>
<td>1945</td>
<td>4</td>
</tr>
<tr>
<td>36</td>
<td>2788</td>
<td>4</td>
</tr>
<tr>
<td>37</td>
<td>3566</td>
<td>1</td>
</tr>
<tr>
<td>37B</td>
<td>4010</td>
<td>1</td>
</tr>
<tr>
<td>38</td>
<td>4659</td>
<td>4</td>
</tr>
<tr>
<td>39</td>
<td>5256</td>
<td>4</td>
</tr>
<tr>
<td>43</td>
<td>5785</td>
<td>1</td>
</tr>
<tr>
<td>41</td>
<td>6604</td>
<td>3</td>
</tr>
<tr>
<td>42</td>
<td>7662</td>
<td>4</td>
</tr>
</tbody>
</table>

**Table 11-XVI:** States Observed at Each Location.
\[ b_R = \begin{array}{cccc}
 1 & 2 & 3 & 4 \\
 1 & .85 & .05 & .05 & .05 \\
 2 & .05 & .85 & .05 & .05 \\
 3 & .05 & .05 & .85 & .05 \\
 4 & .05 & .05 & .05 & .85 \\
\end{array} \]

\[ b_D = \begin{array}{ccc}
 1 & 2 & 3 \\
 1 & .90 & .05 & .05 \\
 2 & .05 & .85 & .10 \\
 3 & .00 & .05 & .95 \\
\end{array} \]

\[ b_E = \begin{array}{cc}
 1 & 2 \\
 1 & .95 & .05 \\
 2 & .05 & .95 \\
\end{array} \]

\[ b_W = \begin{array}{ccc}
 1 & 2 & 3 \\
 1 & .95 & .05 & .00 \\
 2 & .05 & .90 & .05 \\
 3 & .00 & .05 & .95 \\
\end{array} \]

Table 11-XVII: Likelihood (Reliability) Matrices.
11.4 Unit Costs.

In addition to the input necessary for modelling the geology, the unit cost prices for each of the specified construction methods must also be specified so that the cost of the project may be evaluated.

For this purpose, this example uses subjectively assessed unit costs and probabilistic advance rate predictions (Salazar, 1983). This information was available for both "urban deep" and "transmountain" tunnels. In this particular application the tunneling conditions are very similar to the "urban deep" case (Table 11-VIII).

In particular, the available cost prices are broken down into the same categories as the ones used in the linear cost function presented earlier. These categories are the fixed cost of construction, the cost of changing construction methods, the cost of permanent materials and supplies and the time dependent cost. The fixed cost is neglected in this example because it does not depend on the amount of undertaken exploration.

Furthermore, the available advance rate estimates are given in the form typically used for PERT networks:

\[ a = 0.05 \text{ percentile} \]

\[ m = \text{mode} \]

\[ b = 0.95 \text{ percentile} \]

Since the adopted cost function is not linear with respect to \( r_1 \) (the standard form of the advance rate in ft/hour) it is necessary to invert the given advance rate parameters. The use of \( a, m, \) and \( b \) above is very convenient for this purpose, since the resulting PDF uses the same
parameters. In other words, if $Y_1$ (hours/ft) is the inverse of the advance rate $r_1$, then the parameters $1/b$, $1/m$, and $1/a$ are the 0.05 percentile, the mode and the 0.95 percentile for $Y_1$. Using the standard approximation that $Y_1$ is beta distributed (Moder and Phillips, 1964) then its first two moments can be approximated by:

$$E[Y_1] = (1/b + 4/m + 1/a)/6$$

$$Var[Y_1] = [(1/a - 1/b)/3.2]^2$$

Using these formulas the mean and the variance of $U_1$: the variable cost per linear foot of tunnel for each construction method, can be estimated as:

$$E[U_1] = d_1 + e_1 E[Y_1]$$

$$Var[U_1] = e_1^2 Var[Y_1]$$

where $d_1$ is the cost of permanent materials and supplies and $e_1$ is the time dependent cost.

Finally the expected value and the variance of $U_1$ have been adjusted to reflect inflation according to the 1984 construction index published in ENR. The resulting unit costs are shown in Table 11-XIX.

11.5 New Observations and Reliability Matrices.

The required input with respect to the exploration method to be evaluated, consists of:

1. The number of observation to be made.

2. The location of the observations.

3. The reliability matrix for each observation location and for each geologic parameter.
<table>
<thead>
<tr>
<th></th>
<th>CM1</th>
<th>CM2</th>
<th>CM3</th>
<th>CM4</th>
<th>CM5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed Costs</td>
<td>$</td>
<td>1265800</td>
<td>1265800</td>
<td>1610900</td>
<td>1630400</td>
</tr>
<tr>
<td>Permanent Materials and Supplies</td>
<td>$/ft</td>
<td>112.79</td>
<td>219.24</td>
<td>307.21</td>
<td>811.15</td>
</tr>
<tr>
<td>Time dependent</td>
<td>$/hr</td>
<td>632.49</td>
<td>632.49</td>
<td>745.52</td>
<td>745.52</td>
</tr>
<tr>
<td>Time dependent</td>
<td>$/mth</td>
<td>81100</td>
<td>81100</td>
<td>81900</td>
<td>81900</td>
</tr>
<tr>
<td>Change of method</td>
<td>$/shf</td>
<td>2600</td>
<td>2600</td>
<td>2600</td>
<td>2600</td>
</tr>
<tr>
<td>Advance rate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>feet/(8 hr shift)</td>
<td>a:</td>
<td>18</td>
<td>10</td>
<td>9</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>m:</td>
<td>16</td>
<td>8</td>
<td>7</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>b:</td>
<td>13</td>
<td>7</td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 11-XVIII: Unit Costs and Advance Rates (Salazar, 1983).

<table>
<thead>
<tr>
<th></th>
<th>CM1</th>
<th>CM2</th>
<th>CM3</th>
<th>CM4</th>
<th>CM5</th>
</tr>
</thead>
<tbody>
<tr>
<td>E[U_{i}]</td>
<td>$/ft</td>
<td>600</td>
<td>1163</td>
<td>1630</td>
<td>2745</td>
</tr>
<tr>
<td>SD[U_{i}]</td>
<td>$/ft</td>
<td>46.5</td>
<td>93.2</td>
<td>227.8</td>
<td>275</td>
</tr>
</tbody>
</table>

Table 11-XIX: Total Variable Unit Cost (in 1984 dollars per foot).
The exploration method considered in this example is a full length pilot tunnel. Since a pilot tunnel can provide observations at any point along its length, it is necessary to assume that these observations can be approximated by "discrete" observations at closely spaced intervals. For this purpose, it is assumed that the information provided by a pilot tunnel is equivalent to point observations made every 300 ft. over the full length of the tunnel (7662 ft). This assumption has been tested by using several interval lengths and was found to be satisfactory for the geologic conditions of this project.\textsuperscript{87} In general, extremely close spacing should be avoided, unless absolutely necessary, since it entails a large number of computations which can be prohibitively expensive.

Furthermore, the reliability of the pilot tunnel observations was assumed to be perfect; i.e. the true geologic states are the same as the ones observed. This assumption was based on the following factors:

1. The contractors participating in this research felt that a pilot tunnel can be considered as a perfect predictor of geology for small diameter tunnels.

2. Perfect reliability implies that the model's output is equivalent to the expected value of perfect information, which, of course, is an upper limit on the justifiable cost of any exploration program.

As a final comment, it must also be pointed out that the assumption of perfect reliability produces significant savings in running the system without sacrificing the accuracy of the results.

\textsuperscript{87} This issue will be addressed when discussing the system's output.
11.6 Parameter and Ground Class Probability Profiles.

Once the necessary input has been collected, the system performs the Phase I calculations, outlined in the previous chapter. These procedures produce the geologic parameter profiles and the associated ground class profiles based on the specified transition intensity coefficients of the Markov processes and the available borehole observations.

The geologic parameter profiles express the posterior (due to the already undertaken exploration program) PMF's for each parameter and for each point along the tunnel axis. The state probabilities concerning the observation locations are calculated according to the limiting state probabilities of the Markov processes (the original prior). Based on each added observation (observations are added one at a time) and by considering the method's reliability matrix, the system updates all parameter state and interval transition probabilities associated with observation locations. For this purpose the interval transition probabilities of the Markov processes are computed from the complex spectral resolution of the transition intensity matrices using the method described by Cox and Miller (1965).\(^8\) Once the posterior parameter PMF's for the observation locations are calculated, the system computes the updated state probabilities for all other locations based on the formulas presented earlier. In general, the construction of parameter profiles is based on the expression for the interval transition probabilities given

\(^8\)The necessary complex eigenvalues and eigenvectors of these matrices are calculated by subroutine EIGRF of the International Mathematics and Statistics Library.
several non-deterministic observations.

The resulting parameter profiles are shown in Appendix C where X1, X2, X3, and X4 denote rock type, RQD, degree of weathering and availability of water, respectively. Thus, for example, the probability of having state 2 (metaquartzite) of X1 (R) at t=2700 is 0.034 while the probability of having state 4 (quartzite) is .836.

Parameter probability profiles are subsequently used to construct ground class profiles by first computing the probabilities of geologic vectors and then aggregating the results into ground classes. The probability associated with a geologic vector, for example, can be calculated as follows:

\[ P[V(6000) = (1 1 1 1)] = P[R(6000) = 1, D(6000) = 1, E(6000) = 1, W(6000) = 1] = P[R(6000) = 1] P[D(6000) = 1] P[E(6000) = 1] P[W(6000) = 1] = (.616) (.750) (.948) (.904) = 0.396 \]

Once the probabilities of all the geologic vectors are computed for each point along the tunnel axis, the ground class profile can be determined by adding the probabilities of all the vectors belonging to each class. The resulting ground class profile is shown in figure 11-2 and in Appendix D.

The construction of the ground class probability profile based on the available observations from past exploration signals the end of the geologic prediction model.
Figure 11-3: Ground Class Profile (All Classes).
Figure 11-4: Ground Class Profile (Class 1).
Figure 11-5: Ground Class Profile (Class 2).
Figure 11-6: Ground Class Profile (Class 3).
Figure 11-7: Ground Class Profile (Class 4).
Figure 11-8: Ground Class Profile (Class 5).

Class: 5

Ground Class State Probabilities

Horizontal Alignment of Tunnel (ft)
11.7 Checking the Input and Determining the Threshold Probability.

Once the ground class probability profiles are determined, the system can be used for:

- checking the specified input, and
- as a decision aid in establishing the acceptable threshold probability.

Even though these steps are not part of the mathematical model, they are nevertheless necessary for ensuring that the system will produce representative results. For this purpose, the designer should be allowed to evaluate the model's geologic prediction and experiment on the choice of the threshold probability before undertaking the simulation procedure (Phase II).

To this effect, the designer can invoke a graphics subroutine that displays a color representation of the ground class probability profile.\(^8^9\) This graph can be compared to the designer's subjective interpretation of the project's geology, and if any discrepancies are found, the designer has the option to terminate execution and correct the system's input. Unfortunately, this display cannot be reproduced in this report because it requires the use of color. The equivalent black and white display is shown in figures 11-3 to 11-8, where for the clarity of presentation the original graph 11-3 is decomposed into separate profiles

\(^8^9\)This routine was implemented in DEC's Remote Graphics Instruction Set (REGIS) the output of which is an ASCII file containing commands that can be processed and displayed by three types of DEC graphics terminals: VK100, VT125, VT240 and the Professional 350 microcomputer.
for each class (figures 11-4 to 11-8).

In addition to the ground class profiles, the graphics subroutine can be executed in an interactive mode to produce the sequence of design-construction methods corresponding to a particular threshold probability. The system prompts for the input of the threshold probability and produces a special color display of the cumulative ground class profile. This profile uses the threshold probability as a color painting reference line, to produce a graph that shows the corresponding design-construction sequence as a series of colors (each color representing a different method) at the threshold probability line. For practical purposes, the designer need only concentrate on this line because it summarizes all the necessary information.

To facilitate understanding this process the cumulative ground class profile is shown in figure 11-9. This graph shows the probability that the ground conditions will be at least as favorable as ground class 1 (i=1,...,5) at a particular point along the tunnel axis. By definition then, this profile also shows the probability that a particular method CM_i will be adequate at that point. Only 4 curves are shown in the cumulative ground class probability profile, since the worst ground class always corresponds to a horizontal line at p=1.0 (the probability that conditions will be at least as favorable as the worst ground class is by definition 1.0, irrespective of location). By subtracting the probabilities of the cumulative ground class profile from 1.0, one gets the probability of "method inadequacy" as a function of location (figure 11-10). This is the black and white version of the color graph displayed at the terminal, where the regions above the threshold probability line
are painted in different colors each corresponding to different construction methods as shown by the numbers in figure 11-10. The area of the graph below the threshold probability line is painted in a solid color to highlight the sequence of colors above and to help avoid confusion.

The usefulness of this graph is in providing the designer with immediate feedback concerning the consequences in design and construction decisions that are associated with a certain level of "conservatism". Thus, the threshold probability can be calibrated to yield the same sequence of design-construction methods that would have been used in the absence of this model. In this manner, the assessment of the threshold probability is not made "blindly" (i.e. without any information as its consequences) but rather chosen to reflect typical design and construction practice. This is of particular importance, since if the user (i.e., the designer) cannot be convinced of the accuracy (representativeness) of the method, or of the specified input, he will never accept the validity of the model's results.\textsuperscript{90}

11.8 The Evaluation of Exploration.

Once the threshold probability is determined, the system can perform the Phase II calculations to predict the expected value and the variance of the project's cost. These calculations are made for the following two cases:

\textsuperscript{90}A necessary prerequisite for using the system in practice.
Figure 11-9: The Cumulative Ground Class Profile.
Figure 11-10: Probability of Design-Construction Method Inadequacy.

Class: 1(--), 2(...), 3(---), 4(--)
1. Based on the already available geologic information, and

2. Based on the assumption that the proposed exploration program is undertaken.

The former is straightforward, since the constructed ground class profile and the specification of the threshold probability can be directly translated into a sequence of design-construction methods. The system determines the extents in which each of these methods will be used, as well as the number of "transitions" from one method to another, and based on the specified mean and variance of the unit cost prices, it calculates the expected value and the variance of the project's cost.

The estimation of the project's cost under the "exploration" option is more complicated. The system prompts for the number of simulations to be performed (see section 11.8.1), and for each simulation cycle creates an "artificial" set of new observations at the specified locations (i.e., every 300 ft). Based on these observations, the Phase I sequence of calculations is repeated (assuming that these observations are indeed "true") to produce an "experimental realization" of the project's expected cost and variance. This process is repeated for the specified number of simulations (creating a new set of artificial observations for each run) to produce a data set concerning the expected value and the variance of the cost under the option to explore. The collected data points are subsequently aggregated into statistics that are used to produce point estimates of the project's true expected cost and variance.

The results for this particular application, using 100 simulation iterations and various threshold probability levels are shown in table 11-XX (C is the project's cost) and have been plotted in figure 11-11.
<table>
<thead>
<tr>
<th>Thresh. Prob.</th>
<th>No Pilot Tunnel</th>
<th>Pilot Tunnel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E[C]</td>
<td>SD[C]</td>
</tr>
<tr>
<td>0.01</td>
<td>34,467,148</td>
<td>4,848,535</td>
</tr>
<tr>
<td>0.05</td>
<td>29,231,520</td>
<td>3,376,091</td>
</tr>
<tr>
<td>0.10</td>
<td>25,003,520</td>
<td>2,322,125</td>
</tr>
<tr>
<td>0.20</td>
<td>22,347,852</td>
<td>2,145,024</td>
</tr>
<tr>
<td>0.30</td>
<td>21,265,544</td>
<td>1,971,677</td>
</tr>
<tr>
<td>0.40</td>
<td>20,286,096</td>
<td>1,892,578</td>
</tr>
<tr>
<td>0.50</td>
<td>19,432,910</td>
<td>1,798,678</td>
</tr>
<tr>
<td>0.60</td>
<td>19,104,602</td>
<td>1,778,140</td>
</tr>
<tr>
<td>0.70</td>
<td>18,111,314</td>
<td>1,585,047</td>
</tr>
<tr>
<td>0.80</td>
<td>17,416,908</td>
<td>1,627,757</td>
</tr>
<tr>
<td>0.90</td>
<td>15,716,323</td>
<td>1,239,904</td>
</tr>
<tr>
<td>0.95</td>
<td>13,197,727</td>
<td>851,758</td>
</tr>
<tr>
<td>0.99</td>
<td>10,369,969</td>
<td>615,430</td>
</tr>
</tbody>
</table>

Table 11-XX: The Expected Value and the Standard Deviation Of the Project's Cost As a Function of Exploration and the Threshold Probability.
Figure 11-11: The Project's Cost as a Function Of the Threshold Probability. 
(± one standard deviation, σ)
11.8.1 Number of Simulations.

Before analyzing the system's results, it is instructive to show how the necessary number of simulations can be determined. This problem is equivalent to determining the necessary sample size described in most statistics textbooks (Benjamin and Cornell, 1970).

Assuming that $C$ is the random variable representing the project's cost, with mean $E[C]$ and variance $\text{Var}[C]$, then the random variable $C_n$, the sample average of the $n$ simulation experiments, has a mean $E[C]$ and variance $\text{Var}[C]/n$. Furthermore, assuming that the number of simulations is large (i.e., $n > 30$) and using the Central Limit Theorem, the distribution of the sample average can be approximated by the Normal Distribution. As a result, the following $1-a$ confidence interval on the true expected cost can be constructed:

$$P[C_n - k_{1-a/2} \frac{s}{\sqrt{n}} < E[C] < C_n + k_{1-a/2} \frac{s}{\sqrt{n}}] = 1 - a$$

where:

$$F_{\text{N}}[k_{1-a/2}] = 1 - a/2 \quad \text{(from the Normal Distribution Tables)}$$

$s^2$ is the unbiased estimator of $\text{Var}[C]$ (from the system output). For example, considering the case where the threshold probability equals 0.10:

$$C_n = 21,682,494 \text{ and } s = 2,482,630$$

The 90% confidence interval for $E[C]$ is:

$$P\left[21682494 - (1.645)(2482630)/10 < E[C] < 21682494 - (1.645)(2482630)/10\right] = 0.90$$
\[ P[21,274,101 < E[C] < 22,090,387] \]

which has a width that is about 4% of the sample average \( C_n \). By reversing this procedure one can specify \( w \), the desired width of the 1-a confidence interval as a percentage of the sample average, and thus compute \( n \), the sample size:

\[ n = \left( \frac{2 \cdot s \cdot k_{1-a/2}}{w \cdot C_n} \right)^2 \]

In this case, for example, the number of simulations required to yield a 90% confidence on \( E[C] \) whose width is 1% of the sample average is:

\[ n = \left( \frac{2 \times 2482630 \times 1.645}{(21682494 \times 0.01)} \right)^2 = 1420 \]

which is obviously a prohibitively large number, if one considers the cost of running the simulations.

11.8.2 Analysis of the System Results.

The analysis of the option to construct a pilot tunnel was undertaken for several threshold probabilities so that the general behavior of the model for different levels of conservatism can be examined. Several interesting conclusions can be drawn from the results plotted in figure 11-11.

Probably the most striking observation is that the cost of the project without a pilot tunnel \( C \) is higher than the cost \( C^* \) resulting from the construction of a pilot tunnel for small values of the threshold probability (high conservatism), whereas the situation is exactly the opposite for large threshold probabilities (low conservatism). This
phenomenon is easily explained when one considers the amount of geologic information in either case.

In particular, if the pilot tunnel is assumed to provide perfect information on the geology, the expected cost of the project should theoretically be independent of the threshold probability since the designer can never use the wrong method if he knows the project's true geology. In other words, no unexpected geologic conditions can ever occur if the designer makes his decisions after the true geology is revealed (thus no conservatism is needed). For this limiting case, the threshold probability rule loses its meaning; there is no probability of a Type II Error if one knows the quantity to be estimated (in this case, the geology) before a decision is made. The reason the expected cost of the project appears to be a decreasing function of the threshold probability (instead of being horizontal), is due to the fact that the pilot tunnel's continuous observations are being approximated by a series of point observations. Thus, a certain amount of geologic uncertainty concerning the conditions between these points is still present.

On the other hand, if the pilot tunnel is not undertaken, the choice of the design-construction sequence is made before the true geologic conditions are known and thus the potential for using the wrong (inadequate) sequence of methods exists. It is important to notice that specifying a large threshold probability results in the same sequence of design-constructions methods that would have been adopted if very favorable new observations were made, and a conservative threshold probability was used. In other words, large threshold probabilities imply a unjustifiable optimism concerning the project's geology that is not
warranted by the available observations. The project's conditions may indeed prove to be very favorable, allowing thus the use of an inexpensive sequence of methods, but the the probability of this occurring is very small. This "mistake" cannot be made when evaluating the option to construct a pilot tunnel, because even if very favorable conditions are created in the course of simulating the tunnel's geology, the decision on the sequence of design-construction methods is made after the geology is known. Furthermore, these conditions are not simulated often enough to permit an average cost estimate that is as low as the one corresponding to extreme overoptimism. As a result, the potential for miscalculating the project's geologic conditions is a decreasing function of the amount of available information.

The threshold probability rule has been developed as a means of simulating the designer's and the contractor's decision making under current practices. Since this behavior is characterized by conservatism, major failures occur very rarely and as a result, the project's cost function does not include a "cost of failure" term. If the assumption that design and construction decisions are made in a conservative manner is violated (by considering very large threshold probabilities), then the cost function should be modified to reflect the expected cost of "failure", including the cost of monitoring performance, changing design and construction plans during construction and taking corrective

---

91Failure is defined as the inability of the structure to conform to the owner's performance (e.g. watertightness) and safety criteria, and is not limited to structural stability.
action. If the expected cost of failure is included in the cost function, then the expected cost of the project under the assumption that additional exploration is undertaken (excluding the cost of obtaining this information, i.e., the cost of a pilot tunnel in this case) must always be lower than the cost corresponding to less information (i.e., the information available through past exploration). This conclusion is based on the simple observation that further exploration can only enhance decision making, because the more is known about the geology the more the design and construction methods can be adapted to the project's true geologic conditions. To assume otherwise would be equivalent to assuming that less information is expected to result in better decisions, which clearly violates the principle of conducting geologic exploration in the first place. As a result, the threshold probability rule should only be used under the assumption for which it was developed: i.e., that decisions are made in a conservative manner and that the probability of adopting inadequate design-construction methods (the threshold probability) is typically a small number.

11.8.3 The Expected Value of Sampled Information.

From the system results shown in Table 11-XX one can easily compute the EVSI of the proposed exploration program (pilot tunnel) as function of the threshold probability. For this purpose, define:

C: The cost of the project based on the already available geologic information.

C*: The cost of the project if the contemplated exploration program (pilot tunnel) is undertaken.

D: The cost of the exploration program (pilot tunnel).
 Portions of the text on the following page(s) are not legible in the original.
q: The thresholdability.

The EVSI of the tunnel is given by:

\[ \text{EVSI}(q) = E[C] - E[C^*] - D \]

Given the value threshold probability \( q \), and the cost of the pilot tunnel \( D \), the \( \text{EVSI} \) of the pilot tunnel can be calculated directly from the expected \( E[C] \) and \( E[C^*] \). Notice that if the decision maker (i.e., the ones willing to accept the expected value criterion (i.e., he is 'neutral') the calculation of the pilot tunnel's EVSI is not depend the cost variance. For example, if \( q = 0.05 \) and \( D = $8M \) the pinel's EVSI is:

\[ \text{EVSI}(0.05, 231,520 - 21,945,368 - 8,000,000 = -713,848 \]

Since under we assumptions the exploration program's EVSI is negative, the creation of a pilot tunnel does not represent an acceptable expen alternative. In fact, a pilot tunnel should not be undertaken if its cost exceeds $7,286,152, the difference in the expected costs the two options.

In general, the difference between the two expected costs represents the maximum that can be justifiably spent on the contemplated exploration provided of course, that the threshold probability is reasonably (i.e., within the model's range of validity). As a result, one slot say that the pilot tunnel should not be undertaken if the thresholdability \( q \) exceeds 0.45, (the point at which the two costs are equal) since the associated threshold probability is too large. If specified to be close to 0.5, then, on the average, half of the construction methods chosen for points along the axis
of the tunnel would be inadequate; this conclusion clearly contradicts actual practice.

If the owner is not "risk neutral" and a meaningful utility curve can be assessed, the value of exploration can be determined on the basis of decision analysis and utility theory. For this purpose it is also necessary to assume the form of the cost distribution in order to carry out the necessary expectation of utility. Typically, the cost of a project is assumed to follow the Normal Distribution, since the cost of construction is the sum of a large number of component costs. For example, if the owner's utility is exponential with a risk aversion coefficient \( b = 10^6 \), then the value of exploration \( V \) is:

\[
V = E[C] + \frac{Var[C]}{2b} - E[C^*] - \frac{Var[C^*]}{2b} - D
\]

which, under the above assumptions (\( q=0.10 \)) yields:

\[
V = 29,231,520 + \frac{(3,376,071)^2}{(2x10^6)} - 21,945,368 - \frac{(2,538,318)^2}{(2x10^6)} - 8,000,000 = 1,763,550
\]

In this case, the value of exploration is positive and as a result the construction of a pilot tunnel represents an acceptable investment. This conclusion is valid if the cost of the pilot tunnel does not exceed $9,763,550 which is the difference in the "certain equivalents" of the

---

92 This assumption is very crucial if the decision maker is not a single individual, since utility curves for organizations are extremely difficult to encode.
two options. It should be noticed that the assumption of a very large risk aversion coefficient implies that the decision maker's utility curve does not deviate considerably from a straight line (i.e., the decision maker is not extremely risk averse). If this coefficient is reduced to more "realistic" levels, then the amount worth spending on exploration can increase considerably.

Even though the pilot tunnel is an acceptable alternative under the above assumptions, it does not necessarily represent the best exploration program. Based on the general guidelines provided by the contractors participating in this research, a pilot tunnel is not typically expected to be more cost effective than other exploration methods (e.g., boreholes) for small diameter tunnels, such as the one considered in this example. As a result, it is very important that other exploration programs are also considered, in order to determine the one with the highest value.

11.9 Spacing of Observations.

The basic limitation of the proposed model is the fact that it can only accept location-specific observations, and as a result the continuous geologic information provided by a pilot tunnel has to be discretized. An interesting question at this point concerns the validity

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93 The procedure of subtracting the certain equivalents of the two options to determine the maximum amount of money that can be spent on new exploration requires the "delta" property, and as such is valid only for the linear and exponential utility curves.
of modelling the pilot tunnel as series of point observations every 300 ft. and the effect of using a tighter spacing. To answer this question a spacing of 30 ft was assumed and the system was run twice for two extreme values of the threshold probability:

<table>
<thead>
<tr>
<th>Threshold Probability</th>
<th>E[C]</th>
<th>SD[C]</th>
<th>E[C*]</th>
<th>SD[C*]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>34,600,528</td>
<td>4,837,945</td>
<td>22,330,694</td>
<td>2,191,790</td>
</tr>
<tr>
<td>0.99</td>
<td>8,686,359</td>
<td>448,848</td>
<td>17,624,588</td>
<td>1,516,806</td>
</tr>
</tbody>
</table>

A comparison of these results with the ones in Table 11-XX shows that no significant improvement in accuracy is achieved by the new spacing. The situation is similar to the case of the number of simulations needed to achieve very tight confidence intervals; the number of required simulations increases dramatically when a high level of accuracy is required. The same holds true when attempting to approximate a continuous system with a discrete analog. This suggests that in practice the sensitivity of the model to the spacing of observations be examined (through a small number of simulations) before full scale simulations are performed since the cost associated with using this system is an exponential function of the number of simulated observations.

11.10 Advantages of the Proposed System.

The main advantage of the proposed system is that it is probably the only available means for determining the value of future exploration in a rational manner.

At the present time, geologic prediction is usually in the form of
"best estimates", which represent either the conditions most likely to occur, or the worst conceivable conditions to be encountered during construction. Even though this approach is acceptable for estimating the cost of a project on the basis of existing information, it cannot be used for the evaluation of exploration.

Similarly, models like the Tunnel Cost Model (TCM) (Moavenzadeh et al, 1974) which consider the effect of geologic uncertainty in estimating the cost of underground construction, cannot evaluate the effect of future information. The Tunnel Cost Model, for example, divides the tunnel profile into segments of predetermined length inside each of which only one "geologic unit" is assumed to exist. This assumption of using predetermined segments in which only one ground class may exist defeats the purpose of exploration since the extent of ground classes is assumed to be known. In addition, this model is based on a subjectively assessed posterior description of the geology and includes no systematic procedure for updating the geologic profiles based on new observations.

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A geologic unit is a set of geologic conditions which dictates certain excavation and support processes (just like a ground class).
Chapter 12

Summary and Conclusions.

This research has examined the decision to use exploration as a risk reduction strategy in underground construction and in particular the decision to adopt a pilot tunnel as an exploration strategy. This chapter presents some of the general conclusions of this research.

12.1 Subsurface Exploration as a Risk Mitigation Strategy.

The amount of geologic uncertainty inherent in the delivery process of underground projects is the underlying cause of the majority of the problems associated with this type of civil engineering work. Both the ability of the design to fulfill the owner's operational and safety specifications, as well as the final cost of constructing an underground project are directly related to the project's geologic conditions as they actually exist at the site. Since these conditions are imperfectly known before construction, the designer's task in developing the design and the contractor's task in planning and estimating the construction process are typical examples of decision making under uncertainty. Under these conditions, the designer's and the contractor's behavior are determined by the perceived amount of geologic uncertainty, the expected financial consequences of the geologic risk and their risk exposure.

Geologic uncertainty can be primarily reduced through the employment of a comprehensive exploration program. The effectiveness of exploration,
however, is not only dependent on the amount and reliability of the observations provided, but is also dependent on several other factors, such as:

1. The size and characteristics of the project.
2. The homogeneity of the geology.
3. The amount of geologic information that already exists.
4. The timing for conducting the exploration.
5. The adopted risk-sharing approach.

Of these factors, the timing for conducting the exploration is of particular importance in the development of the overall design philosophy. Exploration conducted in the latter stages of the design phase is typically used to validate the design assumptions made earlier (on the basis of less information). Design revisions often occur only if the information provided reveals that the true geologic conditions are worse than originally anticipated. Thus, the economic value of exploration is significantly reduced since it does not always result in less conservative design.

Furthermore, the value of exploration in reducing the cost impact of design conservatism is strongly dependent on the designer's role in selecting the contractor and the extent of the design firm's liability. If the designer does not have any input in selecting a reputable and experienced contractor, or bears an excessive amount of liability, he will be very reluctant to specify innovative or cost saving design approaches. This means that exploration is not used to optimize the design, and hence the cost of the project, but rather to ensure that no
action will be taken against the design professional because of design inadequacy.

The same holds true in examining the contractor's attitude in decreasing construction contingencies as a function of the geologic information provided. The typical practice of disclaiming the validity of the geotechnical information provided as part of the contract documents, has a marked influence on the contractor's willingness to decrease his contingencies. If the contractor has no guarantee that he will be promptly and equitably compensated for expenses occurring due to unforeseen geologic conditions, he will not decrease the amount of contingencies charged, since the magnitude of cost overruns in underground construction can easily drive most contractors to bankruptcy.

As a result, the value of exploration must always be determined as a function of the contractual sharing of the geologic risk, since the latter typically has a strong impact in shaping the design and construction of underground facilities.

12.2 The Value of Pilot Tunnels.

With respect to subsurface exploration, the major usefulness of a pilot tunnel stems from the fact that it provides the designer and the prospective contractors with continuous 3-dimensional observations on the project's geologic conditions. Furthermore, it allows all the interested parties to form their own opinions concerning the quality of the rock, its expected response to different excavation and support methods and the subsurface water conditions. The ability to make a direct visual
assessment of the project's geology is of particular help to the contractors who thus do not have to rely completely on the geologic data provided by the designer.

In addition to their usefulness in providing geologic information, pilot tunnels also have other uses that set them apart from all other exploration methods. Depending upon circumstances, a pilot tunnel can be used for:

- validating design assumptions,
- experimenting with new design approaches,
- field testing of new or untried construction methods,
- estimating production rates and support requirements,
- selecting excavation and support methods,
- identifying and mitigating externally imposed risks and constraints,
- providing benchmark information for the determination of "reasonably anticipated geologic conditions" in the event of litigation or arbitration over changed conditions claims,
- contributing as an integral part of design and construction (e.g., can be used for ventilation, dewatering the rock before and during construction, the installation of presupport, providing access to critical locations, etc.).

As a result, the value of a pilot tunnel is determined by two factors:

1. The geologic information it provides, which can be compared to the effectiveness of other exploration methods, and

2. Its cost-saving contributions listed above, which do not have a counterpart in other exploration methods.

In general, the determination of the economic value of a pilot tunnel is extremely dependent on its cost-saving contributions in
addition to geologic exploration. Since the usefulness of a pilot tunnel is a function of the characteristics of the project and its actual use during design and construction, it is almost impossible to present general cases for which the adoption of a pilot tunnel is certain to be a justifiable investment. With this observation in mind, a pilot tunnel is expected to be of most value when:

1. The main opening has a large cross section. Large projects impose more difficulties in the prediction of excavation and support performance. Small variations in parameters like overbreak, support type and density, the advance rate, etc., result in large changes in the expected cost of the project because of the size effect and economies of scale.

2. The project's location is such that it is very difficult, or very expensive, to conduct a comprehensive exploration program from the ground surface using other methods. This situation arises, for example, in congested urban areas and inaccessible rural locations.

3. The project is located in very unfavorable geologic conditions which can be identified by the pilot tunnel. Examples are highly variable geology, high water pressure and/or flow, faulted formations, etc.

Similarly a pilot tunnel is expected to be of least value when:

1. The project has a small cross section.

2. A comprehensive borehole program is possible.

3. The project is located in uniform geology.

4. The rock conditions within the cross section of the main opening are not uniform and as a result the pilot tunnel observations are not representative of the project's true geologic conditions.

In general, the adoption of a pilot tunnel must be based on a careful quantitative comparison of its benefits against its cost, taking into account all the exploration and construction alternatives available. This decision cannot be prescribed and must be made on a project specific
12.3 The Optimal Exploration Program.

The determination of the optimal exploration program in which the owner should invest is a very difficult problem that cannot be solved analytically. The major difficulties are:

1. The large number of discrete alternatives that must be considered.

2. The need to predict the designer's and the contractor's reaction to additional geologic exploration.

The only possible approach in determining the "best" exploration program is to utilize the designer as the owner's expert and to consider a small set of alternatives selected on the basis of professional experience.

The comparison of these alternatives can be quantified by using the decision support system developed as part of this research. This system provides the owner and the designer with a means of establishing the effectiveness of any exploration program as a function of its extent and reliability. By associating each exploration alternative with a distribution on the project's total cost, the investment in exploration can be made in a rational manner, probably for the first time.
Appendix A

Contractors and Individuals Participating in this Research.

1. MacLean Grove & Company, Incorporated
   - Edward S. Plotkin, Vice President
   - Leon Vincent, General Superintendent
   - Gary Almeraris, Assistant Superintendent

2. J.F. White Contracting Company
   - Philip Bonanno, President & General Manager

3. Perini Corporation
   - Fred Reif, Manager, Tunnel Division

4. Schiavone Construction Company
   - Jodinger S. Bhore, Manager—Tunnel Division

5. J.F. Shea Co., Inc.
   - Robert L. Lehman, Chief Engineer

6. Al Johnson Construction Company
   - Douglas A. Johnson, Ex. V.P., Construction Division

7. Franki Foundation Company
   - Burton P. Kassap, Executive Vice President

   - J.W. Leonard, Vice President—Engineering
Appendix B

The Contractor Questionnaire.

SUBJECT: Pilot Tunnels as an underground exploration strategy.

ASSUMPTIONS: Pilot Tunnel excavated under a separate contract prior to bidding for the main project, as an aid to the design and construction of the main opening.

No other construction information is available in this rock type; i.e. no adjacent tunnel driving records are available.

Pilot Tunnel construction information is available to all bidders.

The project may be located in an urban or a rural (transmountain) environment. The project may be considered similar to a subway cavern (tunnel), or a transmountain highway tunnel.

Pilot Tunnel driven along entire length of the main project, unless otherwise stated.

The pilot tunnel may be small as compared to the main opening, or may be almost as big as the opening itself; some of the questions are conditioned on the relative or absolute size of the pilot tunnel.

If the main opening is very large, the first stage of excavation for the main chamber may be significantly larger than the pilot tunnel, but could be driven full face without a pilot tunnel.

Shaft access used for the construction of the pilot tunnel, can be used for the construction of the main cavern (tunnel). The shaft may be incorporated into permanent facility opening.
PLEASE NOTE:

THE FOLLOWING QUESTIONS REFER TO THE MAIN PROJECT OPENING, UNLESS OTHERWISE SPECIFIED.

THIS QUESTIONNAIRE MAY NOT ADDRESS ALL THE IMPORTANT ISSUES CONCERNING THE USE OF PILOT TUNNELS AS AN EXPLORATION STRATEGY. PLEASE, ATTACH A SEPARATE PAGE WITH YOUR COMMENTS ON WHAT YOU BELIEVE THESE ISSUES ARE.

THANK YOU.
1. **Perfect information on geology**

Suppose that you have access to a source that can provide you with accurate (perfect) information about the geologic conditions of an underground project. Disregard the cost of obtaining this information.

1.1 Please state which parameters or other geotechnical descriptors, you would need to request from this source, so that:

- All the uncertainty in your **cost estimate** that is due to incomplete knowledge of the geology is eliminated. This means that the requested information is sufficient.

- Unnecessary duplication of information is eliminated as much as possible; only the really needed data are requested.

- Information is presented to you (the contractor) in the **most useful form** for the task of construction planning and estimating.

We have prepared a list of parameters that you might consider requesting. This list is only suggestive. Please, substitute any of the parameters with more useful ones, delete any that are not really needed, and add necessary ones that have not been included.

1.2 Please, rank the parameters in order of their importance (1, being the most important).

1.3 Please, indicate their use in construction planning and estimating (e.g. hardness is used to estimate drillability and thus the advance rate).

1.4 Finally, state the percent deviation for each parameter that you feel would not produce any significant impact on cost estimates.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Required</th>
<th>Ranking</th>
<th>% of acceptable variation</th>
<th>Use in construction planning and cost estimating</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Rock type (hardness, compressive strength)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Degree of weathering</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Joint density (is RQD enough? yes_no_)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4. Joint orientation (relative to axis of tunnel)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Joint appearance (e.g. smooth, filled with clay/rough and interlocked)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Fault existence</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Fault conditions (gouge material)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8. Fault extent</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9. Ground water inflow</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10. Ground water pressure</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11. In situ stresses</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>14.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(*) Some of the parameters may require a qualitative rather than a quantitative description of their acceptable variation.
2. **Water Inflow considerations**

The variable "water inflow" may be described as:

(a) Total inflow for a certain length of the project that remains approximately constant with time.

(b) A large localized inflow that persists for a limited amount of time.

If the project slopes upwards from an open portal, then the water can flow freely on the invert, or in a drainage ditch. In all other cases the water has to be pumped.

2.1 For case (a), what would be the approximate ranges (in gallons/min), for categorizing the amount of water that flows freely on the invert (or in a drainage ditch), as:

<table>
<thead>
<tr>
<th>Free flow on invert (or drainage ditch) (gallons per minute)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Negligible (no effect on operations)</td>
</tr>
<tr>
<td>2. Acceptable (some effect on operations)</td>
</tr>
<tr>
<td>3. Considerable (special treatment/abandon project)</td>
</tr>
</tbody>
</table>

2.2 For case (a), and assuming that the contractor's dewatering system is handled by pumping, what would be the approximate ranges (in gallons/min), for categorizing the flow of water to be pumped, as:

<table>
<thead>
<tr>
<th>Amount of water to be pumped (gallons per minute)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Acceptable (conventional control)</td>
</tr>
<tr>
<td>2. Considerable (special treatment/abandon project)</td>
</tr>
</tbody>
</table>
2.2 For case (b), what would be the combinations of intensity of inflow (gallons/min) and duration (time), that would be considered:

<table>
<thead>
<tr>
<th></th>
<th>Free Flow (gpm)/(min)</th>
<th>Pumped (gpm)/(min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Negligible</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>(no treatment required)</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>2. Acceptable</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>(conventional control)</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>3. Considerable</td>
<td>/</td>
<td>/</td>
</tr>
<tr>
<td>(special treatment/ abandon project)</td>
<td>/</td>
<td>/</td>
</tr>
</tbody>
</table>

Do you believe that the above combinations could be replaced by an equation of the type: 
(intensity)X(duration)=Constant?

2.3 What do you think the chances are, that boreholes (water pressure tests) or a pilot tunnel, can identify the true water conditions, in both the above cases? You may condition your answer on the spacing of boreholes or the ratio of the pilot tunnel cross sectional area to that of the cavern (tunnel).

2.4 If there is a significant amount of time between the completion of a pilot tunnel and the commencement of the main chamber excavation, the pilot tunnel can serve as a dewatering system for the surrounding rock. Assume that the contractor observes and takes note of the existing ground water inflow rate into a pilot tunnel at the time of bidding, and that the rate of inflow has decreased substantially from what was encountered during the construction of the pilot tunnel. How would this observation be treated when estimating dewatering costs?
3. Variability of parameter extents

Almost all of the geologic parameters and descriptors vary along the axis of a project in two ways:

(a) There exists variability from one point to an adjacent point because of the way these parameters are defined or measured. For example, two adjacent samples will probably yield two slightly different values of RQD. This variation may be considered as "noise" around the average value of the parameter.

(b) There exists a more macroscopic variability of the average value of a certain parameter. This variability expresses the general tendency of change for the parameter in question.

It would be reasonable to say that "noise" variability may be neglected for all practical purposes, provided its amplitude and wavelength are relatively small.

There are cases, however, where there might be a considerable deviation from the average. For example, an intrusion or a dike may have considerably larger strength or a certain point may have a large inflow of water.

3.1 In preparing a cost estimate for the main project, would you use an "average" curve, or would you rather adopt a conservative "envelope" curve? (see above figure)

3.2 For estimating purposes, one has to consider that a parameter takes on a fixed value that remains constant for a certain length extent. This value of the parameter would subsequently serve as a means of estimating construction performance and costs within that extent. The magnitude of such extents, however, must be large enough to justify the fixed cost of shifting from one construction method to another. An obvious lower bound would be one round length.
Also, short localized changes, can be towards "better" or "worse" parameter values (see figure below). What would be a minimum length extent (in feet) for the following parameters?

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MINIMUM EXTENT (ft) FOR:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock type</td>
<td>Change to better</td>
</tr>
<tr>
<td>Degree of weathering</td>
<td></td>
</tr>
<tr>
<td>Joint density</td>
<td></td>
</tr>
<tr>
<td>Joint appearance</td>
<td></td>
</tr>
<tr>
<td>Joint orientation</td>
<td></td>
</tr>
<tr>
<td>Fault extent</td>
<td></td>
</tr>
<tr>
<td>Ground water inflow</td>
<td></td>
</tr>
<tr>
<td>Ground water pressure</td>
<td></td>
</tr>
<tr>
<td>In situ stresses</td>
<td></td>
</tr>
<tr>
<td>Other:</td>
<td></td>
</tr>
</tbody>
</table>

3.3 The above question on extents is closely related to the magnitude of change in a parameter value. Suppose a certain parameter remains almost constant for a significant part of the project's length, with the exception of a small extent, S, where it takes on a smaller (larger) value. If S is long enough, then it may be considered as a separate extent. If, however, S is short, then the localized parameter deviation may be ignored.

<table>
<thead>
<tr>
<th>Parameter values</th>
</tr>
</thead>
<tbody>
<tr>
<td>small change to better</td>
</tr>
<tr>
<td>larger change to worse</td>
</tr>
<tr>
<td>etc.</td>
</tr>
<tr>
<td>&lt;---S--&gt;</td>
</tr>
</tbody>
</table>

What is the minimum change in the value of a parameter that would be significant enough, to be treated as a separate extent for construction planning and estimating purposes? (see above figure)
<table>
<thead>
<tr>
<th>Parameter</th>
<th>MIN % CHANGE</th>
<th>OF PARAMETER:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock hardness/comp. strength</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Degree of weathering</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Joint density</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Joint appearance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Joint orientation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ground water inflow</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ground water pressure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>In situ stresses</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other:</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.4 In the case where a parameter takes on a worse value for a short length, and you decide not to treat this as separate extent, would the value of the parameter for the resulting large extent be affected, i.e. would you use an envelope curve governed by the worst conditions within the resulting larger extent?
4. Prediction within a cross section

Boreholes provide information for their full depth, but only in their specific locations (assume that boreholes extend to the bottom of the underground project). Pilot tunnels, on the other hand, provide information that is continuous for their length, but restricted within the volume of the pilot tunnel. Since neither method covers the cross sectional area of the project, it is conceivable that actual conditions within a cross section will be different than estimated from a pilot tunnel or boreholes.

4.1 What is the quantitative or qualitative deviation that might occur within a cross section?:

<table>
<thead>
<tr>
<th>Rock type/hard./stren.</th>
<th>P.T. AREA/CAV. AREA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Boreholes 20% 40% 60%</td>
</tr>
<tr>
<td>Degree of weathering</td>
<td></td>
</tr>
<tr>
<td>Joint density</td>
<td></td>
</tr>
<tr>
<td>Joint appearance</td>
<td></td>
</tr>
<tr>
<td>Joint orientation</td>
<td></td>
</tr>
<tr>
<td>Fault existence</td>
<td></td>
</tr>
<tr>
<td>Fault conditions</td>
<td></td>
</tr>
<tr>
<td>Fault extent</td>
<td></td>
</tr>
<tr>
<td>Ground water inflow</td>
<td></td>
</tr>
<tr>
<td>Ground water pressure</td>
<td></td>
</tr>
<tr>
<td>Other:</td>
<td></td>
</tr>
</tbody>
</table>

4.2 Is there a ratio of pilot tunnel area to cavern (tunnel) area for which the pilot tunnel is not a better predictor than a borehole?

Yes: No: Ratio:

4.3 Is there a similar ratio that could make a pilot tunnel a perfect descriptor (for all practical purposes) of the whole cross sectional area of the cavern (tunnel)?

Yes: No: Ratio:
4.4 Pilot tunnels provide a continuous profile of underground geology, and thus help to identify the extents over which certain conditions persist. Boreholes, on the other hand, provide information only for their specific locations. Is there a spacing of boreholes that might make the information from both sources equivalent?

Yes: No: Spacing:

Comments on desirable borehole arrangement:

4.5 Please specify the conditions (geology, size of project, borehole arrangement, etc.) under which boreholes might be a better predictor of extents than a pilot tunnel.
5. Definition of Ground Classes

Geologic parameter values may be grouped into "ground classes" as a practical means of assessing advance rates and initial support requirements. Such an approach is used by the Terzaghi Rockload Method (and other empirical methods) for required support prediction. Ground classes are defined so that each ground class corresponds to a certain support type.

5.1 Do you use such a classification scheme?

Yes: No:

5.2 If yes, which one? How are ground classes defined in terms of parameter values?

5.3 Do you use the same ground classification for both support and advance rate prediction?

Yes: No:

5.4 Do you believe that the greatest uncertainty lies in predicting the ground class, or rather the extent over which a ground class persists?
6. **Initial Support prediction**

Safety of the underground project is usually part of the contractor's responsibility, even though a certain minimum initial support may be contractually specified by the designer.

The contractor then has to decide what particular initial support to use, and the extents over which each type of support will be needed.

\[ o<--------o<--------o<--------o \text{ etc.} \]
\[ \text{support} \quad \text{support} \quad \text{support} \quad \ldots \]
\[ \#1 \quad \#2 \quad \#3 \]

The initial support required is a function of the geology, the size of the opening, the distance of support to the face, the damage to the rock due to construction methods, etc. The type of initial support should also be compatible with the type of final lining required.

6.1 Which geologic parameters do you use in estimating the initial support required?:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock type/hardness/strength</td>
<td></td>
</tr>
<tr>
<td>Degree of weathering</td>
<td></td>
</tr>
<tr>
<td>Joint density</td>
<td></td>
</tr>
<tr>
<td>Joint appearance</td>
<td></td>
</tr>
<tr>
<td>Joint orientation</td>
<td></td>
</tr>
<tr>
<td>Fault existence</td>
<td></td>
</tr>
<tr>
<td>Fault conditions</td>
<td></td>
</tr>
<tr>
<td>Fault extent</td>
<td></td>
</tr>
<tr>
<td>Ground water inflow</td>
<td></td>
</tr>
<tr>
<td>Ground water pressure</td>
<td></td>
</tr>
<tr>
<td>In situ stresses</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td></td>
</tr>
</tbody>
</table>

A recent study has shown a dampening effect when one goes from geologic variability to required support variability; even though geologic variability may be high, it results in low variability in the required support. A reason for this, is that the ground classification schemes allow individual parameters to vary within certain regions without affecting the support requirements.
6.2 Do you believe that this conclusion is correct?

Yes: No:

Comments:

6.3 Do you believe that there are other causes of such a dampening effect that have more to do with economies of scale, construction methods used, etc.?

Yes: No:

Comments:

6.4 What enters into the decision to determine initial support, in addition to geologic parameters?

6.5 In addition to selecting the type of the initial support, the contractor has to estimate the length over which the support will be employed. How is this done?

6.6 Do you believe that a pilot tunnel can be a better predictor of this length than boreholes?

Yes: No:

Comments:
6.7 Can you relate the geology observed and the support placed in the pilot tunnel to the support required for the cavern (tunnel)?

Yes: No:

Comments:
7. **Advance rate estimation**

Progress in tunneling can be measured by the advance rate (feet/day). In order to establish an advance rate that can be achieved over a certain length of the tunnel, one has to consider the sequence of activities within each round:

```
  excavation
    o------------------->
  support
    o - - -- -- -- -- -->
  tunnel services
  o-------------------
```

The time needed for excavation (drilling, loading, firing, ventilation, mucking) depends on geologic parameters, labor and equipment productivity, the area of the face and the round length.

The time needed for support placement can be computed from the type and amount of support required, including installation procedures.

7.1 Which of the following parameters do you need for estimating excavation production?:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Ranking</th>
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</thead>
<tbody>
<tr>
<td>Rock type/hardness/strength</td>
<td></td>
</tr>
<tr>
<td>Degree of weathering</td>
<td></td>
</tr>
<tr>
<td>Joint density</td>
<td></td>
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<tr>
<td>Joint appearance</td>
<td></td>
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<td>Joint orientation</td>
<td></td>
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<tr>
<td>In situ stresses</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td></td>
</tr>
</tbody>
</table>

A pilot tunnel can provide contractors with additional construction related information, like:

(a) Rock drillability data (force penetration curves for a certain drill)
(b) Experimentation with drilling and blasting patterns.
(c) Average excavation and support rates (feet/shift)
(d) Average cycle time (shifts/round)
(e) Rock breaking and rock swelling characteristics.
(f) Blasting vibrations for different blasting schemes.
(g) Overbreak characteristics.
(h) Rock stand-up time characteristics.
(i) Dewatering requirements.

Some of the above are conditioned on the round length and the methods and equipment used in the construction of the pilot tunnel.

7.2 Please state which of the above information you consider helpful in reducing your uncertainty on the advance rate for the actual cavern (tunnel).

7.3 Would you use such information to determine production or would you use it only for verification of your estimate?

Yes: No:

Comments:

7.4 In the latter case, what would you do if there is a large discrepancy between the production estimated and the one reported for the pilot tunnel?
7.5 Would your attitude towards such information change depending on who (including your company) was the pilot tunnel contractor?

Yes:  No:

Comments:

7.6 The maximum round length and maximum distance of support to the face are often prescribed by the designer. When estimating the advance rate, do you consider that you will achieve the maximum round length as given by the designer, or do you make allowances for worse than anticipated conditions? Why?

7.7 Do you prefer the case where, instead of being given the maximum round length, you are given the maximum allowable rock deformation?

Yes:  No:

Comments:
8. Cost Classes

In estimating the cost of tunneling one may classify costs as being:
(a) Time dependent (e.g. labor, equipment operating costs, overhead)
(b) Distance dependent (e.g. permanent materials, supplies, muck haulage operating costs, etc.)
(c) Fixed costs (e.g. fixed portal and shaft costs, site preparation, water treatment facilities, lump sum costs for plant and equipment purchases, camp facilities, etc.)

8.0 Please state which cost items belong to each of the above cost classes.

<table>
<thead>
<tr>
<th>Cost Class</th>
<th>Cost Items</th>
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<tbody>
<tr>
<td>(a) Time dependent</td>
<td></td>
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<tr>
<td>(b) Distance dependent</td>
<td></td>
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<tr>
<td>(c) Fixed</td>
<td></td>
</tr>
</tbody>
</table>

8.1 Please specify the ranges for the percent of total cost that each of the above categories represents in a typical project (urban and transmountain).

<table>
<thead>
<tr>
<th>Cost Class</th>
<th>Percentage of total cost</th>
<th>Urban</th>
<th>Transmountain</th>
</tr>
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<tbody>
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<td>(a) Time dependent</td>
<td>100%</td>
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<td></td>
</tr>
<tr>
<td>(b) Distance dependent</td>
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<td></td>
</tr>
<tr>
<td>(c) Fixed</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

8.2 For each of the above categories, please assess the deviation from the estimated cost (as a percentage) that may be experienced in practice.

<table>
<thead>
<tr>
<th>Cost Class</th>
<th>Deviation from estimate</th>
<th>Urban</th>
<th>Transmountain</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Time dependent</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(b) Distance dependent</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>(c) Fixed</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
8.3 Do you believe that the most uncertain factor affecting the time related costs is the advance rate?

Yes: No:

Comments:

The advance rate is influenced by many factors, like geology, labor and equipment productivity, the location and the geometry of the project, external constraints (blasting vibration limits, no blasting at night, small round length to minimize damage to the ground arch, etc.).

8.4 Assume that the variability of the average advance rate is A%. This variability expresses the fact that the advance rate is a random variable, whose value the contractor does not know in advance, but has to estimate, using all available information and his professional judgement. Can the information stemming from a pilot tunnel reduce A?

Yes: No:

By how much? (upper and lower limits):

Comments:

Distance related costs depend mainly on the amount of material placed as initial support and final lining. Initial support depends on geology, the geometry of the excavation, the construction method used, external constraints (like minimum support required by contract), etc.

The amount of materials required for the final lining depends mainly on the design requirements and the amount of overbreak to backfill.
8.5 Assume that the variability in the initial support cost is B%, whereas the variability for the cost of the final lining is C%. Can the pilot tunnel information reduce B?

Yes:    No:

By how much? (upper and lower limits):

Comments:

Can the pilot tunnel information reduce C?

Yes:    No:

By how much? (upper and lower limits):

Comments:
9. Location and size of a pilot tunnel

9.1 Which of the following elevations do you believe is the most appropriate location for a pilot tunnel? Please state the conditions under which the specified location would correspond to the best choice.

Conditions

(a) Crown

(b) Center

(c) Invert

(d) Outside and parallel to cavern (tunnel)

Elevation:

9.2 Pilot tunnels must have a cross section that allows their efficient construction. Would a minimum of 6'x6' be reasonable?

On the other hand, the diameter for the main cavern (tunnel), must be large enough to justify the adoption of a pilot tunnel before letting the main contract. What is the minimum diameter of the main tunnel/cavern for which the adoption of the minimum diameter pilot tunnel would be reasonable?

9.3 In the same context, what would be the minimum length of a project for which the use of a pilot tunnel would make sense?

For cavern:

For tunnel:
10. Construction benefits

10.1 The construction of a pilot tunnel includes some of the work that would otherwise be done under the main contract. The excavation and support of the access shaft being an example. What are some other such items?

10.2 Do you believe that the cost of an access shaft would be different, if no pilot tunnel was undertaken?

Yes: No:

By how much? (upper and lower limits):

Comments:

10.3 Choosing the size of an access shaft for the pilot tunnel, limits the decision making flexibility of the main project contractor. How big is this problem? Can this problem be alleviated by having the owner or the designer specify characteristics that would be reasonable (no matter who undertakes the main contract)?

Yes: No:

Comments:

A pilot tunnel that runs the full length of a cavern (tunnel), can be used as a ventilation duct. This scheme may reduce the cycle time for the excavation support sequence. Savings can occur because no ventilation duct has to be extended in each round, and the smoking time may decrease due to increased flow capacity.

10.4 Please estimate the reduction in the total cost due to the elimination (reduction) of the duct and the labor required for its installation. Also estimate the increase in the advance rate.
Decrease in cost (in percent):

Increase in advance rate (in percent):

10.5 Do you believe that a pilot tunnel provides relief for the subsequent heading rounds, thus making blast rounds easier to design and excavate, by reducing vibration levels and decreasing the cycle time per round?

Yes: No:

How much of an impact would this have on the advance rate?

Comments:

10.6 A crown pilot tunnel allows installation of rock bolts in the crown of the future opening, acting as pre-support for the first stage of excavation for the main opening. Do you feel that the installation of this pre-support will result in less overbreak and less initial support in the cavern, as compared to Stage 1 full face excavation without any pre-support?

Yes: No:

How much of an effect on overbreak? (upper and lower limits):

Comments:

10.7 Do you believe that the existence of the pre-support will result in an increase in the advance rate during excavation, compared to the case where no pre-support were installed but the pilot tunnel still had been driven?

Yes: No:

How much of an effect on the advance rate? (upper and lower limits):

Comments:
10.8 Do you believe that the overall time saved due to an increase in the advance rate offsets the time required to install the pre-support?

Yes:    No:

By how much? (upper and lower limits):

Comments:

10.9 Please state the problems that might arise, during the main cavern (tunnel) excavation, because of the existence of a pilot tunnel.

10.10 In the case of bad rock conditions, steel sets, blocking and lagging may be necessary for the support of the pilot tunnel. Grouting may be required in the case of severe water problems. What are the problems that the pilot tunnel support may present during the main excavation-support process?

10.11 Do you believe that a pilot tunnel can serve as a small scale experiment that helps identify and mitigate problems like, union work jurisdictions, blasting constraints, etc., that could be more costly if recognized after work for the main project begins?

Yes:    No:

Comments:

10.12 According to your experience, what are some of the "external" problems (e.g. blasting constraints, acceptable noise levels, etc.) that can be identified, and what is the magnitude of their implications?
10.13 Please state the most important conditions under which you believe a pilot tunnel is most beneficial and should be employed.

10.14 Please, also, state the conditions under which you believe that a pilot tunnel does not contribute much, if anything at all, in decreasing the uncertainty in a project's cost.

10.15 Contractors argue that the amount of time allowed to examine all the geologic information and contract documents before submitting their bids is not adequate. Does the employment of a pilot tunnel help, or does it make the problem even worse?

Yes:  No:

Comments:
11. **Extrapolation from a pilot tunnel**

In the case where the cross section of the main tunnel is too small to allow the construction of a smaller diameter pilot tunnel, one might consider letting out a portion of the length of the main project that is to serve the same purpose as a pilot tunnel: provide information on the geology, the support requirements, and construction performance. The main difference in this case is that information thus acquired, can only serve for extrapolation, and especially to regions that have been identified to have similar geologic characteristics. It can also help to provide upper and lower bounds for regions where worse or better conditions are anticipated.

11.1 Assume that a portion of the main tunnel has been constructed. You have some information on the remaining work to be done from boreholes. How does the information from the already constructed portion of the work help you in estimating the work to be done, beyond the information provided from the boreholes? Can such staging of the construction be beneficial in reducing the uncertainty in construction cost estimating?

11.2 What would be the minimum lengths for both the pilot tunnel and the whole project, so that staging of construction would be reasonable?

11.3 In a transmountain tunnel the amount of additional information from boreholes may be limited or non-existent. Please answer the above the questions for this case. Would there be any difference?
11.4 What would be the general conditions under which you believe that staging of construction would be most helpful?
12. Risk allocation

The value of geologic exploration is highly dependent on the consequences of geologic uncertainty.

The contractor may face a situation where he is given little information on geologic conditions, the accuracy of which is not warranted by the owner and the contract does not contain a "changed conditions" clause. In such a case, the uncertainty on the final cost of the project is highest, and completely born by the contractor who in turn has to pass it on to the owner in the form of inflated contingencies.

On the other extreme we may have an owner who undertakes a complete and comprehensive exploration program, passes all available information to the contractor, and accepts the risk of changed conditions by specifically defining the anticipated work to be done and tying unit prices to specific descriptions of the geology.

It is evident, that the less information one has about the geology, the higher the value of a new piece of information is. After a certain amount of information has been acquired, subsequent pieces of information have less value, or may even be useless.

In the other dimension, the value of information depends on the assigned contractual responsibilities of each party, that control the way in which the impact of the uncertain outcomes will be shared. The less responsibility for bearing the cost of the outcomes the less the value of information.

The important thing is, that the owner is the party who will invariably pay for the geologic uncertainty, either directly or indirectly (through inflated contingencies). Therefore, it is only logical that the owner should provide enough information, and retain most of the risk of the unknown geologic conditions.

12.1 Considering current contractual practices, what is the interpretation and use of "changed conditions", or "unanticipated geologic conditions" clauses?
12.2 What is the impact of the existence or the absence of a changed conditions clause in your estimating and bidding strategy.

12.3 Do you believe that the adoption of a pilot tunnel may be used as a means of shielding the owner from any changed conditions claims during subsequent contracts? The rationale might be that a pilot tunnel should have provided the contractor with practically all the necessary information on geology.

Yes: No:

Comments:

The British suggest the use of "Reference Conditions" in underground project contracts. According to this scheme the owner undertakes a comprehensive exploration program, and provides the contractor with all the results. In addition, the owner bases the contract on a particular and defined interpretation of the ground investigation, even though other interpretations might be possible. The Reference Conditions define exactly the geologic conditions on which the bids are to be based, and include all likely conditions under different bid items. The owner, thus, accepts all the risk of the unknown geology, whereas the rest of the elements are being left to the contractor to postulate and to take the risk of his assumption being incorrect.
12.4 Do you believe that the adoption of "Reference Conditions" would result in far greater reduction of the variability of the project's outcome (profit) to the contractor? Compare against current contractual practice.

Yes:  No:

By how much? (upper and lower limits):

Comments:

What would be the value of a pilot tunnel under these conditions?

Under a lump sum contract the owner basically tries to fix the cost of the project, whereas the contractor is subject to all the variability in the total project cost. The more variable the total cost is, the more contingency or markup has to be added to the bid, either implicitly or explicitly.

12.5 Without giving away your overall bidding strategy, assume that you have decided to set your bid at such a level so that, to the best of your knowledge, the chance of losing money on the job is P%. What would a reasonable value for P, be? Please take into account that P has to be greater than zero, and that you are also trying to be the low bidder.

12.6 What would be the limits on a typical contractor's markup? Please consider the best and worst project cases that might affect your answer.
12.7 Do you believe that the employment of a pilot tunnel might decrease a contractor's markup?

Yes:    No:

By how much? (upper and lower limits):

Under what conditions?:

12.8 In a competitive bid situation, do you believe that a pilot tunnel, or excessive subsurface exploration information in general, may benefit the inexperienced contractors more than it does the experienced ones? Why?

Yes:    No:

Comments:

Engineers have been blamed for producing overconservative designs, given the geologic information available. Some of the factors encouraging conservative design are:

(a) The engineer does not know who the successful bidder will be, his experience and capabilities. If an "incompetent" contractor wins the job, the engineer may end up in litigation defending his design.

(b) The owner imposes stiff design criteria aimed at reducing the operating and maintenance cost of the project, that inflate the project's construction cost (the owner may have to pay for the former but not for the latter).

(c) The extent of the engineering firm's responsibility. In the event of a failure due to a design or construction error or in the case of a "novel" design (not standard practice), "the engineer can be sued and is sued by everybody" (H. Sutcliffe). Courts don't help either, by recognizing that deviation from traditional established practice puts the engineer at fault.
12.9 Do you believe that the above factors have a significantly larger effect on inflating the total cost of the project, than the conservatism the contractor may include in his bid as insurance against losing money on the job?

Yes:    No:

By how much? (upper and lower limits):

Comments:

12.10 What are some symptoms of design conservatism that you believe can be identified and corrected. How important would such corrections be in terms of the project's cost?
## Appendix C

The Geologic Parameter Profiles.

### PROBABILITY PROFILE OF X1

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PROBABILITY PROFILE OF X2

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Appendix D

The Ground Class Profile.

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Sponsored by ASCE Construction Division Committee on Contract Administration and Tunneling and Underground Construction.


