The application of "Decision Aids for Tunneling (DAT)" to the Sucheon tunnel in Korea

by

Sangyoon Min

Bachelor of Engineering in Mining and Mineral Engineering (1999)
Inha University, Korea

Submitted to the Department of Civil and Environmental Engineering
in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Civil and Environmental Engineering

at the

Massachusetts Institute of Technology
September 2003

Signature of Author…………………………………………………………………………...
Department of Civil and Environmental Engineering
August 15, 2003

Certified by……………………………………………………………………………….
Herbert H. Einstein
Professor of Civil and Environmental Engineering
Thesis Supervisor

Accepted by……………………………………………………………………………...
Prof. Heidi Nepf
Chairman, Department Committee on Graduate Studies

The application of “Decision Aids for Tunneling (DAT)” to the Sucheon tunnel in Korea

by

Sangyoon Min

Submitted to the Department of Civil and Environmental Engineering
on August 15, 2003 in Partial Fulfillment of the Requirements for the Degree of
Master of Science in Civil and Environmental Engineering

Abstract

The Decision Aids for Tunneling (DAT) allow engineers to simulate tunnel construction considering uncertainties in geology and construction processes for a given tunnel project and to obtain, as a result, distributions of the total cost and duration of tunnel construction. The DAT can be applied to every tunnel situation and can deal with any condition regarding a particular tunnel. The research presented in this thesis demonstrates the applicability and suitability of the DAT for the Sucheon tunnel in Korea.

For this study, several developments or modifications of the program, SIMSUPER (the computer code of the DAT) were made and many simulations were run with several case studies and some parametric studies. The different time-cost distributions and other results reflecting differences in tunnel construction were analyzed.

A new development of the DAT in form of calendars in SIMSUPER was made to be able to keep track of specific and real calendar dates.

This study on the DAT application to the real tunnel project in Korea can be a model for the future DAT applications in tunnel projects and this will also lead and accelerate further applications of the DAT to other tunnel projects.

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

Acknowledgments

I would like to give special thanks to Prof. Einstein for all of his support and guidance. It has been my great honor to work with him.

I would like to thank Claude Indermitte for his help and patient explanations about the program during course of my research.

I also would like to thank Cedric Marzer and Christoph Haas for providing me with creative ideas for my research.

I am grateful to the KRRI and SKEC for providing financial support for this research and especially I wish to thank to Dr. Jun-Suk Lee and Dr. Taek-Kon Kim who provided me with some excellent engineering practices and advice.

I would like to thank my officemates, Jean Louis and Karim Karam for being such excellent officemates. My special appreciation is extended to my Korean colleagues and Geotech. colleagues: Yun, Taeyoung, Phillseung, Sunghwa, Joonsang, Brian and Pong for being my friends and making my life here enjoyable.

Finally, I owe my deepest gratitude to my parents in Korea. They have provided unconditional love and support.
Most importantly, I would like to give special thanks and love to my wife, Heeok Jung and my son, Henry Min for all the love, support and encouragement.

6

Table of Contents

List of Figures

List of Tables

Chapter 1. Introduction

Tunneling usually involves high degrees of uncertainty in geology and in the construction process. These uncertainties in tunneling need to be considered in decision making and they affect tunnel construction cost and time as well as resources.

The Decision Aids for Tunneling (DAT) allow engineers to simulate tunnel construction considering uncertainties in geology and construction processes for a given tunnel and obtain, as a result, distributions of the total cost and duration of tunnel construction.

In the application of the DAT for the Sucheon tunnel, we will demonstrate the applicability and suitability of the DAT for tunnel construction in Korea.

This study is conducted in three phase: 1. DAT simulation with present information. 2. Feedback from Korean client. 3. Final simulation.

The study in phase 1 was again divided into two parts;

Study I: DAT simulation with initial data (see section 3-1)

Study II: DAT simulation with follow-up data (see section 3-2)

Study III was performed in phase 3 considering the feedback from the Korean client including specific information on the construction processes and on some parameters.

The thesis is structured as follows: Chapter 2 gives a brief description of the project and information for the DAT simulation. In Chapter 3, studies I, II and III will be presented with several cases and parametric studies and details on the simulation process. In Chapter 4, the results and analyses of the final simulations (study III) will be studied in more detailed. Chapter 5 is devoted to giving a brief introduction of a new development of the

DAT using calendars in SIMSUPER. Finally the conclusions drawn from this research and the perspectives for future research are developed in Chapter 6.

Chapter 2. The Sucheon tunnel project

In this chapter, a brief description of the Sucheon tunnel project and information for the DAT simulation are presented. This includes the location of the Sucheon tunnel, tunnel layout, overall geology and tunnel support patterns. The project area is shown in Figure 1. The Sucheon is located between Dolsan and Soonchon in Korea as shown in Figure 1. The tunnel is a road tunnel and consists of two parallel tunnels (2 lane tunnels). One is built in the direction of Soonchon (the Soonchon tunnel) and the other is built in the direction of Dolsan (the Dolsan tunnel) as shown in Figure 2. The total length of the Sucheon tunnel is 1910m and the Dolsan tunnel is 1900m long.

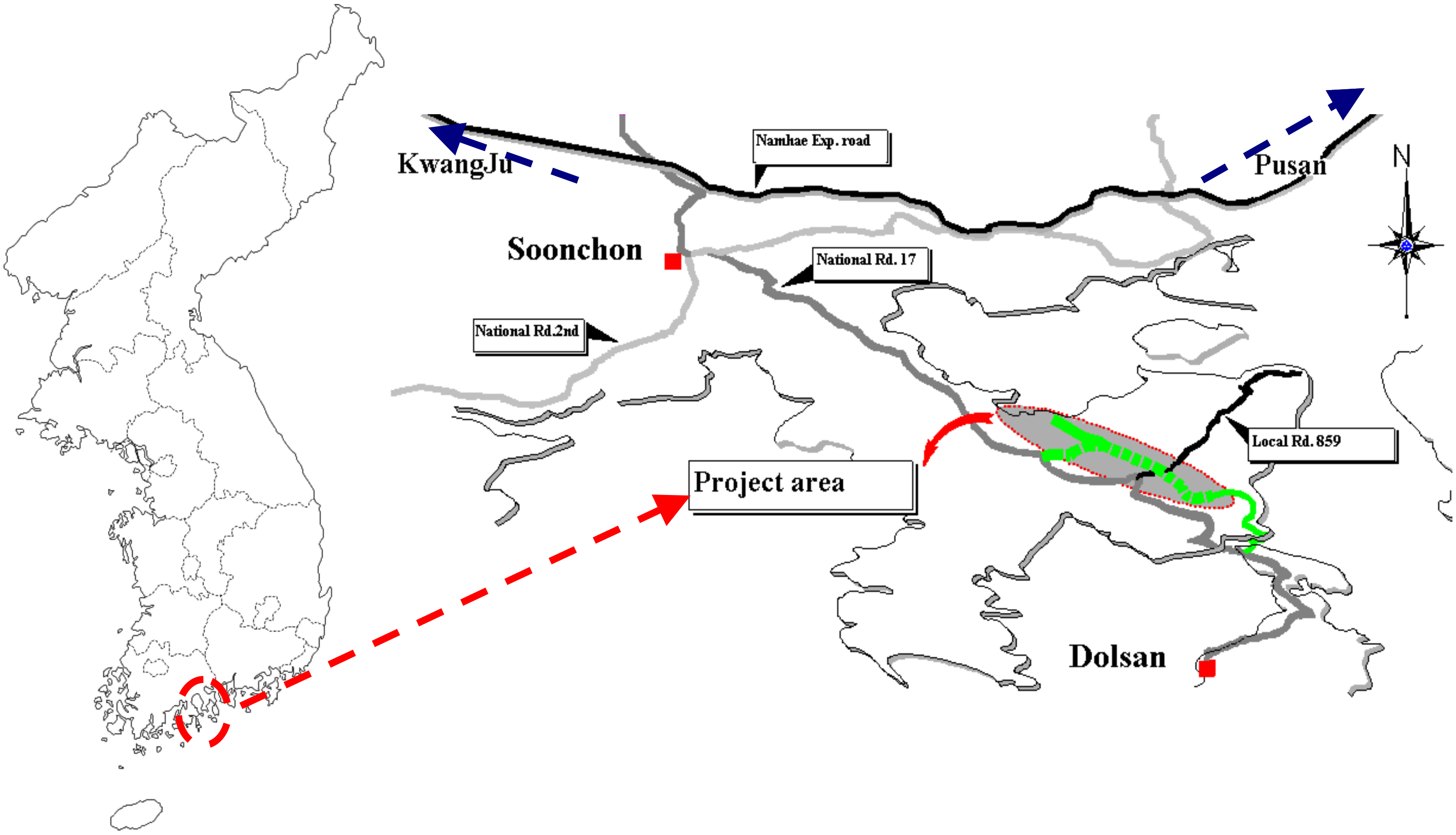


Figure 1. Project area

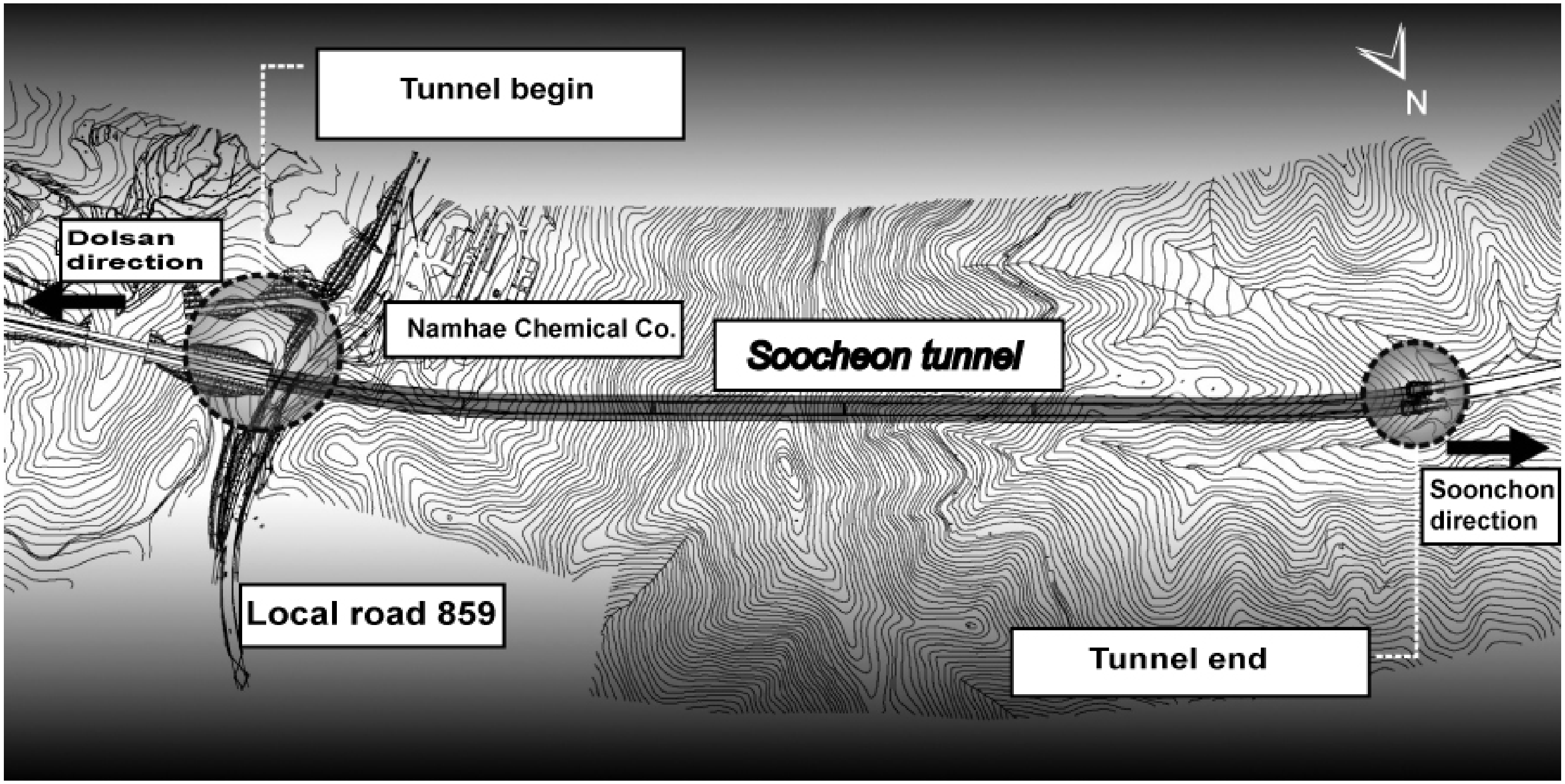


Figure 2. Plan view of the Sucheon tunnel

2-1. Tunnel Geology

The geological conditions at the Sucheon tunnel are generally uniform and good. The geology of the Sucheon tunnel has been investigated using different methods such as borehole drilling, electrical resistivity surveys and seismic exploration. The geology of the Sucheon tunnel consists of two types of rock, namely “Micrographic Granite” and “Diorite”(Figure 3). Generally, both rock types have high strength.

As shown in Figure 3, “Diorite” is widely distributed throughout the entire tunnel area except in the tunnel portal area, where “Micrographic Granite” exists.

The geologic profile is shown in Figure 4. This also shows that the rock classification and overburden are the main geologic parameters for this tunnel. The rock classification shown in this figure was developed by Korean engineers and their assessment of the rock classification is based on the Electrical resistivity, RMR and Q values as shown in Table 1.

Ground parameter	**Ground parameter states**				
Rock classification	**I**	**II**	**III**	**IV**	**V**
RMR	> 81	80 ~ 61	60 ~ 41	40 ~ 21	< 20
Resistivity (Ωm)	> 3,000	1,000~3,000	300~1,000	100 ~ 300	< 100
Q-value	> 40	4 ~ 40	1 ~ 4	0.1 ~ 1	< 0.1

Table 1. Definition of the rock classification

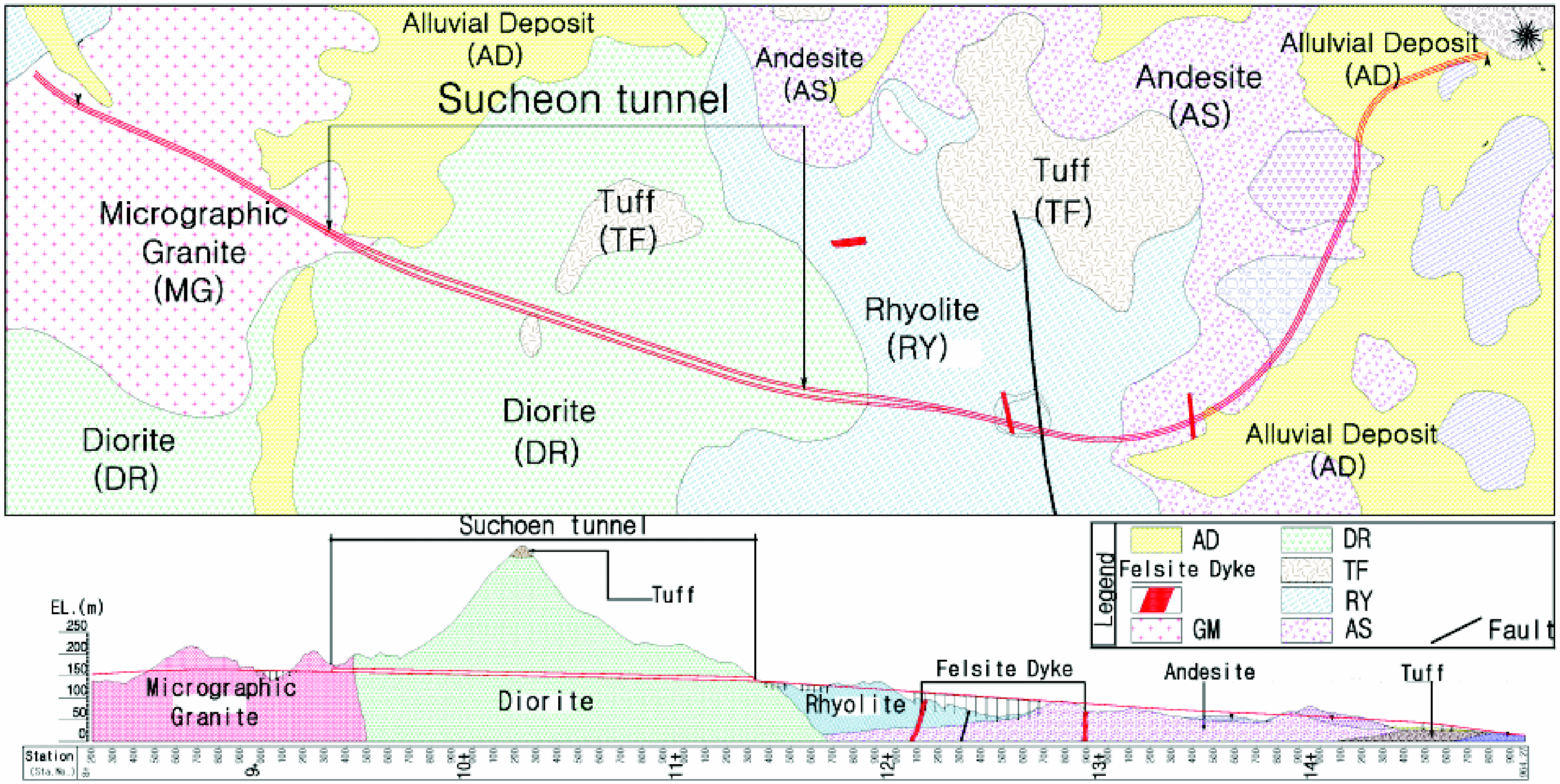


Figure 3. Geology of the Sucheon tunnel

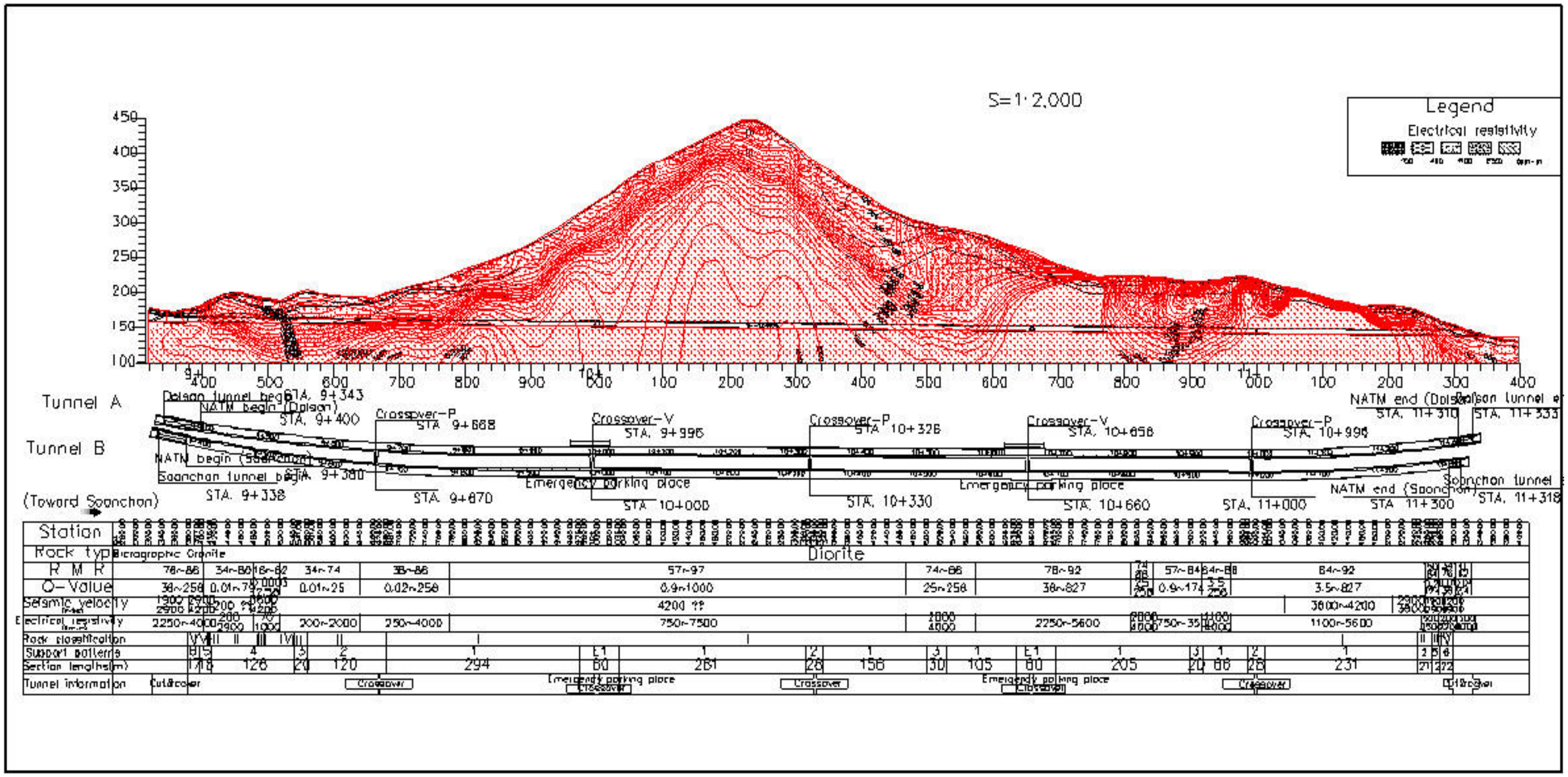


Figure 4. Geologic profile and tunnel layout of the Sucheon tunnel

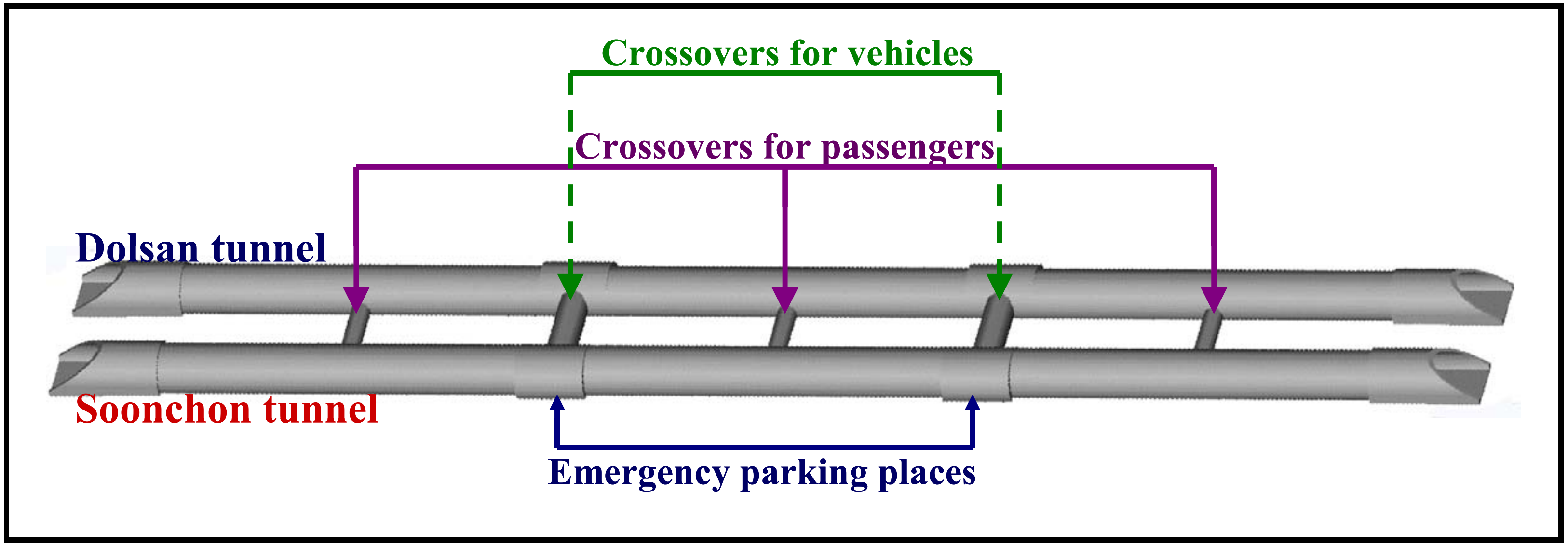


Figure 5. Tunnel layout

2-2. Tunnel layout and geometries

The tunnel layout is shown in Figures 4 and 5. The Sucheon tunnel consists of two parallel tunnels. There are five crossovers (two for the vehicles and three for the passengers) which are located between two parallel tunnels and two emergency parking places at STA. 10+100 and STA. 10+660. Basically, each tunnel has same geometry. The cross-sectional views of each tunnel, crossovers and emergency parking places are shown in Figures 6, 7 and 8.

The two tunnels (the Dolsan/Soonchon tunnel) will be built along the same geologic profiles and with the same cross-sections.

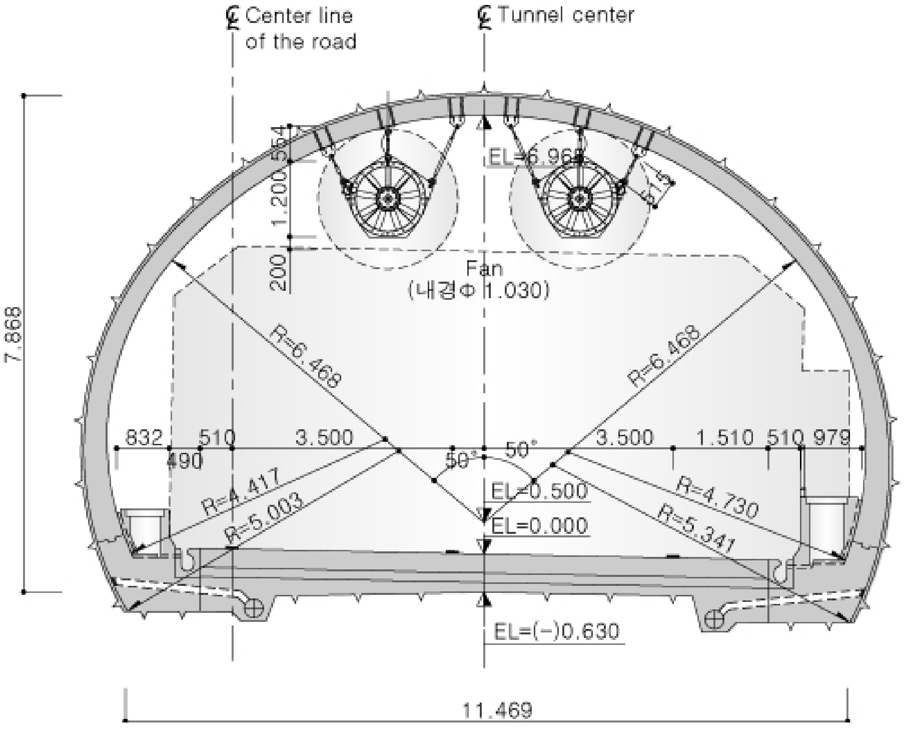


Figure 6. Cross-sectional view of main tunnel

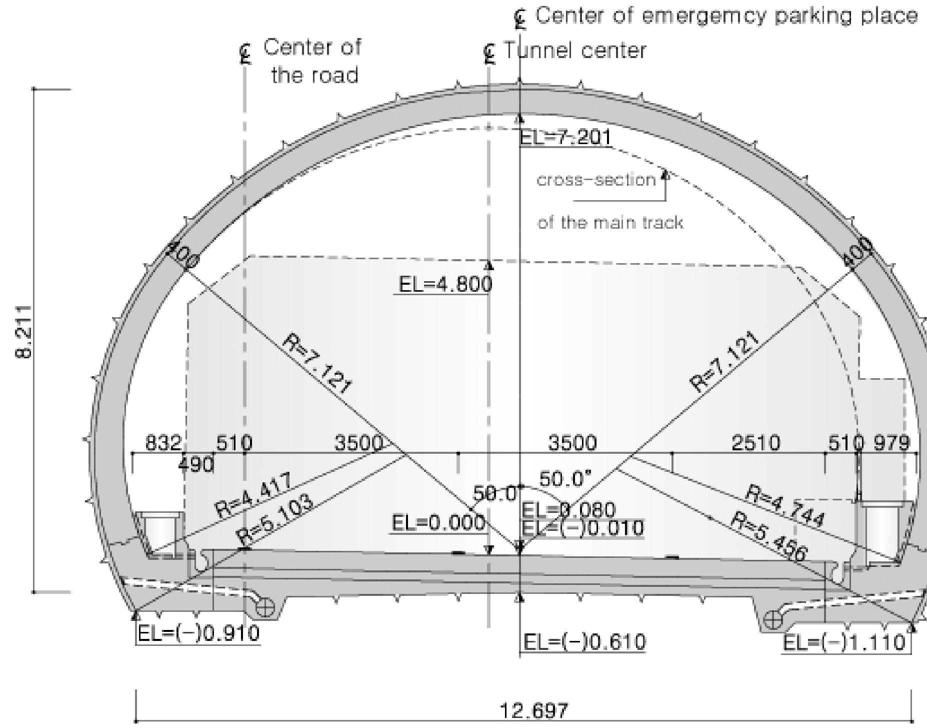


Figure 7. Cross-sectional view of emergency parking place

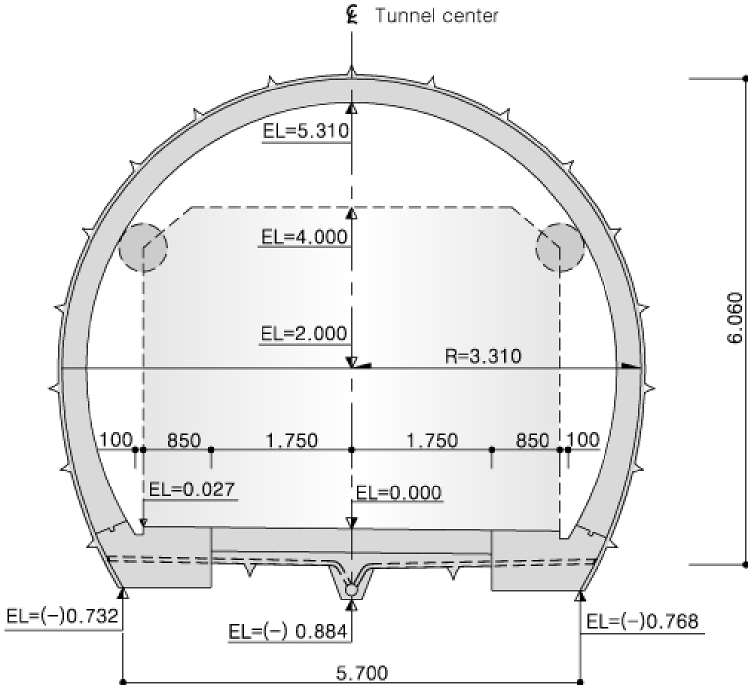


Figure 8. Cross-sectional view of crossover for vehicles

2-3. Tunnel construction methods

The NATM with drilling and blasting is used in the Sucheon tunnel. There are several tunnel support patterns, and they are selected considering the geologic conditions and geometries. Table 2 shows the cross-sections, excavation types and support patterns for tunnel construction, as well as geologic conditions such as rock classification or specific areas in which the specific support patterns are applied.

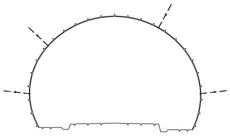
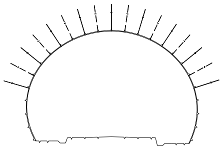
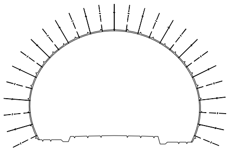
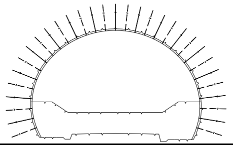
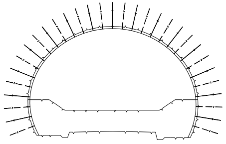
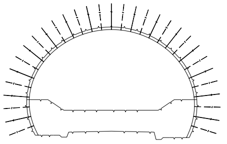
Support patterns	**Pattern 1**	**Pattern 2**	**Pattern 3**
Cross-sections			
Excavation types	Full face	Full face	Full face
Geologic conditions (Rock classification)	I	II	III
Support patterns	**Pattern 4**	**Pattern 5**	**Pattern 6**
Cross-sections			
Excavation types	Bench cut	Bench cut	Bench cut
Geologic conditions (Rock classification)	IV	V	Tunnel portal

Table 2. Construction methods "Patterns"

(include tunnel support patters and excavation types)

Chapter 3. DAT simulations

In this study, the applicability and suitability of the DAT for tunnel construction in Korea is demonstrated. As mentioned earlier the study is conducted in three phases: 1. DAT simulation with present information. 2. Feedback from Korean client. 3. Final simulation.

The study in phase 1 was again divided into two parts;

Study I: DAT simulation with initial data (see section 3-1)

Study II: DAT simulation with follow-up data (see section 3-2)

Study III was performed in phase 3 considering the feedback from the Korean client including specific information on the construction processes and on some parameters such as method variables.

Each of three studies will be presented in this chapter.

3.1. DAT simulation with initial data (study I)

In this section, the DAT simulation with initial data will be presented. The initial information provided by the Korean client was relatively limited, especially some detailed information on geologic parameters, construction methods and their advance rates and unit costs, tunnel construction sequences and tunnel dimensions were not available. Therefore, several assumptions were made regarding these unknown data. Also since information on construction costs was not provided, tunnel construction simulation and the analyses of the results could be done only in terms of construction duration.

The basic input data for the simulations are summarized in the following sections 3-1-1 to 3-1-3, and the simulation process will be explained in section 3-1-4. Details on geology and construction input data for the Sucheon tunnel are attached at the end of this thesis (See Appendix).

3-1-1. Geologic inputs

The geology of the Sucheon tunnel is divided into 8 so-called “areas” which are the top level of input data for the geologic simulations (Table 3) in the DAT. The “NATM start” and “NATM end” sections were introduced to represent slow advance rates regardless of the geology which was the same as in the adjacent main tunnel section; this is facilitated by assigning separate areas to these sections. Similar reasons led to assigning separate areas to each of the crossover tunnels.

Area name (Length)	**Description**
1. Begin (L = 85m)	NATM start section
2. Soonchon-Dolsan (L = 1,835m)	Main tunnel section
3. End (L = 50m)	NATM end section
4. Co1_P (L = 18.2m)	Crossovers for passengers
5. Co2-V (L = 17.6m)	Crossovers for vehicles
6. Co3_P (L = 18.2m)	Crossovers for passengers
7. Co4-V (L = 17.6m)	Crossovers for vehicles
8. Co3_P (L = 18.2m)	Crossovers for passengers

Table 3. Areas

The 8 areas in turn are subdivided into 23 zones considering the geology. The zone is the basic unit of geology in the DAT and the extent of each zone is defined deterministically in this study. The zones are defined here by assigning a ground parameter set to each; a ground parameter set in turn is defined by two parameters, namely overburden (high, medium and low) and rock classification (I~V) with the parameter states shown in Table 4. The rock classification parameters and parameter states are probabilistically defined. With the geology input, one can obtain the ground classes which are a particular combination of parameter states (see Table 5) and resulting ground class profiles that describe the ground conditions along the tunnel. These ground classes will ultimately be used to determine the construction methods that are used to construct a tunnel.

<table>
<tr><th>Ground parameter</th><th colspan="5">Ground parameter states</th></tr>
<tr><th>Rock classification</th><th>I</th><th>II</th><th>III</th><th>IV</th><th>V</th></tr>
<tr><td>RMR</td><td>> 81</td><td>80 ~ 61</td><td>60 ~ 41</td><td>40 ~ 21</td><td>< 20</td></tr>
<tr><td>Resistivity (Ωm)</td><td>> 3,000</td><td>1,000~3,000</td><td>300~1,000</td><td>100 ~ 300</td><td>< 100</td></tr>
<tr><td>Q-value</td><td>> 40</td><td>4 ~ 40</td><td>1 ~ 4</td><td>0.1 ~ 1</td><td>< 0.1</td></tr>
<tr><th>Overburden</th><th colspan="2">Low</th><th colspan="2">Medium</th><th>High</th></tr>
<tr><td>Elevation (m)</td><td colspan="2">200<</td><td colspan="2">200~250</td><td>>250</td></tr>
</table>

Table 4. Ground parameter states and ground parameter states

Ground parameters	Ground classes				
	L-I	**L-II**	**L-III**	**L-IV**	**L-V**
***RC**	I	II	III	IV	V
Overburden	Low	Low	Low	Low	Low

Ground parameters	Ground classes				
	M-I	**M-II**	**M-III**	**M-IV**	**M-V**
***RC**	I	II	III	IV	V
Overburden	Medium	Medium	Medium	Medium	Medium

Ground parameters	Ground classes				
	H-I	**H-II**	**H-III**	**H-IV**	**H-V**
***RC**	I	II	III	IV	V
Overburden	High	High	High	High	High

Table 5. Ground classes (*RC: rock classification)

3-1-2. Tunnel geometries

Construction methods are determined by the combination of a particular ground class and tunnel “geometry”. 10 tunnel “geometries” are defined for the DAT simulation. A separate “geometry” is assigned to the main tunnels, the start and end of the tunnels, the emergency parking places, the crossover tunnels and the lining. The assignment of different tunnel “geometries” for the same geology allows one to specify different construction methods for the same geology (e.g. the start and end of the tunnel and lining). In some special cases, the tunnel “geometry” can be used to consider environmental effects (e.g. the existence of the chemical plant near the specific part of the Dolsan tunnel). This case will be explained in section 3-1-4-1.

3-1-3. Tunnel construction inputs

A construction method specifies method variables such as the round (cycle) length, advance rate and cost. The mean values of advance rates for each construction method are shown in Table 6. The cross-sections and excavation types of construction methods, “patterns 1~6” were shown in Table 2. “Patterns 2-1, 2-2 and 2-3” have the same cross-sections and excavation types as “pattern 2” has but they have different advance rates than “pattern 2”. “Pattern EPP” is a construction method for the emergency parking places, and the cross-section of emergency parking places was shown in Figure 7. “Crossover_v” and “Crossover_p” are construction methods for crossovers for vehicles and passengers, respectively, and they have different geometries and method variables (the cross-section of the crossover for vehicles was shown in Figure 8).

However, the advance rates for “pattern 2-2, 2-3, Crossover_v and Crossover_p” were not available in study I and hence they were assumed. The costs for each construction methods were not available in study I as well.

Construction methods	Method variables		Construction methods	Method variables	
	Mean adv. Rate (meter/day)	Mean cost (cost/meter)		Mean adv. Rate (meter/day)	Mean cost (cost/meter)
Pattern 1	3.61	N/A	**Pattern 4 (Bench cut)**	1.91	N/A
Pattern 2	3.50	N/A	**Pattern 5 (Bench cut)**	0.58	N/A
Pattern 2-1	3.16	N/A	**Pattern 6 (Bench cut)**	1.44	N/A
Pattern 2-2	[1]N/A(1.2)	N/A	**Pattern EPP**	3.08	N/A
Pattern 2-3	[1]N/A(1.0)	N/A	**Lining**	10/3	N/A
Pattern 3	2.92	N/A	**Crossover_v** **Crossover_p**	[1]N/A(2.0)	N/A

Table 6. Information on method variables in Study I ([1]: assumed values)

3-1-4. Simulations

Several developments of the program (SIMSUPER) were made for this project. They are related to three issues:

Existence of a chemical plant near the Dolsan tunnel

Representing the lining process

Construction of 5 crossover tunnels

Several cases studies were carried out to consider these three factors.

3-1-4-1. The location of the chemical plant

As the chemical plant is located near the left side of the Dolsan tunnel (See Figure 9), the cycle lengths and explosive charge per hole have to be reduced to minimize blasting vibration and noise due to tunnel construction. Considering this, different construction methods (i.e. “patterns 2-2 and 2-3”), which have lower advance rates than “patterns 2 and 2-1” that are applied in the corresponding part of the tunnel in the Soonchon direction, have to be applied in this section of the Dolsan tunnel. Since the advance rates of “patterns 2-2 and 2-3” were not provided, we assumed that “pattern 2-2 and 2-3” have lower advance rates than “patterns 2 and 2-1” as shown in Table 6.

Since construction methods can be specified by a combination of ground class and geometry, different construction methods can be used in tunnel sections that have the same geologic conditions (i.e. ground class) by specifying different geometries. Therefore, an additional “geometry” is assigned to the specific part of the Dolsan tunnel in the neighborhood of the chemical plant. As a consequence, the Dolsan tunnel has a greater total construction time than the Soonchon tunnel.

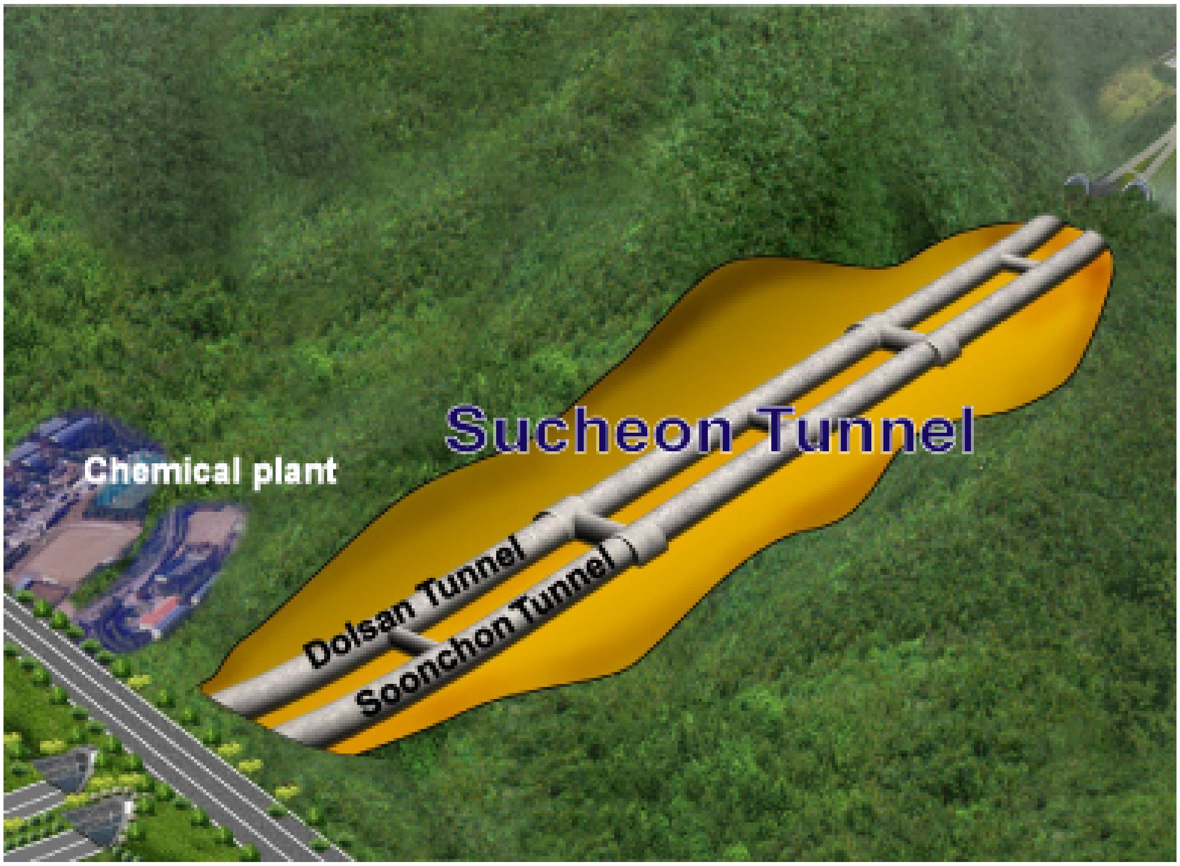


Figure 9. Location of the chemical plant

3-1-4-2. The lining process

Since the Sucheon tunnel (Soonchon/ Dolsan tunnel) is relatively short, we assume that the lining will be built after the entire tunnel is excavated. Two different ways can be used to represent the lining process in a tunnel. First, this can be dealt with by using the “Heading and bench” feature of the DAT. This assumes that a tunnel cross section is divided into two parts with one part (the “main tunnel”) driven ahead of the other (the “lining tunnel”) as shown in Figure 10. In order to perform the lining process after the entire main tunnel is excavated, one has to define the minimum and the maximum distance between the leading heading and the following heading (“distance x” in Figure 10) as the total length of the main tunnel. As a consequence, the following heading, the “lining tunnel” will start after the leading heading, the “main tunnel” is excavated.

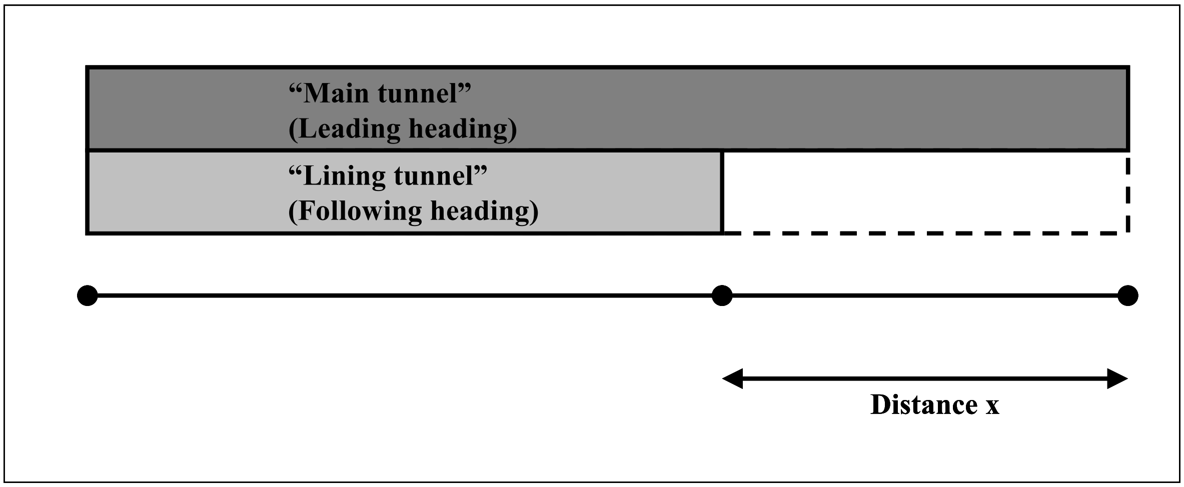


Figure 10. “Heading and Bench” process used to model excavation and lining

One can also represent the lining process by defining it as a different construction method in an imaginary “lining tunnel”. As shown in Figure 11, the lining tunnel is connected by a “dummy tunnel” to the main tunnel. The lining tunnel will be driven after the main tunnel is excavated. The second approach has been chosen for representing the lining process in this study because the main tunnel consists of several sub-tunnels and the second approach is simpler to simulate.

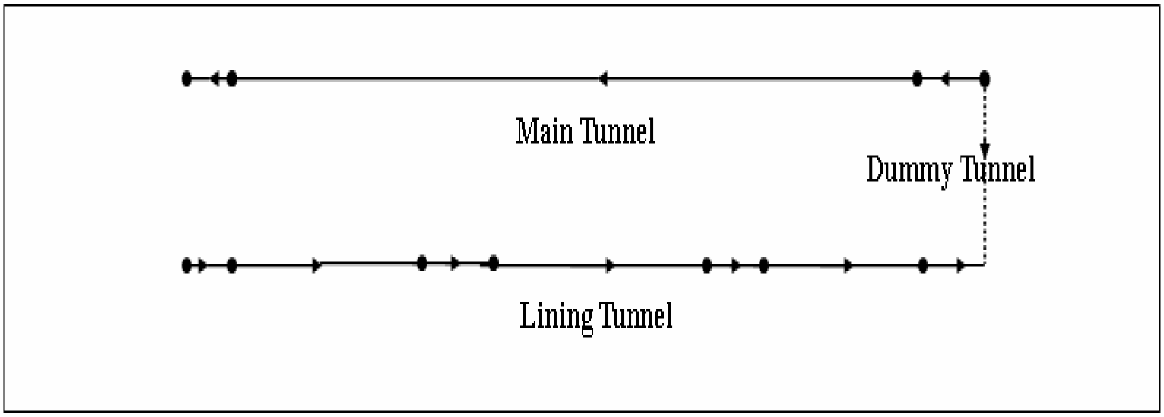


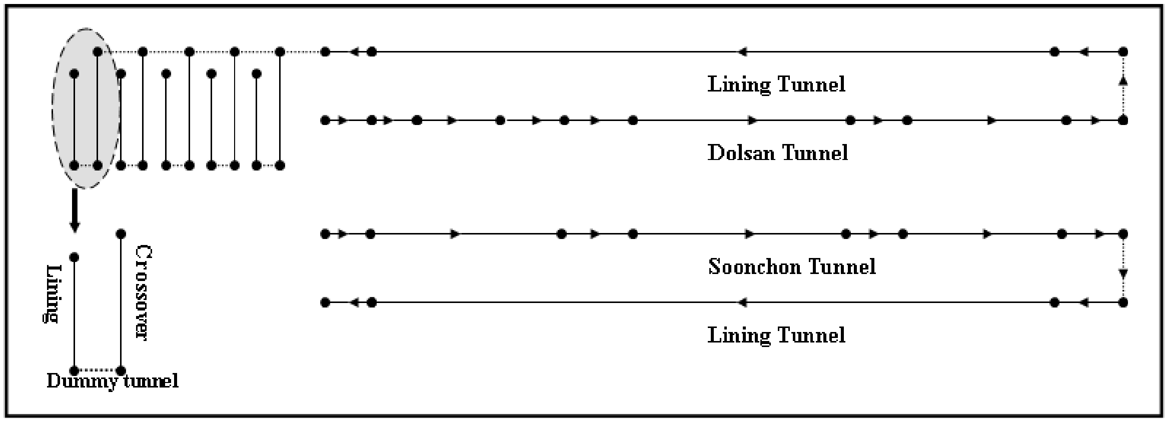
Figure 11. Tunnel network with a dummy and lining tunnel

3-1-4-3. Crossover tunnels

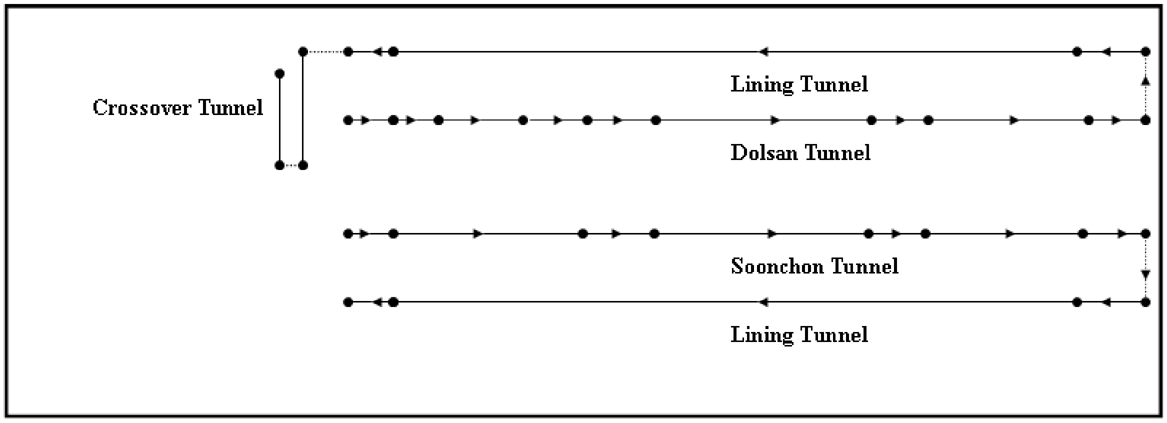
The simulation of crossover tunnel construction is another important factor that needs to be considered. Four case studies were performed with different approaches to simulate the construction of the five crossovers, which connect the Dolsan tunnel with the Soonchon tunnel as show in Figure 5.

• Cases 1 and 2

In case 1, five crossover tunnels are connected to the end of the lining tunnel in the Dolsan direction (see Figure 12). Each crossover tunnel consists of a crossover tunnel, a dummy tunnel and lining tunnel. Also each crossover tunnel has a different construction method depending on the ground classes where each tunnel is driven. In case 2, the structure of the tunnel network is similar to case 1. If all crossover tunnels have the same construction method regardless of the geology where they are driven and the construction of all crossover tunnels starts at the same time, one “crossover tunnel” can represent all 5 crossover tunnels. This case makes the tunnel network much simpler than the one used in case 1 as shown in Figure 12. Both case 1 and case 2 represent cases in which the crossover tunnels are built after the main tunnel is excavated and lined.



<Case 1>



<Case 2>

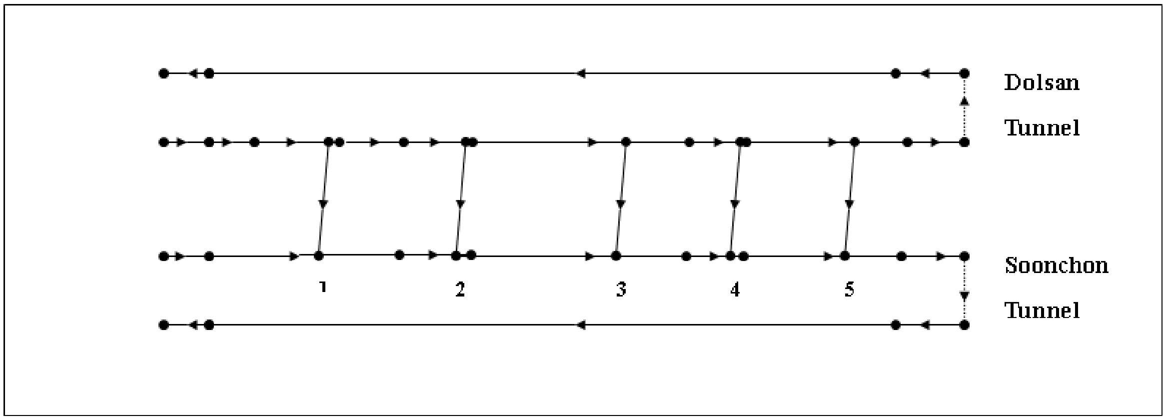
Figure 12. Construction of crossover tunnels (cases 1 and 2)

• Cases 3 and 4

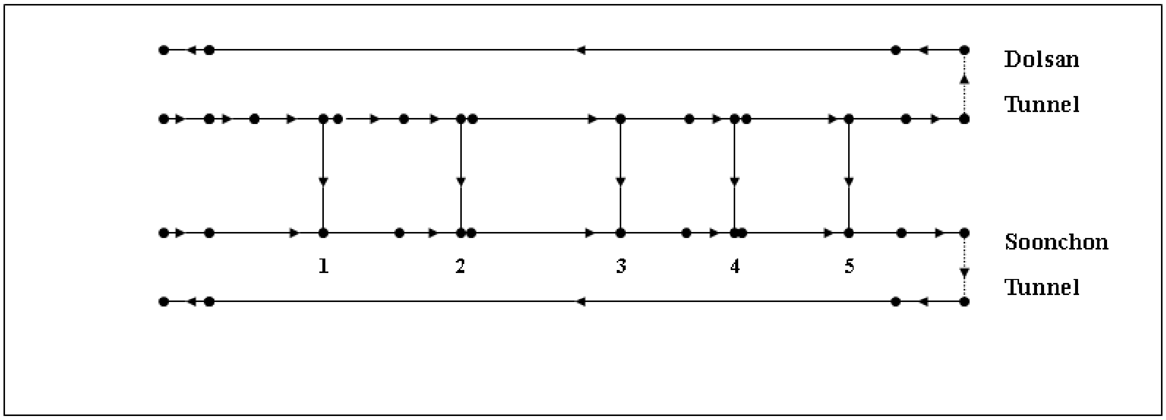
In these cases, each crossover tunnel is simulated at its actual location between the Dolsan tunnel and the Soonchon tunnel. It is assumed that the construction of each crossover tunnel advances toward the tunnel in the Soonchon direction as shown in Figure 13. Each crossover tunnel should reach nodes 1~5 respectively after the tunnel in the Soonchon direction reaches each node. There are two ways to make this possible. First, one can allocate a time delay or position delay to each crossover tunnel to make sure each crossover tunnel reaches nodes 1~5 after the tunnel in the Soonchon direction reaches each node. One can also change the locations of the beginning point of each crossover tunnel toward the right (about the length of 30m is added to the actual locations of each crossover tunnel). This would delay the construction of crossover tunnels and this is shown with 5 oblique lines representing the crossover tunnels in case 3 (Figure 13).

However, as discussed before, the Dolsan tunnel does have a greater construction time compared to the Soonchon tunnel due to the existence of the chemical plant. Given this fact and the fact that crossover construction time is relatively short, such an “artificial” delay may not be necessary and the simulation can be done without any manipulation as represented by the orthogonal lines for the crossover tunnels in case 4 (Figure 13).

In each of the cases, 3 and 4, the activity network for each crossover tunnel has a “two heading option”. The leading heading represents the tunnel excavation process and the following heading represents the lining process.



<Case 3>



<Case 4>

Figure 13. Construction of crossover tunnels (cases 3 and 4)

3-1-5. Initial simulation results and analyses for study I

Several simulations were performed to consider all the factors mentioned in sections 3-1-4-1 to 3-1-4-3, namely the location of the chemical plant adjacent to the Dolsan tunnel, the lining process and several possible tunnel networks with different crossover simulations. Even if the initial input data are quite limited, one can simulate tunnel construction and analyze the result in terms of construction duration. Table 7 shows the results of 400 simulations for cases 1, 2 and 4. The effect of the chemical plant and the lining process were considered in the same way in all cases. The total construction times are tabulated and compared in terms of minimum, mean and standard deviation values. Case 3 was not considered because the "artificial" delay of case 3 was not necessary.

Case	Number of simulations	Construction duration (days)			
		Min.	Mean	Max.	Stdev.
Case 1	400	1221	1316	1449	39
Case 2	400	1190	1310	1427	43
Case 4	400	1153	1300	1436	42

Table 7. The results of each case study in terms of time distribution

Since the results of the simulation do not include the total construction cost of the tunnel, one can analyze the simulation results only in terms of the tunnel construction duration.

The time-frequency histograms for cases 1 and 4 are shown in Figure 14 and these two histograms show the construction time distribution. The time distribution for each case can be used to determine the probability of completing the project within a specific time. Hence, this figure could be used to compare each case with a completion deadline.

Supposing that the completion deadline is 1300 days (the expected completion deadline was not provided by the Korean client), the probability of completing the construction with case 1 within 1300 days is 0.38 and this probability for case 4 is 0.52. Therefore, case 4 has a greater chance to complete the tunnel construction within 1300 days. If a case cannot meet the completion deadline, one needs to find ways to accelerate the construction.

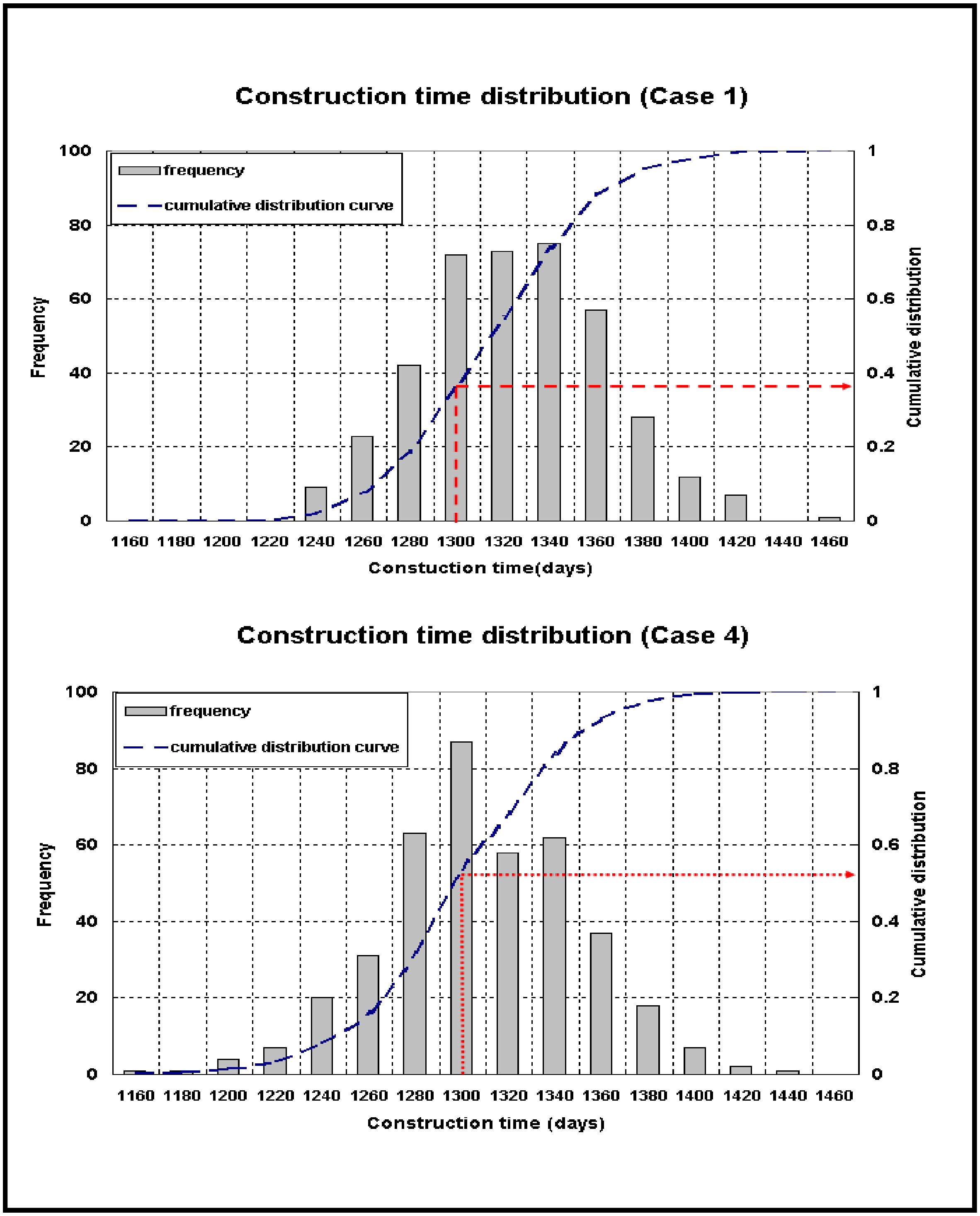


Figure 14. Construction time distributions for case 1 and case 4

3-2. DAT simulation with follow-up data (study II)

In study II (phase 1), additional and important information such as cost for each construction method, construction-related variables, tunnel excavation directions and sequencing of tunnel construction were provided by the Korean client. With this information, one could obtain not only the construction time distribution but also the construction cost distribution. Some modifications of the input data had to be made for this study.

3-2-1. Additional information and modifications of input data

• The geologic input data were not changed since no additional geologic information was provided (see Appendix for details on geologic input data).

• Cost information for each construction method is now available and has been defined probabilistically within the DAT. Table 8 shows how the minimum and the maximum values of the cost variables and advance rates for each construction method are defined.

Type of variables	Minimum values	Maximum values
Cost variables (cost/meter)	95% of the mode values	105% of the mode values
Advance rate (meter/day)	95% of the mode values	115% of the mode values

Table 8. Range of values for the method variables

- The comparisons of method variables between initial data (study I) and follow-up data (study II) are shown in Table 9. As shown in Table 9, all cost information became available and most of advance rates were changed in study II compared to study I. Advance rates for the upper (heading) and lower (bench) part of the patterns 4, 5 and 6 are provided as well. As mentioned in section 3-1-3, “patterns 2-1, 2-2 and 2-3” have the same cross-section as “pattern 2” but each of them has different advance rates from “pattern 2”. “Pattern EPP” is used for emergency parking places. The advance rates and costs for “Crossover_v” and “Crossover_p” were available in study II as shown in Table 9.

- Actual advance rates for the tunnel support patterns 2-2 and 2-3 were provided as shown in Table 9. Before this information was available i.e. in study I (refer to section 3-1-4-1), it was assumed that tunnel support patterns 2-2 and 2-3 would have lower advance rates based on given information on cycle lengths. This was done because patterns 2-2 and 2-3 were the construction methods in the Dolsan tunnel which consider the location of the chemical plant.

Therefore, in study I, the total construction time of the Dolsan tunnel was a bit greater than that of the Soonchon tunnel. However, the new advance rates for patterns 2-2 and 2-3 are greater than the values that we assumed earlier. In other words, even if the physical cycle lengths (meter/cycle) of these methods are short, the advance rates (meter/day) of these methods are not low as assumed in study I. This is because 2 or 3 sets of blasting can be done in a day without affecting the chemical plant. More details will be given in Chapter 4.

Construction methods	**Initial data (study I)**		**Follow-up data (study II)**	
	Mean advance rate (meter/day)	Mean cost (won/meter)	Mean advance rate (meter/day)	Mean cost (won/meter)
Pattern 1	3.61	N/A	3.60	6,848,009
Pattern 2	3.50	N/A	3.51	7,570,405
Pattern 2-1	3.16	N/A	3.12	7,570,405
Pattern 2-2	[1]N/A (1.2)	N/A	2.94	7,570,405
Pattern 2-3	[1]N/A(1.0)	N/A	2.78	7,570,405
Pattern 3	2.92	N/A	2.96	7,969,888
Pattern 4 (bench cut)	1.91	N/A	2.68 (heading) 6.56 (bench)	10,140,761
Pattern 5 (bench cut)	0.58	N/A	2.40 (heading) 4.73 (bench)	11,194,954
Pattern 6 (Bench cut)	1.44	N/A	2.18 (heading) 4.31 (bench)	11,944,117
[2] **Pattern EPP**	3.08	N/A	3.12	7,202,979
Lining	10/3	N/A	[3]13.32	[4]
Crossover_v	[1]N/A (2.0)	N/A	6.03	2,603,867
Crossover_p	[1]N/A (2.0)	N/A	8.64	2,603,867

Table 9. Method variables for “initial data” and “follow-up data”

[1]: assumed values, [2]: patterns for emergency parking places, [3]: 6.67m/day for study III

[4]: each pattern has different lining costs (range from 465,862 to 476,605 won/meter)

- The crossover tunnels will be built together with the main tunnel as shown in Figure 15. Hence crossover tunnels in the DAT simulation are represented at their actual locations as in case 4 in study I. Lengths of each crossover tunnel and advance rates of the crossover tunnels were specified according to the new information in study II (see Table 9). The two types of crossover tunnels (vehicles/ passengers) have different geometries (e.g. cross-sections and lengths) and different advance rates and costs from each other. These facts are considered in the DAT simulation.

- The simulation of the lining tunnel was also changed. The actual construction of the lining is divided into 4 parts performed simultaneously with an advance rate of 3.33 meter/day. Hence the estimated time for the lining construction was 4 times smaller than the time in study I. Instead of having 4 separate lining tunnels in the tunnel network, one lining tunnel with the advance rate that is 4 times greater (13.32 meter/day) than the actual advance rates (3.33 meter/day) is used. However, based on new information, this lining tunnel itself needs to be divided into several sub-tunnels in the DAT simulation because each construction method has a slightly different lining method (each lining method has the same mean value of advance rate (13.32 meter/day), but different mean values of cost). In study I, only one construction method was assigned to the entire "lining tunnel".

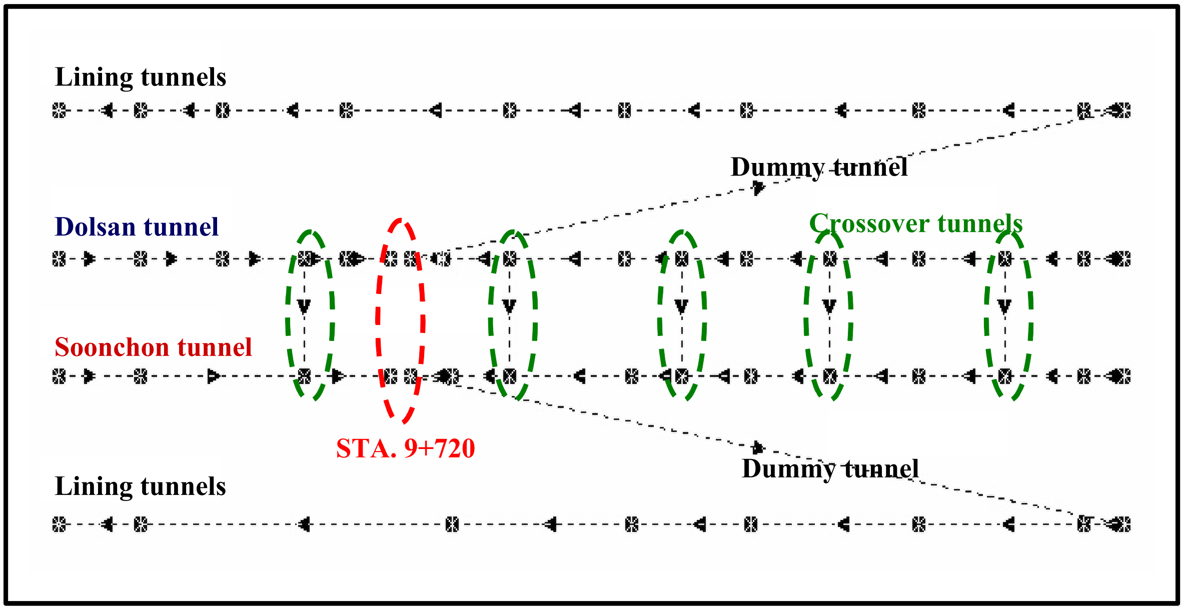


Figure 15. Tunnel network for the DAT simulation in study II

- The information for study I showed that the both tunnels (the Dolsan/ Soonchon tunnel) would be excavated in one direction and the tunnel network was structured correspondingly. The new information, however, shows that both tunnels will be excavated from both ends and the two sides of the tunnel will meet at STA. 9+720 as shown in Figure 15. During construction, if one side of tunnels reaches this point this tunnel will not be excavated any further. Considering construction from both ends, the total construction time will be reduced compared to that of study I.

3-2-2. Simulation results for study II

Table 10 shows the result of 900 simulations in study II.

	Minimum	**Mean**	**Maximum**
Total construction time (days)	627	646	673
Total construction cost (won)	32,508,212,367	32,703,345,453	33,321,817,213

Table 10. Results of the simulations for study II

*** The client's estimation: total construction time: 605 days; total construction cost:30,476,527,822 won**

Because of the fact that the tunnel will be excavated from both ends and based on the new information that the estimated time for the lining construction is 4 times smaller than that of study I, the total construction time is considerably reduced compared to the total construction time obtained from study I. Total construction time and cost can be compared with the client's estimation. Both the total construction time and the total construction cost estimated with the DAT are greater compared to the Korean client's estimation.

3-3. Study III – Final simulation with modifications of study II

There was some new information and feedback from Korean client in phase 2 which were considered in study III. Study III was done based on study II, however, there are some modifications of input data in study III and several features of the DAT have been modified in study III. Also, some parametric studies have been done in study III. Details will be explained in the following section and Chapter 4.

- The location where the two sides of the tunnel will meet has been changed from STA. 9+720 to STA. 10+010. As a consequence, the tunnel network for the final simulation is slightly changed as shown in Figure 16. One can notice that there are two crossover tunnels at the left side of the main tunnel while there was only one crossover tunnel at the left side of the main tunnel in study II.

- The lining process was considered differently in studies I and II. In study I, one lining tunnel was built from one end of the main tunnel to the other with the advance rate of 3.33 meter/day, in study II, however one lining tunnel with the advance rate of 13.32 meter/day, which was 4 times greater than the actual advance rate; was built to simulate the case in which the actual lining construction is performed at 4 different locations.

According to the new information in study III, the lining tunnel will be built from both ends with the actual advance rate of 3.33 meter/day (the actual advance rate for the lining is same for all studies). Since each lining method has the same advance rate, if the advance rate for the all lining methods is doubled (6.66 meter/day), this can reflect the fact that the lining tunnel is built from the both ends. Hence the lining tunnel will be simulated in one direction (red-dashed lines) with a doubled advance rate in the final simulation (study III) as shown in Figure 16.

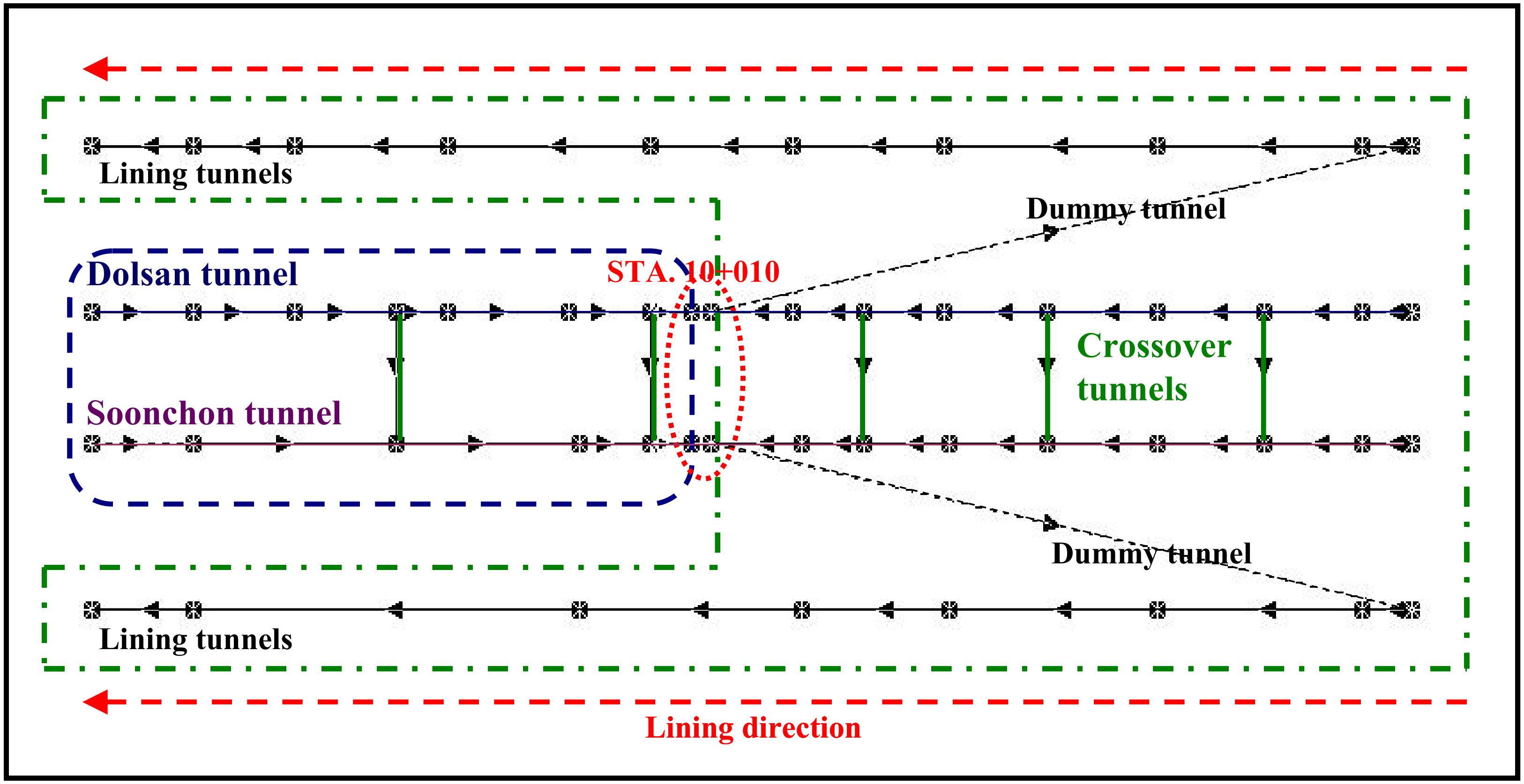


Figure 16. Tunnel network for the DAT simulation – Study III

- In study I, it was assumed that the Dolsan tunnel has a greater construction time than the Soonchon tunnel due to the effect of the chemical plant and as a consequence, any artificial delay was not necessary. However, as mentioned before, the main tunnel is divided into two parts and in fact, there is little effect of the chemical plant on the advance rates of the construction methods that are applied to the specific part of the Dolsan tunnel (see section 3-2-1 and Chapter 4). Therefore, the “position delay” needs to be applied at the beginning of each crossover tunnel to make sure that the Soonchon tunnel reaches each node, “a~e” (Figure 17) before each crossover tunnel reaches it (The “position delay” can delay construction of a specific tunnel at a specific location of this tunnel for a given duration of delay). Durations of the delays for each crossover tunnel are determined by the time to reach “1~5 (the beginning of the crossover tunnels)” in the Dolsan tunnel and time to reach “a~e (the end of the crossover tunnels)” in the Soonchon tunnel (Figure 17). Larger duration delays need to be applied to two crossover tunnels in “part A” compared to the three crossover tunnels in “part B” because the left side of the Soonchon tunnel begins 20 meter ahead (is 20 meter longer) of the left side of the Dolsan tunnel in “part A” (Figure 17) and there is little effect of the chemical plant (the left side of the Soonchon tunnel reaches nodes a and b much later than the left side of the Dolsan tunnel reaches nodes 1 and 2 while the right side of the Dolsan tunnel reaches nodes c, d and e later than the right side of the Soonchon tunnel reaches nodes 3, 4 and 5).

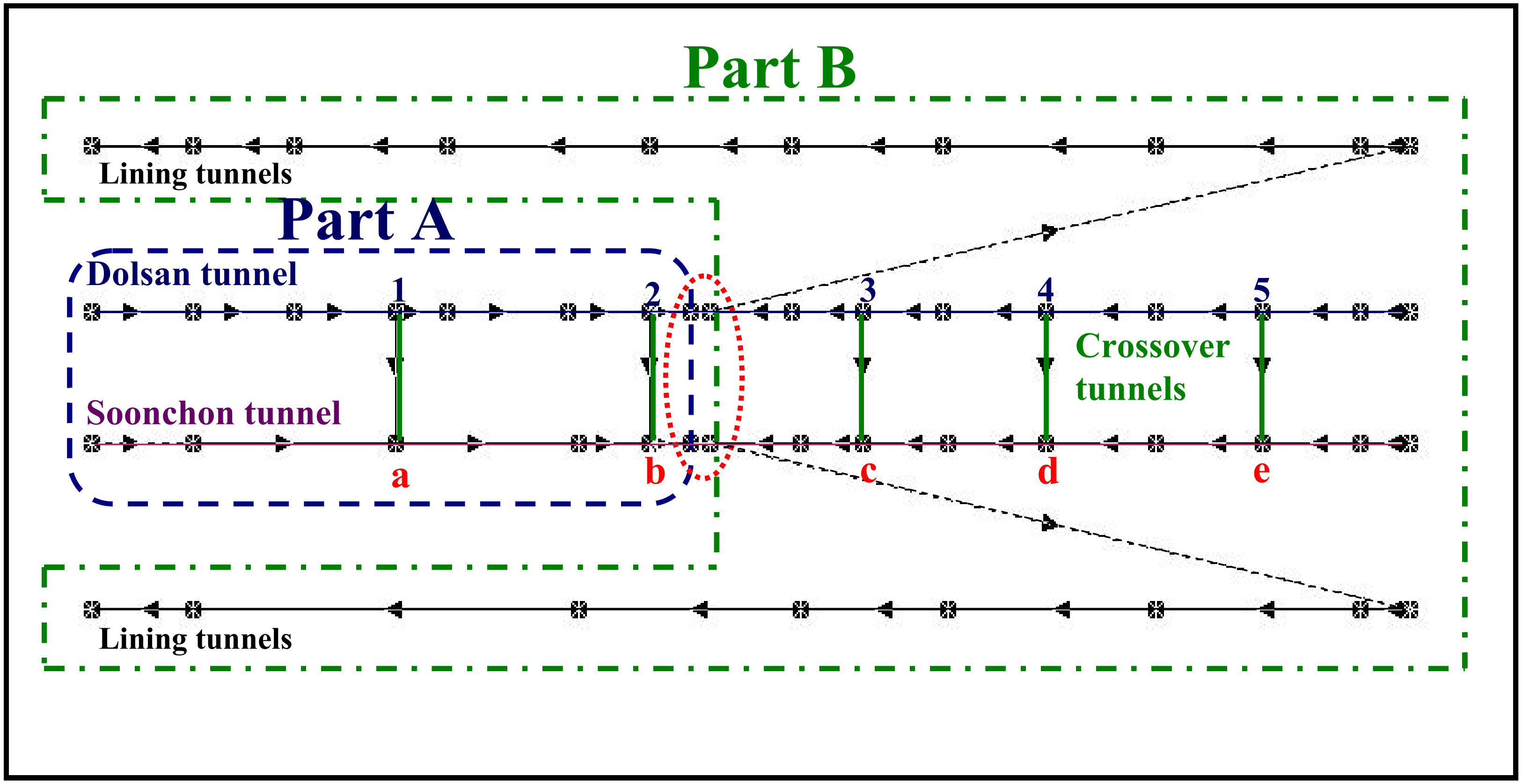


Figure 17. Construction of crossover tunnels

Chapter 4. Simulation results and analyses

In this chapter, the results and analyses of the final simulations (study III) will be studied. First, two major sources of uncertainty (the uncertainty about geology and about the construction methods) will be studied to find out how these two sources of uncertainty contribute to the overall uncertainty in the time-cost distributions of the Sucheon tunnel. Four different sets of simulations will be analyzed and compared to each other in this regard. Finally, the time-cost distributions for each side of the main tunnel and the lining tunnel will be examined separately before the overall simulation results for the Sucheon tunnel are discussed.

4-1. Observation of the major sources of uncertainty in the Sucheon tunnel construction

There are two major sources of uncertainty in the DAT:

- the uncertainty about geology
- the uncertainty about construction methods

Of these two sources of uncertainty, the former is associated with the uncertainty in zones or ground parameter states which are defined using the Markov mode or the Semi-deterministic mode and the latter is related to the variations of method variables (e.g. advance rates and cost per length). In addition, there are also tunnel-related uncertainties such as “delays” and “fixed costs”; in this study, however, this source of uncertainty is not considered.

4-1-1. Geology simulations and the uncertainty about geology

The uncertainty about geology can be observed by looking at the results of the geology simulations. The ultimate goal of the geology simulation is to generate the ground class profiles. The ground class profiles implicitly involve the uncertainty about geology which is mainly caused by the uncertainty in zone lengths or the Markov parameters. Hence, it is possible to determine how much the uncertainty about geology contributes to the overall uncertainty in tunnel construction (e.g. the distributions of the total construction time and cost) by examining the generated ground class profiles.

Figure 18 illustrates the possible portions of ground class profiles in the Sucheon tunnel (since all geology input data for studies I, II and III are same, the generated ground class profiles are applicable to any of three studies). This figure shows that there is a large variability in the generated ground class profiles. For instance, the ground class, “H-I” can be generated with the probabilities of 8.44% to 26.33%.

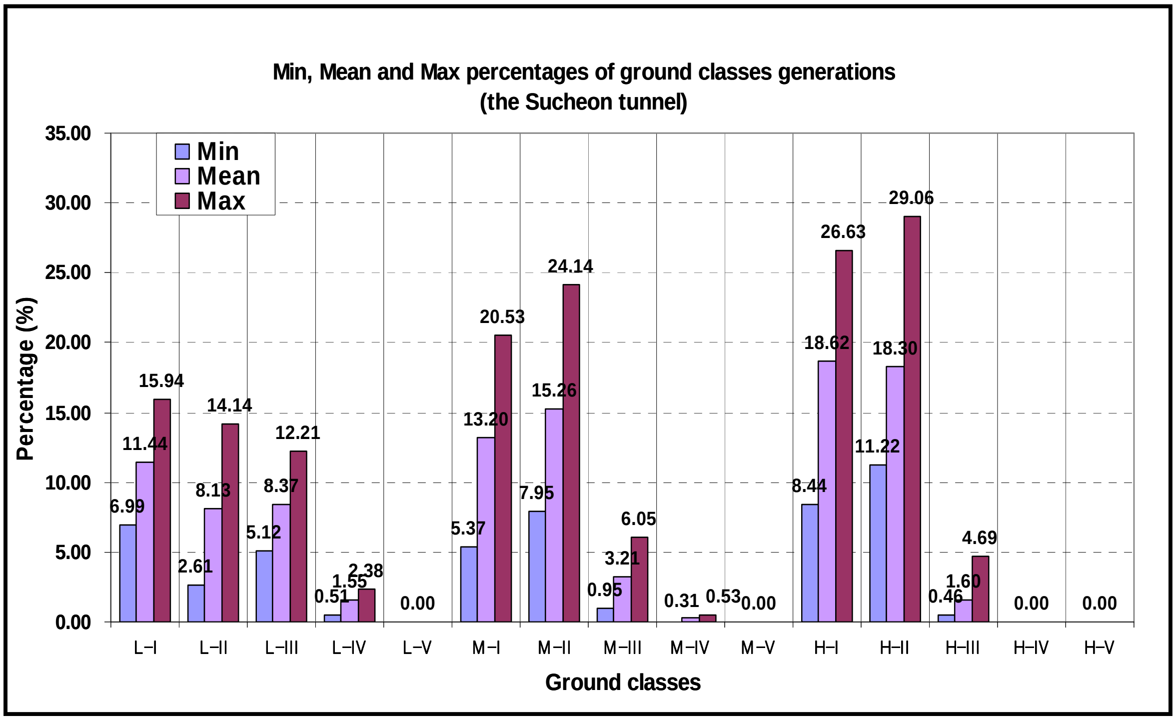


Figure 18. Generated ground class profiles in the Sucheon tunnel

(Refer to Table 5 in section 3-1-1 for the definition of each ground class)

4-1-2. Construction simulations and the uncertainty about construction methods

There are several factors that are associated with the uncertainty about construction methods:

- Variations of the method variables
- Correlation of the method variables
- Simulations with daily fluctuations (“each cycle”) or long-term averages (“one time”)

Each of these three factors can be specified for the construction simulation in the DAT.

In the following sections 4-1-2-1 ~ 4-1-2-3, each of these factors will be explained in detail.

4-1-2-1. Variations of the method variables

The uncertainty about construction methods is mainly caused by the uncertainty in the method variables such as advance rate and cost per length. Since construction will be simulated through the generated ground class profiles, the construction methods which are applied to a particular geologic condition change as the generation of the ground class profiles varies. However, if the geology is fixed (or deterministic), the construction methods which are applied to the given geologic condition are also fixed but the method variables may vary. This can be considered as a case in which only the uncertainty about the construction method variables is considered. In other words, the ranges of values for the method variables are the only source of uncertainty.

As shown in Table 8 (see section 3-2-1), for the Sucheon tunnel, the range of values for advance rates is greater than the range of values for costs per length for every construction method. As a consequence, if only the uncertainty of the method variables is considered for the simulation, the uncertainty in the total construction time (i.e. the time distribution) would be greater than the uncertainty in the total construction cost (i.e. the cost distribution).

4-1-2-2. Correlation of the method variables of the construction methods

The correlation of the method variables in a specific construction method can be specified in the DAT. For example, time-related variables (e.g. advance rates) and cost-related variables (e.g. cost per length) can be positively or negatively correlated or can be uncorrelated. E.g. if advance rates and cost per length (meter) are negatively correlated, the time increases with cost. For this study, the advance rate and cost per length (meter) for every construction method are negatively correlated.

In addition, generally, if a specific construction method has a higher cost and lower advance rate than others or vice versa, the total construction cost is proportional to the total construction time. The relation between advance rates and costs for each construction method in the Sucheon tunnel shows this correlation as shown in Figure 19. As a consequence, one can expect that the total construction time would increase with the total construction cost.

As a result, the two facts mentioned above will affect the trend of time-cost scattergrams for a given tunnel construction.

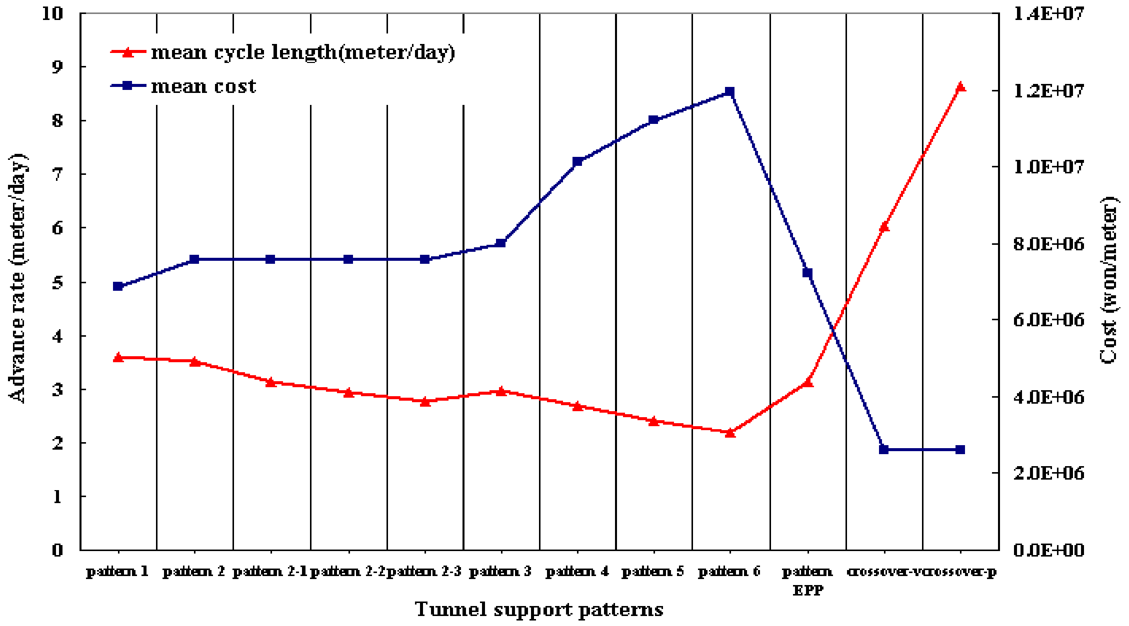


Figure 19. Relation between advance rate and cost for each construction method

4-1-2-3. Simulations with daily fluctuations (“each cycle”) or long-term averages (“one time”)

The values of method variables (e.g. advance rates and cost per length) are usually subject to daily fluctuations. This is, however, only one source of the uncertainty. The average value around which they fluctuate can be also uncertain. In fact, the effect of daily fluctuations in long tunnels cancels out and only the uncertainty about the long-term average is important. On the other hand, in short tunnels, the effect of daily fluctuations can outweigh the uncertainty about the long-term average.

The DAT can accommodate both situations for the construction simulation and hence, the DAT can evaluate the values of the method variables in two ways.

If one simulates tunnel construction with the daily fluctuation option called “each cycle”, the simulator plays a lottery for the method variables in every round of the simulations anew. Therefore, the distributions for these variables represent the range of fluctuations from cycle to cycle. The cost-related methods variables (e.g. cost per length) and time-related method variables will average out in the same manner during every single simulation.

If tunnel construction is simulated with the long-term averages option called “one time” in the program, the simulator plays lottery for the method variables only once at the beginning of each simulation. Therefore, during any particular simulation, the advance rates and cost per length associated with any cycle of such a construction method remain constant. This describes the uncertainty about the long-term average. One of these two options can be chosen for each tunnel individually. Therefore, it is possible to use “each cycle” option for a short shaft tunnel and “one cycle” options for a long main tunnel.

The effect of the “each cycle” option and “one time” option can be compared directly only when the uncertainty about the geology is not involved in the overall uncertainty in the time and cost distributions (e.g. when a given geologic condition is the same or fixed). This is so because the uncertainty in the time or cost distribution of the simulations with the two options are affected in the same way by the uncertainty about geology and therefore, the uncertainty in the time or cost distribution (or both) which is caused by the uncertainty about geology can outweigh the effect of the “each cycle” option.

4-2. Analyses of the simulation results of the Sucheon tunnel considering two major sources of uncertainty

It is interesting to analyze and compare the simulations results (e.g. the time and cost distributions) considering the two sources of uncertainty (e.g. uncertainty about geology and uncertainty about construction methods). Four different settings for the simulations are used in order to find out how each of these two sources of uncertainty contributes to the overall uncertainty in the time-cost distributions of the Sucheon tunnel. These four different simulations were run based on information and input data used in study III. Table 11 shows the four different simulation settings.

settings	**Options for the method variables**	**Number of geology simulations**	**Number of construction simulations**	**Uncertainty about geology**	**Uncertainty about construction methods**
A	“one time”	1000	1	Yes	Yes
B	“one time”	1	1000	No	Yes
C	“each cycle”	1000	1	Yes	No
D	“each cycle”	1	1000	No	No

Table 11. Four different simulation settings

Setting A includes all sources of uncertainty. Setting B includes only uncertainty about construction method (e.g. method variables) since all construction simulations are run with the same geologic condition. Setting C includes only uncertainty about geology.

Setting D excludes all source of uncertainty since all construction simulations are run with the same geology and if simulations are run with the "each cycle" option, all method variables are considered to represent daily fluctuations and they will almost perfectly average out during every single simulation. Therefore, one can assume that every simulation uses the same values of the method variables.

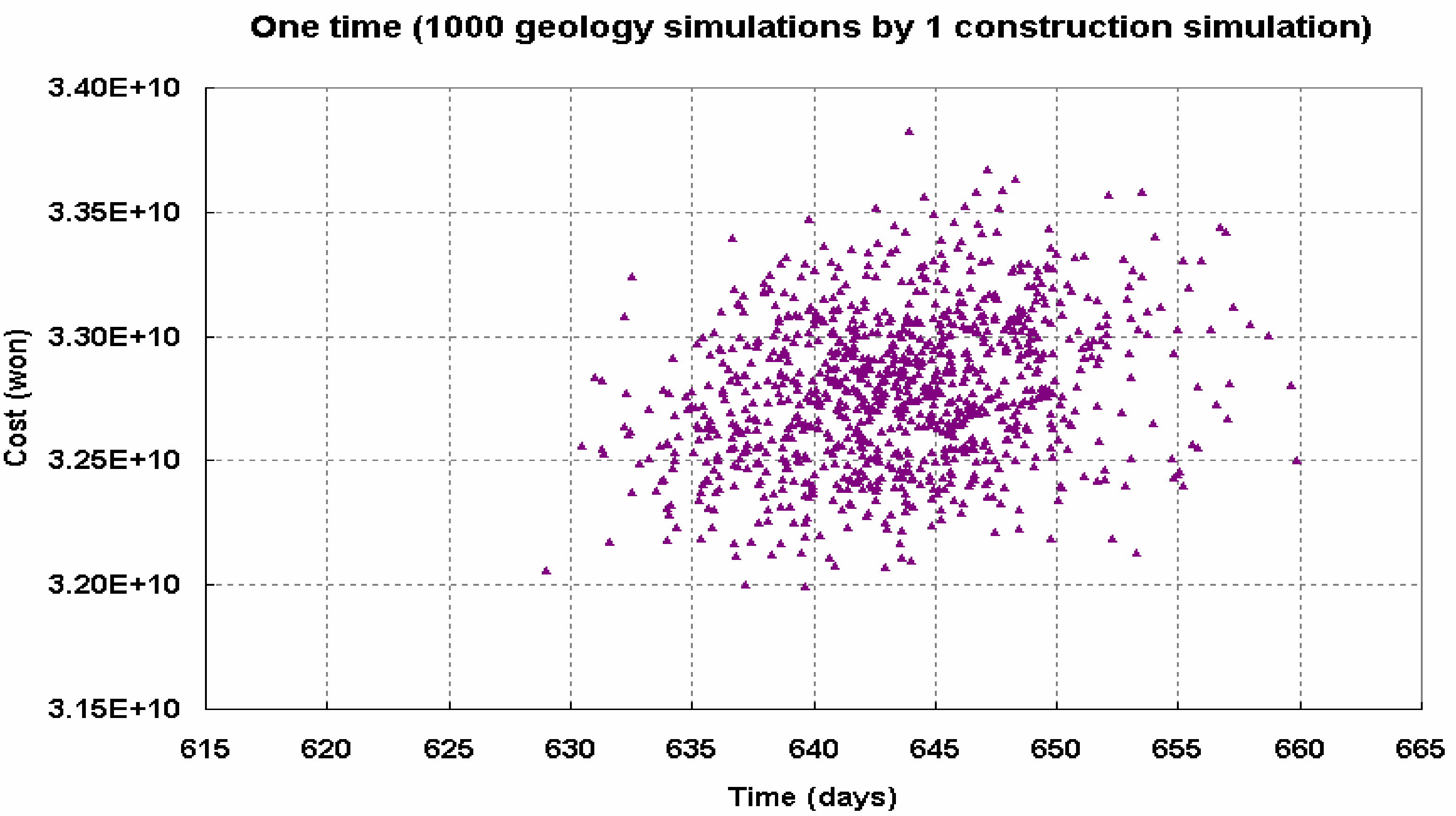
If only uncertainty about construction methods is considered for the simulations (e.g. "setting B" in Figure 21), the time distribution is greater than the cost distribution. Since all construction simulations are run with the same geologic condition, the uncertainty in time and cost depends on the variability of values of method variables. As mentioned in section 4-1-2-1, since the variability of values for advance rates is greater than the variability of values for cost per length, there is a greater uncertainty in the time distribution than in the cost distribution. However, if only uncertainty about geology is considered for the simulations (e.g. "setting C" in Figure 22), the cost distribution dominates the time distribution. Since all geology simulations are run with the same construction simulation, the uncertainty about the time and cost depends on the differences between method variables of different construction methods which are related to the range of possible geologic conditions. Since the difference between costs of different construction methods is considerable while the difference between advance rates of different construction methods is fairly small, there is a greater uncertainty in the cost distribution than in the time distribution.

If all sources of uncertainty are considered in the simulations (e.g. “setting A” in Figure 20), the time distribution follows the time distribution as in “setting B” which involves only uncertainty about construction methods. On the other hand, the cost distribution is similar to the cost distribution in “setting C” which represents uncertainty about geology.

Both “setting A” and “setting B” represent the simulations with the “one time” option. Since the uncertainty about construction methods is considered in both simulation settings, the time distributions of the two settings are about the same. However, since “setting A” also considers the uncertainty about geology, the cost distribution of “setting A” is greater than that of “setting B”

Both “setting C” and “setting D” represent the simulations with the “each cycle” option. The difference between the two settings is that the uncertainty about geology is considered in the “setting C” . Since the 1000 simulations were run with the “each cycle” option for “setting D”, all method variables average out and hence, it is assumed that the uncertainty about construction methods is not considered in the simulations. Figure 22 and Figure 23 show that the uncertainty about geology causes the greater uncertainty in the cost distribution than the time distribution.

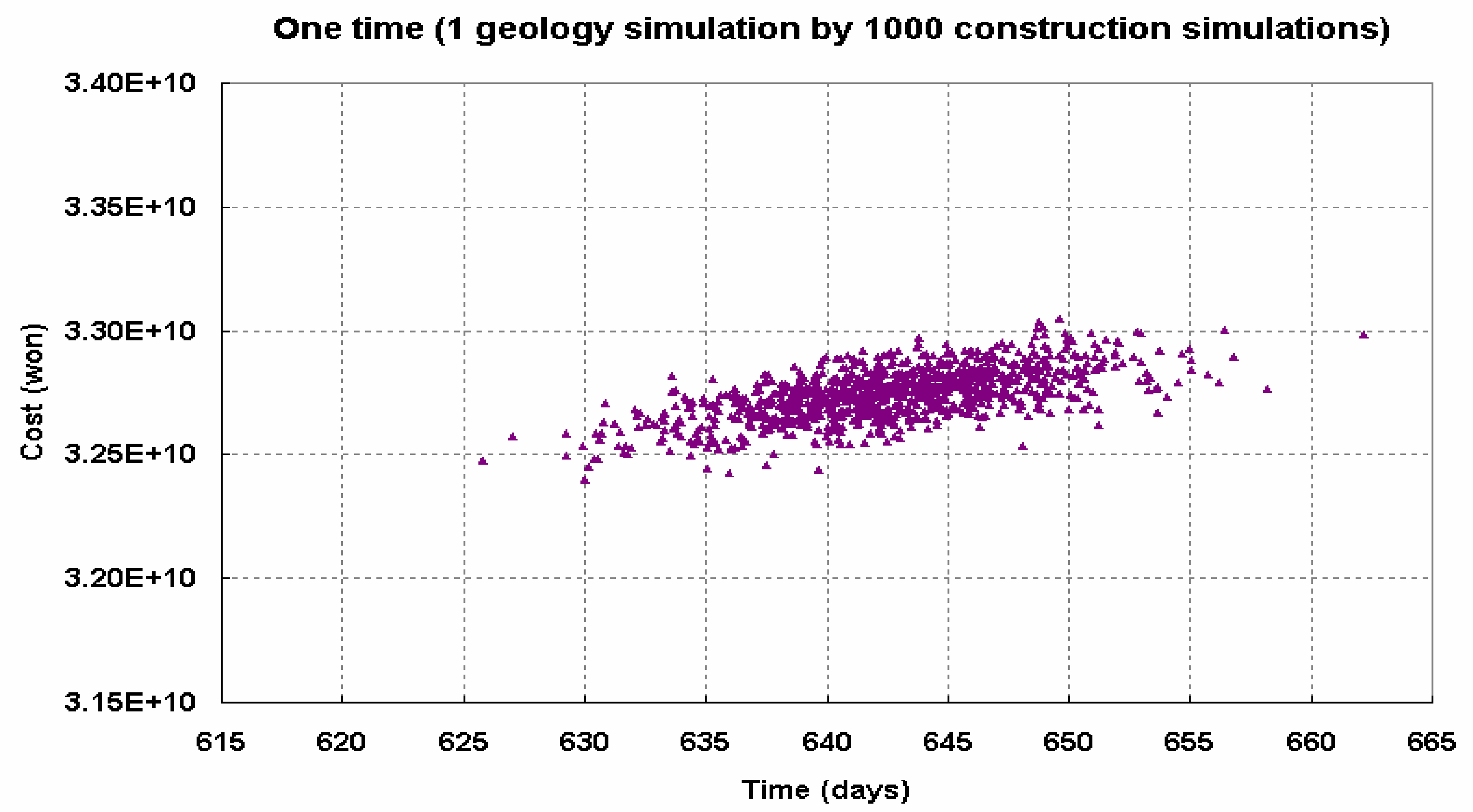
In order to make a true comparison between the simulation with the “each cycle” option and with the “one time” option, the geologic condition has to be same. Among four different simulation settings, “setting B” and “setting D” can be compared in this regard. This is because two simulations (setting B and setting D) were run with the same geologic condition and with the same number of construction simulations (1000 construction simulations). Both time and cost distribution for the “setting B (one time)” are greater than those for the “setting D (each cycle)”. This comparison shows that the uncertainty in the time and cost distribution for the “setting D (each cycle)” averages out compared to the “setting B (one time)”.



One time	Min	Mean	Max	Stdev	COV
Time	629	644	660	5.06	0.79%
Cost	31996722191	32786673442	33826274239	303826309	0.93%

Figure 20. Setting A

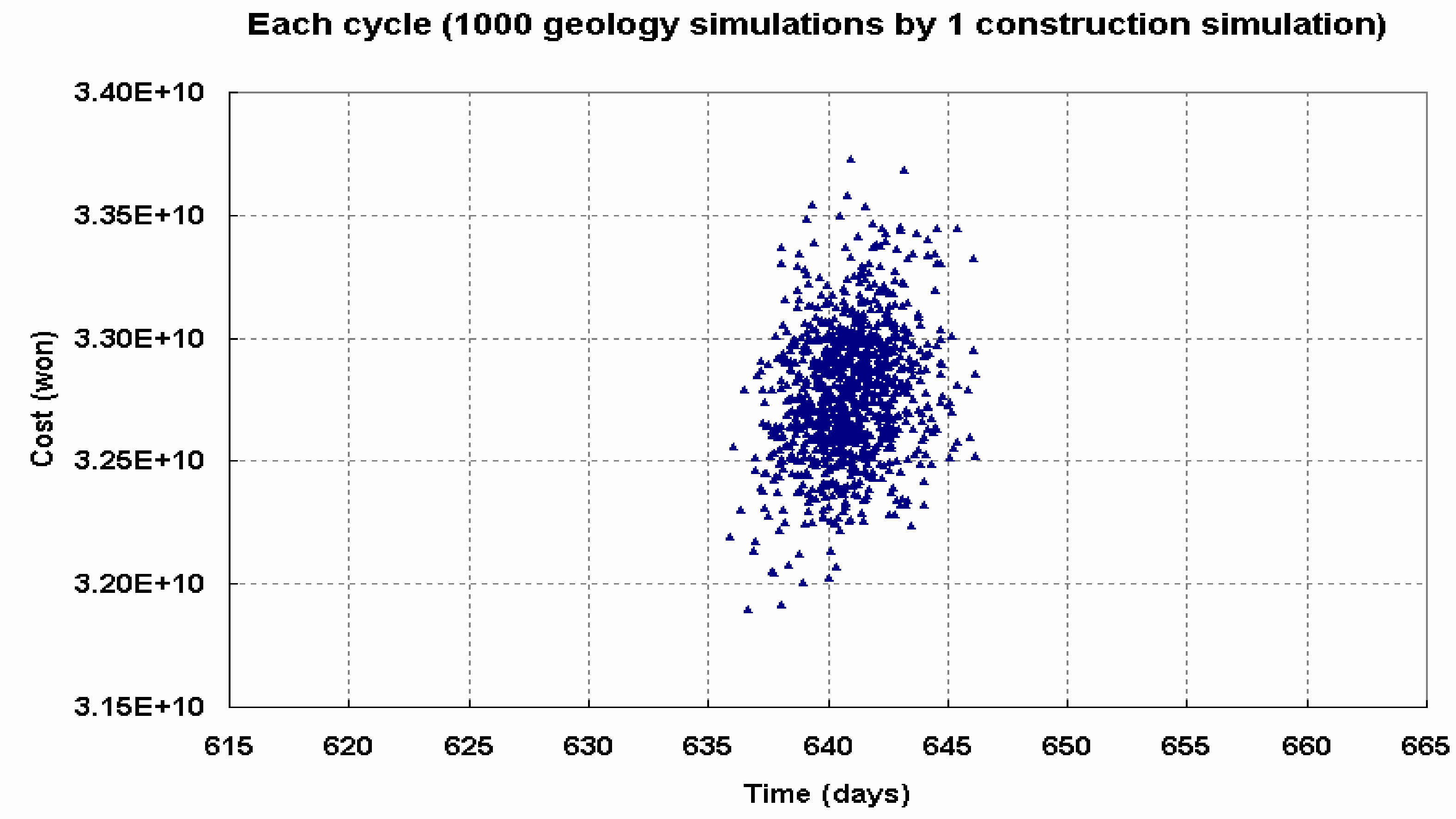
(Simulation using “one time” option: 1000 geology simulations by 1 construction simulation)



One time	Min	Mean	Max	Stdev	COV
Time	626	643	662	5.00	0.78%
Cost	32402069148	32745272485	33051437783	101471361	0.31%

Figure 21. Setting B

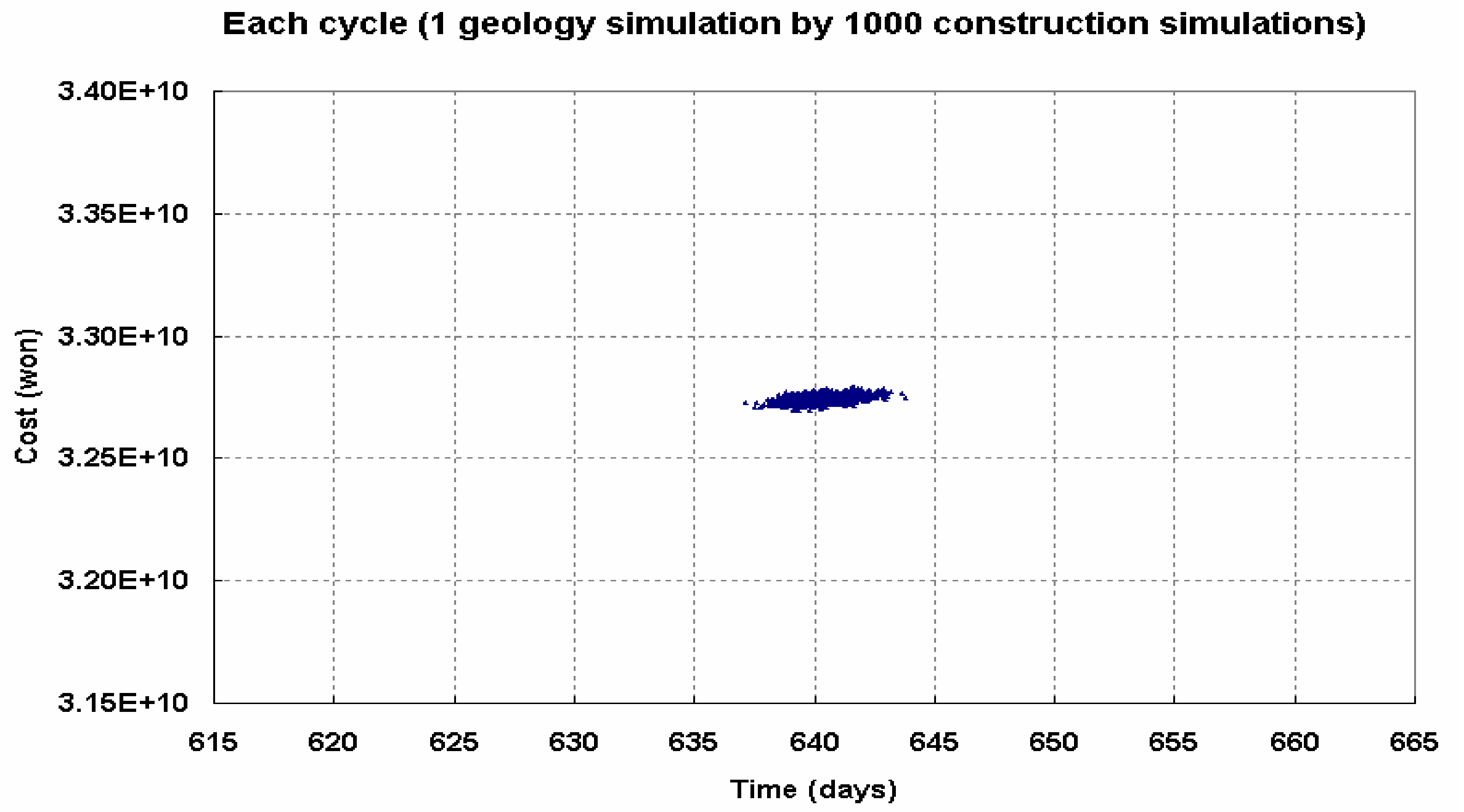
(Simulation using "one time" option: 1 geology simulation by 1000 construction simulations)



Each cycle	Min	Mean	Max	Stdev	COV
Time	636	641	646	1.74	0.27%
Cost	31898494106	32777438742	33732793964	270965857	0.83%

Figure 22. Setting C

(Simulation using "each cycle" option: 1000 geology simulations by 1 construction simulation)



Each cycle	Min	Mean	Max	Stdev	COV
Time	637	640	644	1.02	0.16%
Cost	32694100636	32744542595	32794522097	16195607	0.05%

Figure 23. Setting D

(Simulation using “each cycle” option: 1 geology simulation by 1000 construction simulations)

4-3. Analyses of the time-cost distributions of the Sucheon tunnel

In this section, time-cost distributions, which are obtained from the final simulation in study III, for each side of the main tunnel, the lining tunnel and the entire Sucheon tunnel will be examined separately.

4-3-1. Time-cost distributions of the left side of the main tunnel

Figure 25 and Figure 26 show the simulation results for the left side of the main tunnel ("part A" in Figure 17) in terms of the time-cost scattergrams, which show the results of multiple simulations (2500 simulation in this study; 50 geology simulations and 50 construction simulations) all in one graph (each time-cost pair from each simulation appears as a point on the graph). Tables below each figure show the total construction time and cost in terms of the minimum, mean, maximum, standard deviation and coefficient of variation.

Figure 25 shows two 2500 simulations runs with the "one time (long-term average)". This illustrates the time-cost scattergrams for the left side of the Dolsan tunnel and left side of the Soonchon tunnel in one graph.

As shown in Figure 25, the trend and distribution of the left side of the Dolsan tunnel (purple cloud) and the Soonchon tunnel (blue cloud) are slightly different from each other. The time-cost scattergram of the left side of the Soonchon tunnel (blue cloud) lies above and is shifted to the right of the scattergram for the left side of the Dolsan tunnel (purple cloud). This trend indicates that the total construction time and cost for the left side of the Soonchon tunnel is greater than those for the left side of the Dolsan tunnel. This is mainly because the left side of the Soonchon tunnel is 20 meters longer than the left side of the Dolsan tunnel.

Figure 26 shows that an imaginary case in which the left side of each tunnel has same length. Since the two parallel tunnels (the Soonchon and the Dolsan tunnel) are driven along the same geologic profiles, the time-cost scattergrams for the left side of each tunnel should be similar to each other.

However, as shown in Figure 26, they are slightly different even if the left side of each tunnel has the same length (the left side of the Soonchon tunnel has a lower mean construction time but greater mean construction cost compared to the left side of the Dolsan tunnel). This is due to the effect of the chemical plant. The construction methods, “patterns 2-1, 2-2 and 2-3” are applied to the specific section near the chemical plant of the left side of the Dolsan tunnel while “patterns 1, 2-1 and 3” are applied in this part of the left side of the Soonchon tunnel as shown in Figure 24.

As mentioned earlier, even if there is little effect of the chemical plant on the advance rates of the construction methods, “patterns 2-2 and 2-3” still have slightly lower advance rates than “patterns 1, 2-1 and 3” (see Table 9 in section 3-2-1). This leads to a greater total construction time for the left side of the Dolsan tunnel than that of the left side of the Soonchon tunnel. One of the reasons that the left side of the Soonchon tunnel still has a greater mean construction cost is that “pattern 3” is applied in this section of the Soonchon tunnel and it has a higher mean cost than “patterns 2-1 and 2-2”. All this explains why the left side of the two tunnels shows different distributions in this imaginary case (Figure 26).

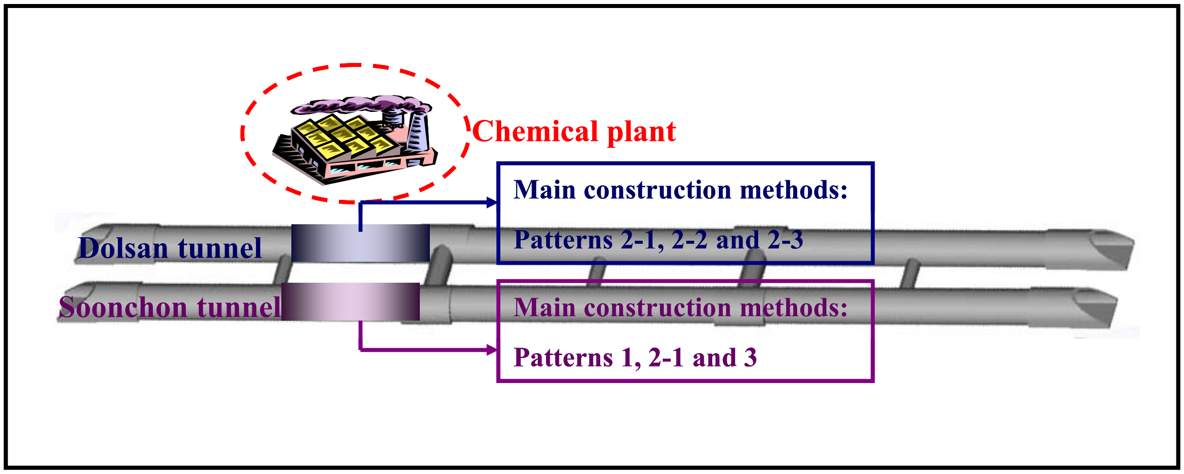
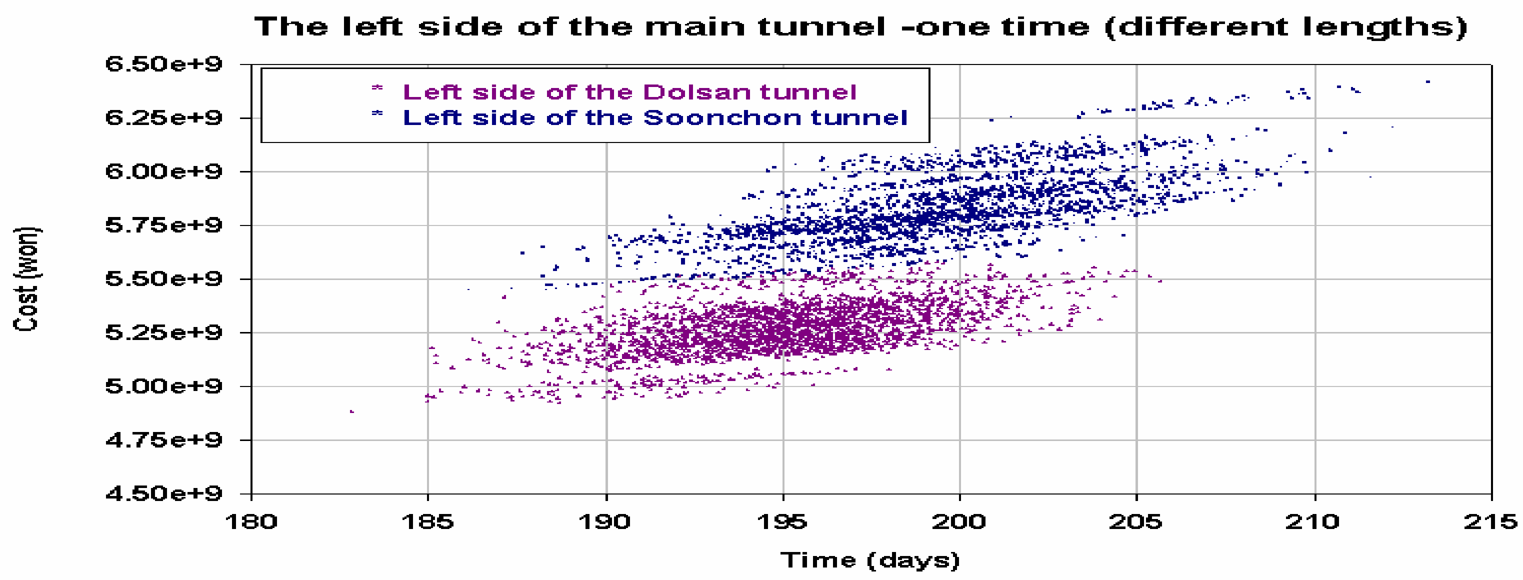


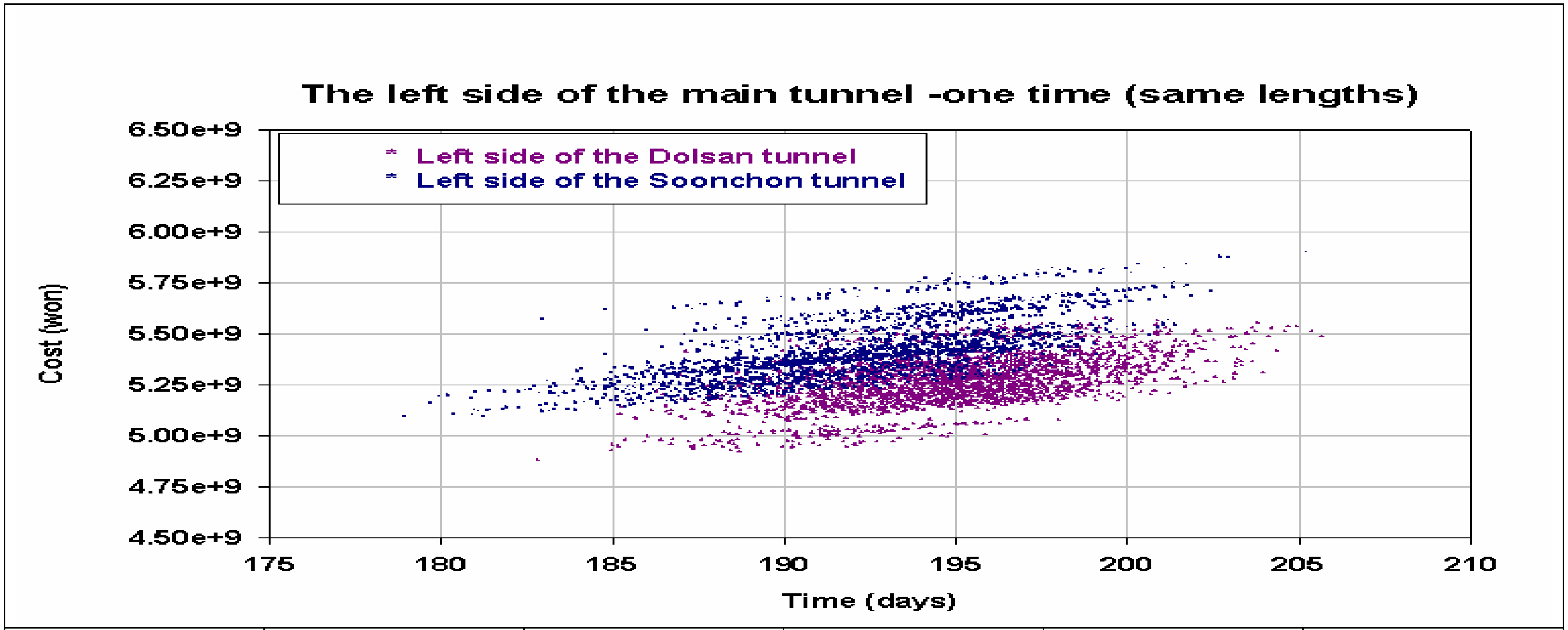
Figure 24. Construction methods applied to the specific part of the left side of the main tunnel

The trend of the time-cost scattergram shown in Figure 25 also shows that the total construction time is almost independent of the total construction cost. The main construction methods for the left side of the main tunnel are “patterns 1, 2, 2-1, 2-2, 2-3, 3 and 4”; “patterns 2-1, 2-2 and 2-3” have all same cost but different advance rates. This is one of the reasons why the trend of the time-cost scattergram of the left side of the main tunnel does not show that cost increases as time increases.



Left Soonchon	Min	Mean	Max	Stdev	COV
Time	186	200	214	3.97	1.99%
Cost	5448786281	5828714393	6417217502	163175841	2.80%
Left Dolsan	Min	Mean	Max	Stdev	COV
Time	183	195	206	3.39	1.74%
Cost	4884310885	5267690780	5577394887	118734150	2.25%

Figure 25. Time-cost scattergrams for the left side of the main tunnel using "one time" simulation



Left Soonchon	Min	Mean	Max	Stdev	COV
Time	179	192	206	3.79	1.97%
Cost	5091153670	5414547035	5902620723	142420465	2.63%
Left Dolsan	Min	Mean	Max	Stdev	COV
Time	183	195	206	3.39	1.74%
Cost	4884310885	5267690779	5577394887	118734150	2.25%

Figure 26. Time-cost scattergrams for the left side of the main tunnel using "one time" simulations (if two tunnels have same length

4-3-2. Time-cost distributions of the right side of the main tunnel

Figure 27 and Figure 28 show the simulation results for the right side of the main tunnel with time-cost scattergrams. Since the lining tunnels are connected to the right side of the main tunnel, the total construction time and cost for the right side of the main tunnel include the total construction time and cost for the lining tunnels.

Figure 27 shows two 2500 simulations run with the “one time” simulation illustrating the time-cost scattergrams for the right side of the Dolsan tunnel (purple cloud) and the right side of the Soonchon tunnel (blue cloud) in one graph.

As shown in Figure 27, the trend and distribution of the right side of the Dolsan tunnel and the Soonchon tunnel are very close to each other. Since the two tunnels are driven along the same geologic profiles and with the same tunnel geometries, the differences in the time-cost distributions between two tunnels only depend on the lengths of each tunnel.

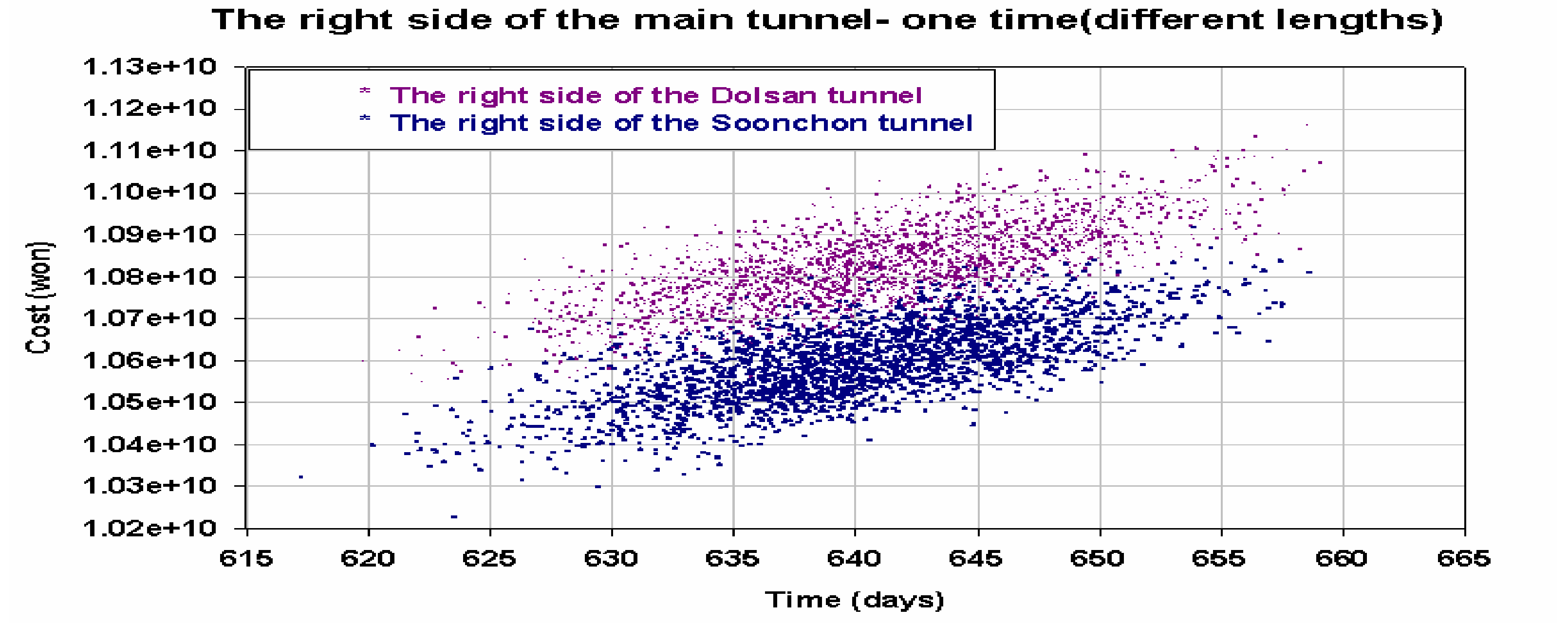
The time-cost scattergram of the right side of the Dolsan tunnel lies above and is slightly shifted to the right of the scattergram for the right side of the Soonchon tunnel because the right side of the Dolsan tunnel is 10 meters longer.

Figure 28 shows an imaginary case in which the right side of the two tunnels has the same length. As shown in Figure 28, the two scattergrams are almost identical.

From Figure 27 and Figure 28, one can conclude that the differences in the time-cost distribution between two tunnels only depend on the length differences between them.

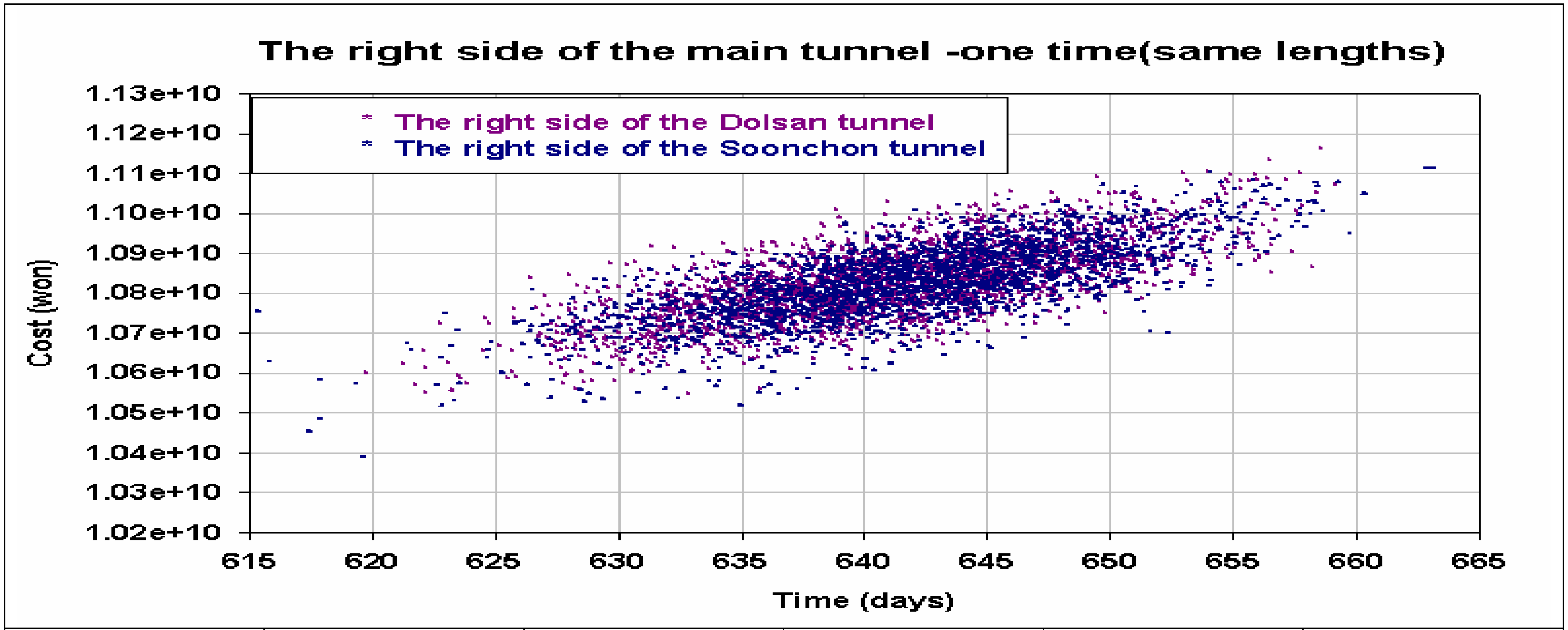
As already mentioned in section 4-1-2-2, if the cost-related variables and the time-related variables are inversely related to each other, the trend of time-cost scattergram is that the total construction time increases as the total construction cost increases.

Since the total construction time of the left side of the main tunnel is much smaller than that of the right side of the main tunnel, the total construction time of the entire tunnel, the Sucheon tunnel will be determined by the total construction time of the right side of the main tunnel and the lining tunnel.



Right Soonchon	Min	Mean	Max	Stdev	COV
Time	617	640	659	6.36	0.99%
Cost	10226345468	10595626386	10919607108	91951751	0.87%
Right Dolsan	Min	Mean	Max	Stdev	COV
Time	620	641	660	6.18	0.96%
Cost	10476053813	10831582899	11112393218	88965674	0.82%

Figure 27. Time-cost scattergrams for the right side of the main tunnel using “one time” simulation



Right Soonchon	Min	Mean	Max	Stdev	COV
Time	616	642	663	6.58	1.03%
Cost	10391860113	10827934082	11115516403	93660589	0.87%
Right Dolsan	Min	Mean	Max	Stdev	COV
Time	620	641	660	6.18	0.96%
Cost	10476053813	10831582899	11112393218	88965674	0.82%

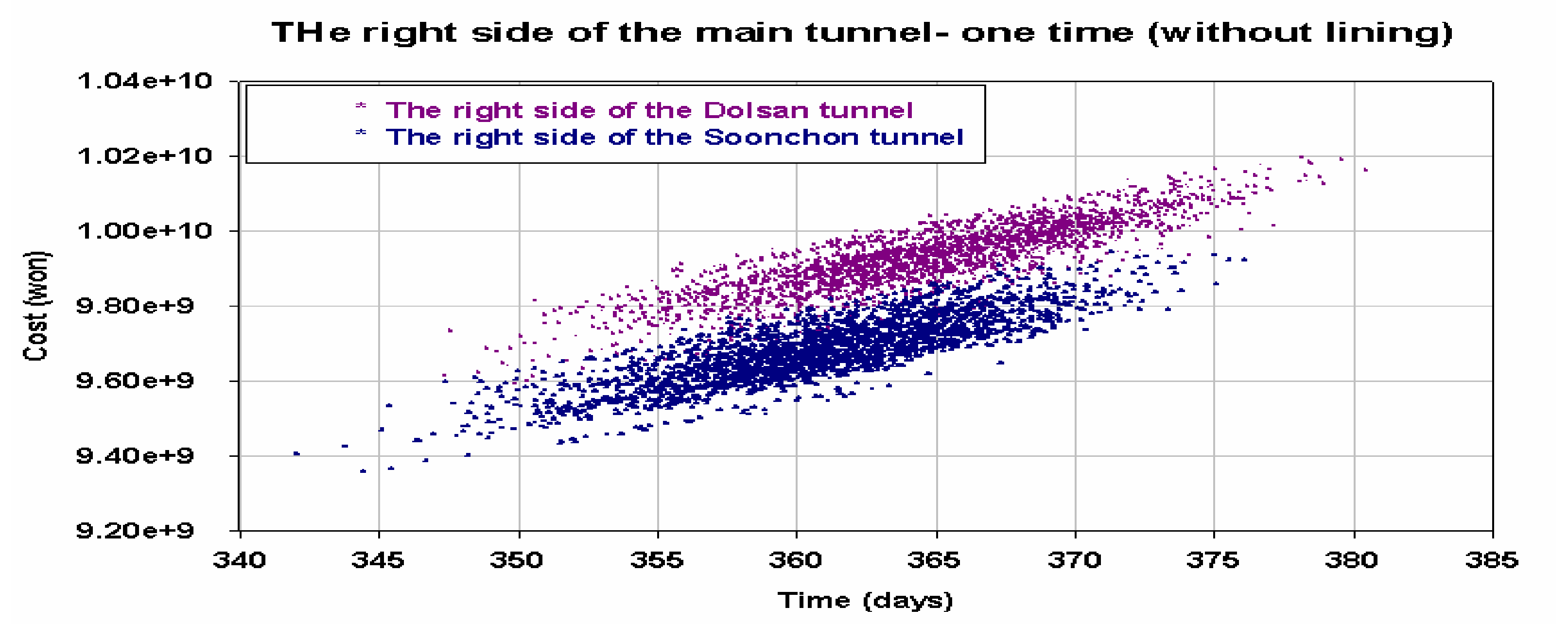
Figure 28. Time-cost scattergrams for the right side of the main tunnel using "one time" simulation (if two tunnels have the same length

4-3-3. Time-cost distributions of the lining tunnel

Figures 29 and 30 show the simulation result for the right side of the main tunnel without lining and the simulation result for the lining tunnel respectively. Differences in time-cost distribution between two simulations (purple cloud for the Dolsan tunnel and blue cloud for the Soonchon tunnel) in Figure 29 and Figure 30 are due to the length differences of the tunnels.

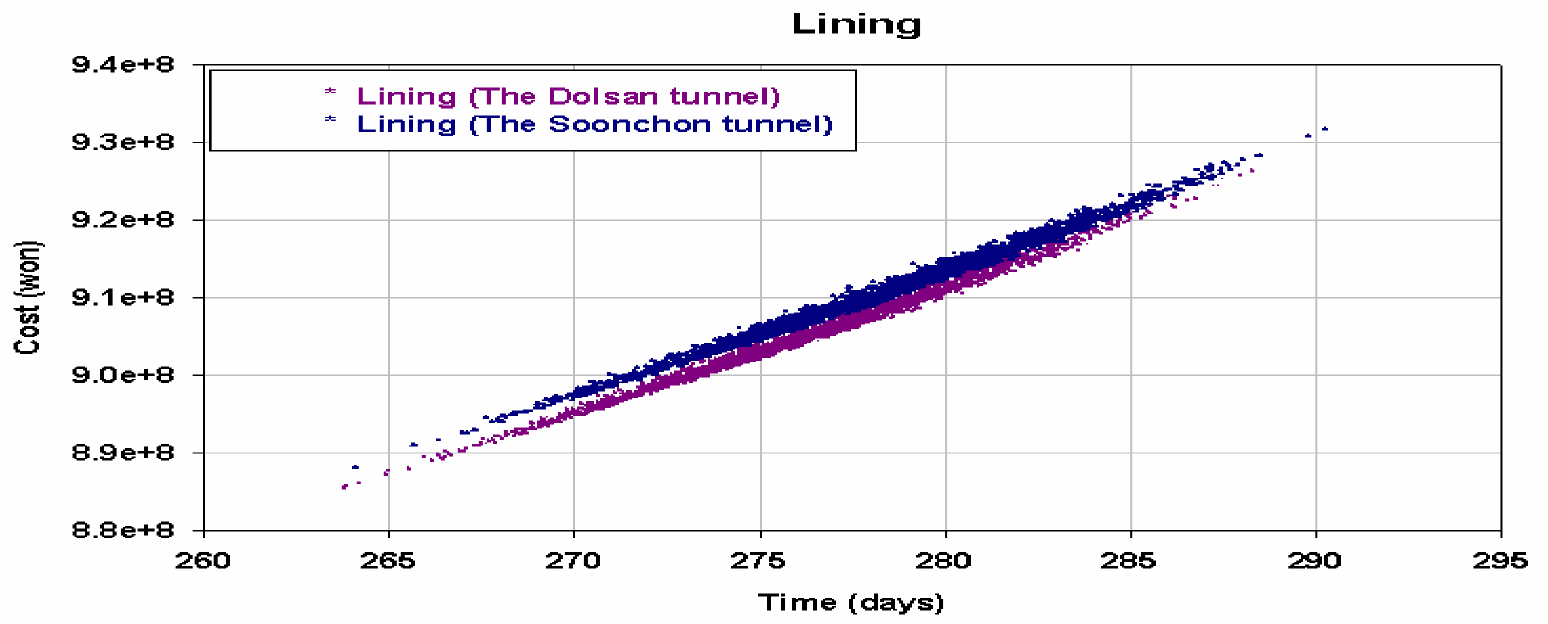
It is important to note that the lining method has a much higher advance rate than other construction methods (see Table 9 and notes) and as a result, the variations in advance rate (6.33 ~ 7.66 meter/day) for the lining are greater than those for other construction methods. Due to the greater variation in advance rate for the lining there is more uncertainty in the time distribution of the lining tunnel compared to that of cost-distribution as shown in Figure 30.

In addition, total construction time of the lining tunnel is almost half of the total construction time of the right side of the main tunnel (see tables below Figure 29 and Figure 30) but the total construction cost of the lining tunnel is a small portion of the total construction cost of the right side of the main tunnel. Considering the facts just mentioned, the higher uncertainty in the time distribution for the lining construction may cause the higher uncertainty in the total (tunnel + lining) time distribution for the right side of the main tunnel. This leads to the greater uncertainty on time distribution for the entire Sucheon tunnel.



Right Soonchon	Min	Mean	Max	Stdev	COV
Time	342	361	376	4.94	1.37%
Cost	9358760428	9682490359	9945395994	89129393	0.92%
Right Dolsan	Min	Mean	Max	Stdev	COV
Time	347	365	381	5.21	1.43%
Cost	9590384121	9925319598	10196379229	91241149	0.92%

Figure 29. Time-cost scattergrams for the right side of the main tunnel using “one time” simulation (without lining)



Soonchon lining	Min	Mean	Max	Stdev	COV
Time	264	278	290	3.94	1.42%
Cost	888032040	910382070	931686315	6508460	0.72%
Dolsan lining	Min	Mean	Max	Stdev	COV
Time	264	277	289	3.83	1.39%
Cost	885290062	905489439	926260443	6339050	0.70%

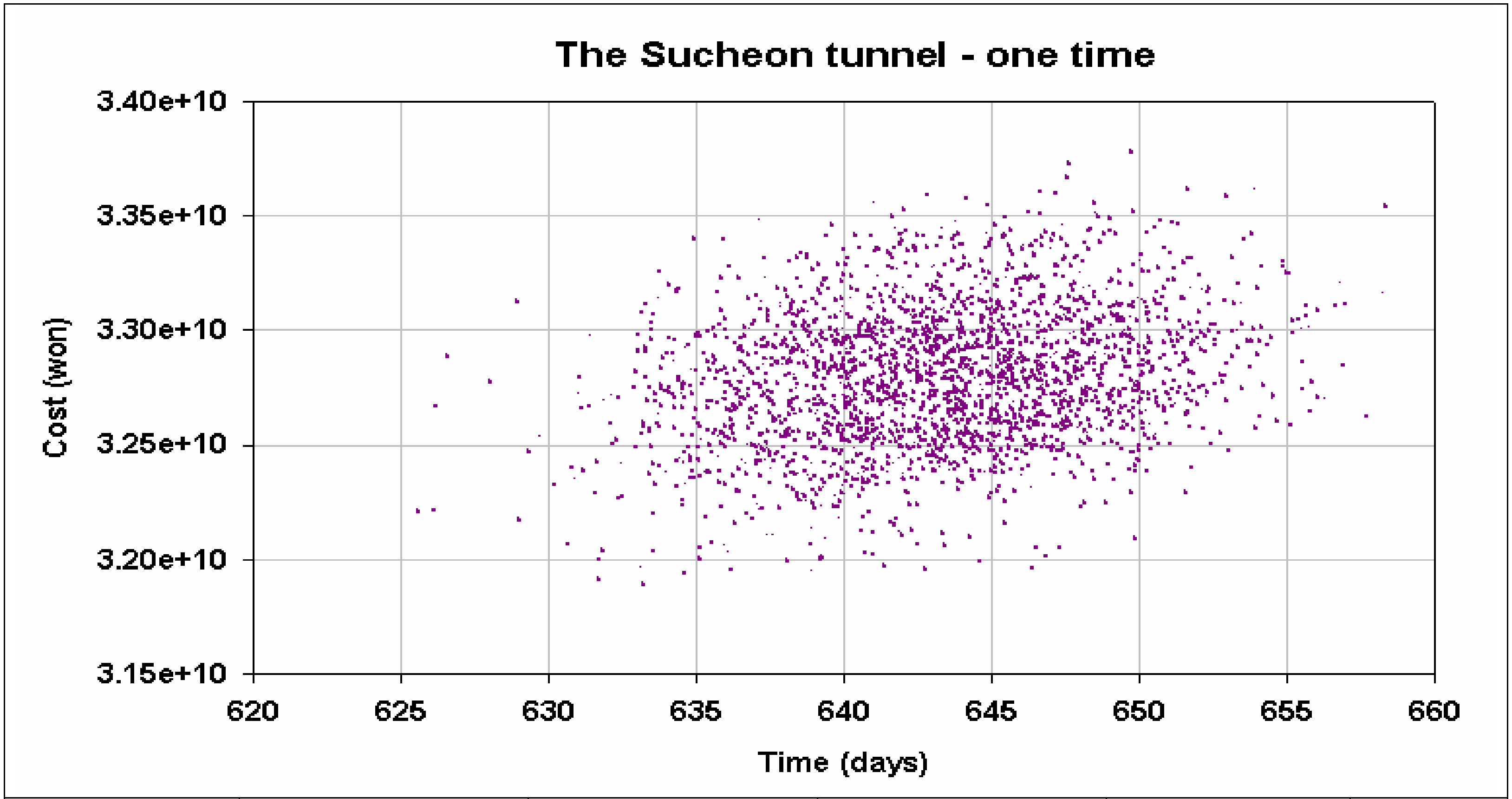
Figure 30. Time-cost scattergrams for lining tunnels using "one time" simulation

4-3-4. Time-cost distributions of the entire Sucheon tunnel

As mentioned in the previous sections, the total construction time of the Sucheon tunnel is determined only by the total construction time of the right side of the main tunnel. The construction of the crossover tunnels does not affect the total construction time of the Sucheon tunnel since the crossover tunnels are built together with the main tunnel. However, the total construction cost of the entire tunnel is affected by all tunnel components since costs are accumulated.

Figure 31 illustrates time-cost scattergram for the Sucheon tunnel for the “one time” simulation (50 geology simulations by 50 construction simulations).

The trend of the time-cost scattergram shown in Figure 31 does not show the distinct relation between time and cost. This is because the Sucheon tunnel is divided into two parts and each side of the main tunnel affects the time and cost distributions for the Sucheon tunnel differently; the right side of the main tunnel has a strong time-cost dependence in that the time increases with the cost, while for the left side of the main tunnel this relation is somewhat weaker. Very importantly, the uncertainty in the cost distribution for the entire Sucheon tunnel is affected by the uncertainties in the cost distributions of all tunnel components, while the uncertainty in the time distribution for the entire Sucheon tunnel is affected only by the right side of the main tunnel and the lining tunnel.



Sucheon tunnel	Min	Mean	Max	Stdev	COV
Time	626	643	659	5.02	0.78%
Cost	31886551409	32794643747	33776763220	295005594	0.90%

Figure 31. Time-cost scattergrams for the Sucheon tunnel using "one time" simulation

4-4. Time vs. position graphs

Figure 32 and Figure 33 are “time vs. position” graphs. Each line with a different color represents a sub-tunnel in the DAT tunnel network (see Appendix I). Even if the Sucheon tunnel consists of two parallel tunnels, each tunnel consists of many sub-tunnels considering excavation direction, application of different geometries to some specific areas, imaginary lining tunnels and crossover tunnels as well (refer to Appendix I).

The graphs in Figures 32 and 33 are obtained from the simulation using the “each cycle” and “one time” options, respectively. The “time vs. position” graph obtained from the simulation with the “one time” option (Figure 33) shows that there are greater uncertainties about time.

The reason why lines in the graphs are relatively straight is that the variation of the advance rates for each construction method is relatively small and differences in advance rates between the construction methods are small as well.

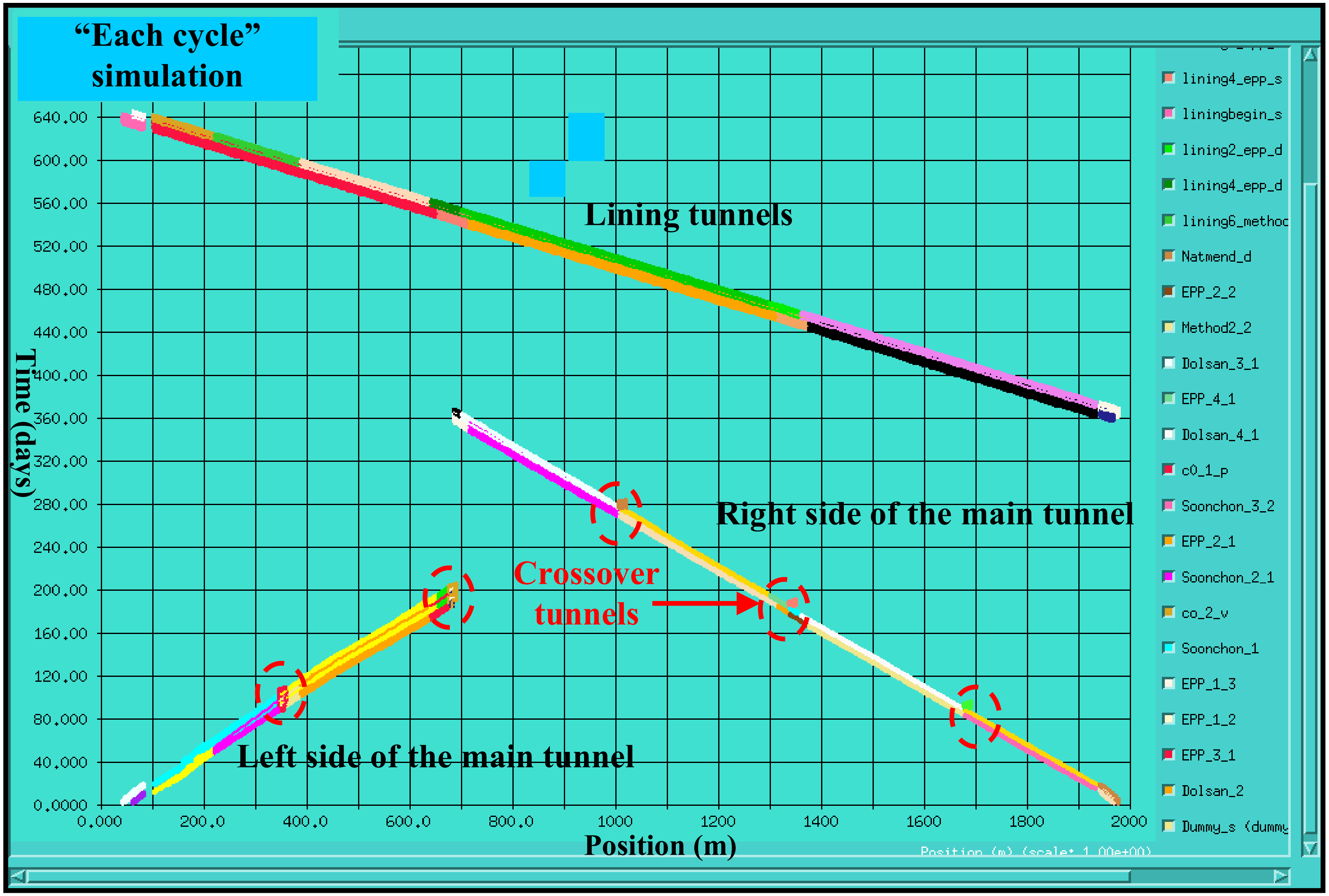


Figure 32. Time vs. position graph (simulation with "each cycle")

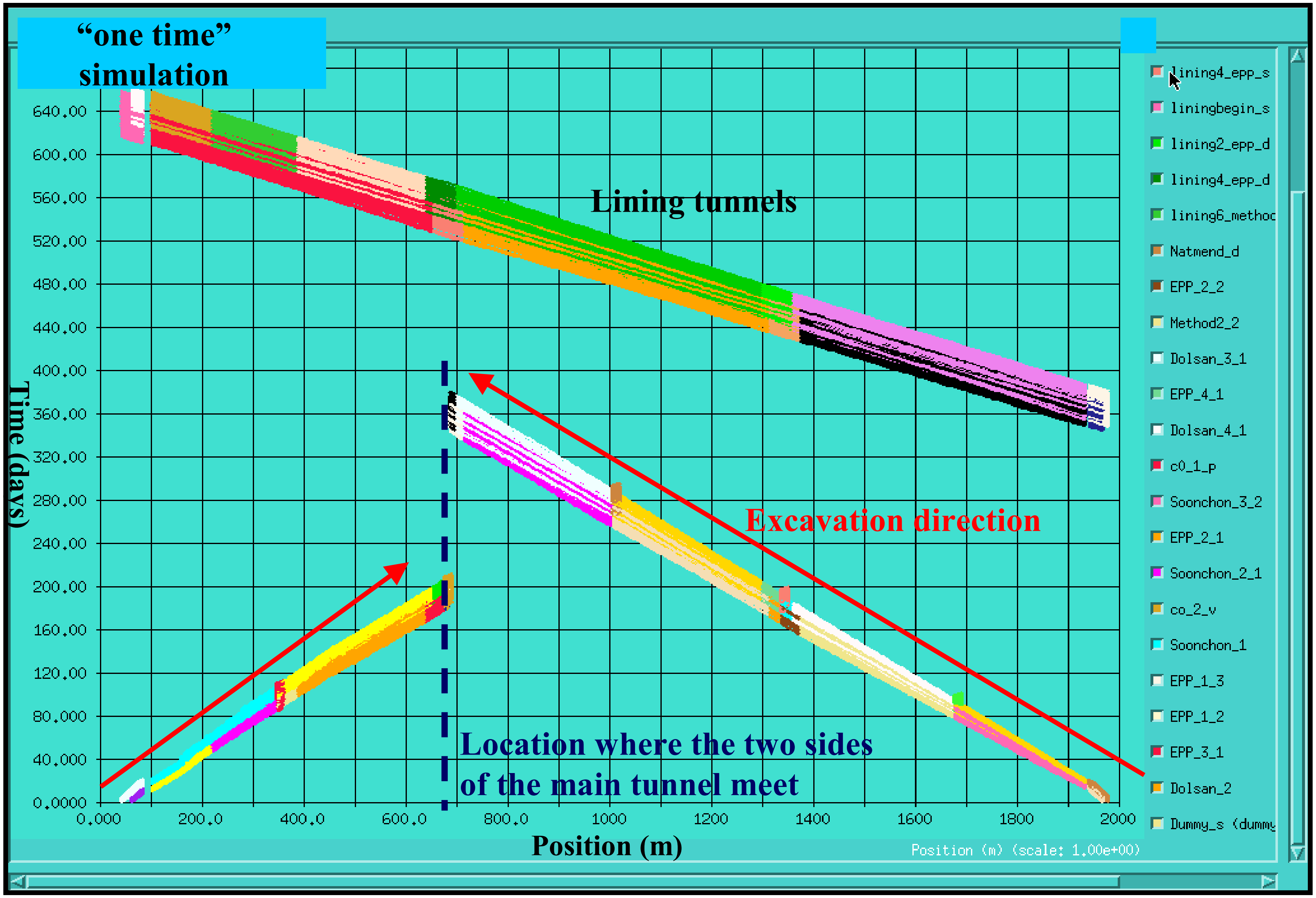


Figure 33. Time vs. position graph (simulation with "one time")

Chapter 5. Calendars

In this chapter, the development of the DAT to include calendars in SIMSUPER will be introduced. This includes the reasons for using calendars in SIMSUPER (the computer code of the DAT), the structure of the "calendars" and the way of defining calendar data.

5-1. Calendars in SIMSUPER

The basic concept of using calendars in SIMSUPER comes from the idea that one needs to not only estimate the duration of tunnel construction but also keep track of specific and real calendar dates. In particular, some activities cannot be performed on certain days (e.g. weekends) or they may depend on a crew that works during daytime only. Other situations in which the calendar dates need to be expressed include for example; during winter the working hours per unit working day could be reduced because of cold weather or when the blasting method is applied one may have to accommodate restrictions that one cannot blast during specific time intervals. Another simple example of the application of calendars is that one may need to define specific off-days, for example, public holidays when tunnel construction may not take place.

The usual way to take into account days-off and different working schedules (e.g. working hours/day) in the past simulations was to reduce excavation rate, which is not very realistic. By adopting real calendars in SIMSUPER, it is not necessary anymore to change the time-related variables, such as an advance rate. One can also specify when one starts and stops working on each activity during a unit working day (usually one day).

5-2. The structure of the “calendars”

The structure of the “calendars” consists first in a set of calendar data and second in the association between activities and a specific calendar. A calendar specifies the start and stop times for any activity associated with it. Figure 34 shows the structure of such a calendar. Shaded sections in Figure 34 (a) represent times when activities are on and white sections indicate time-off for the given activity. This information is specified in a calendar table as shown in Figure 34 (b).

For example, there are two activities, TBM and Drill & Blast in Figure 34. TBM will be performed 24 hours a day while Drill & Blast will only be performed 16 hours a day. As shown in Figure 34, TBM operations will go on for 7 days a week without a day off. On the other hand, Drill & Blast starts working at 8 AM and stops working at 24 AM Monday to Friday and will not work on Saturday and Sunday. Two tables (Figure 34 (b)) show how to define the corresponding calendars for simulations. Numbers shown in the calendar tables represent start times and stop times for a given activity. For example, the TBM activity will work from 0 (which represents Monday 0 AM) to 7 (Sunday 24 AM). Drill & Blast will be ‘off’ between 0 and 0.33 (Monday 8 AM), it will then be ‘on’ between 0.33 and 1 (Monday 24 AM).

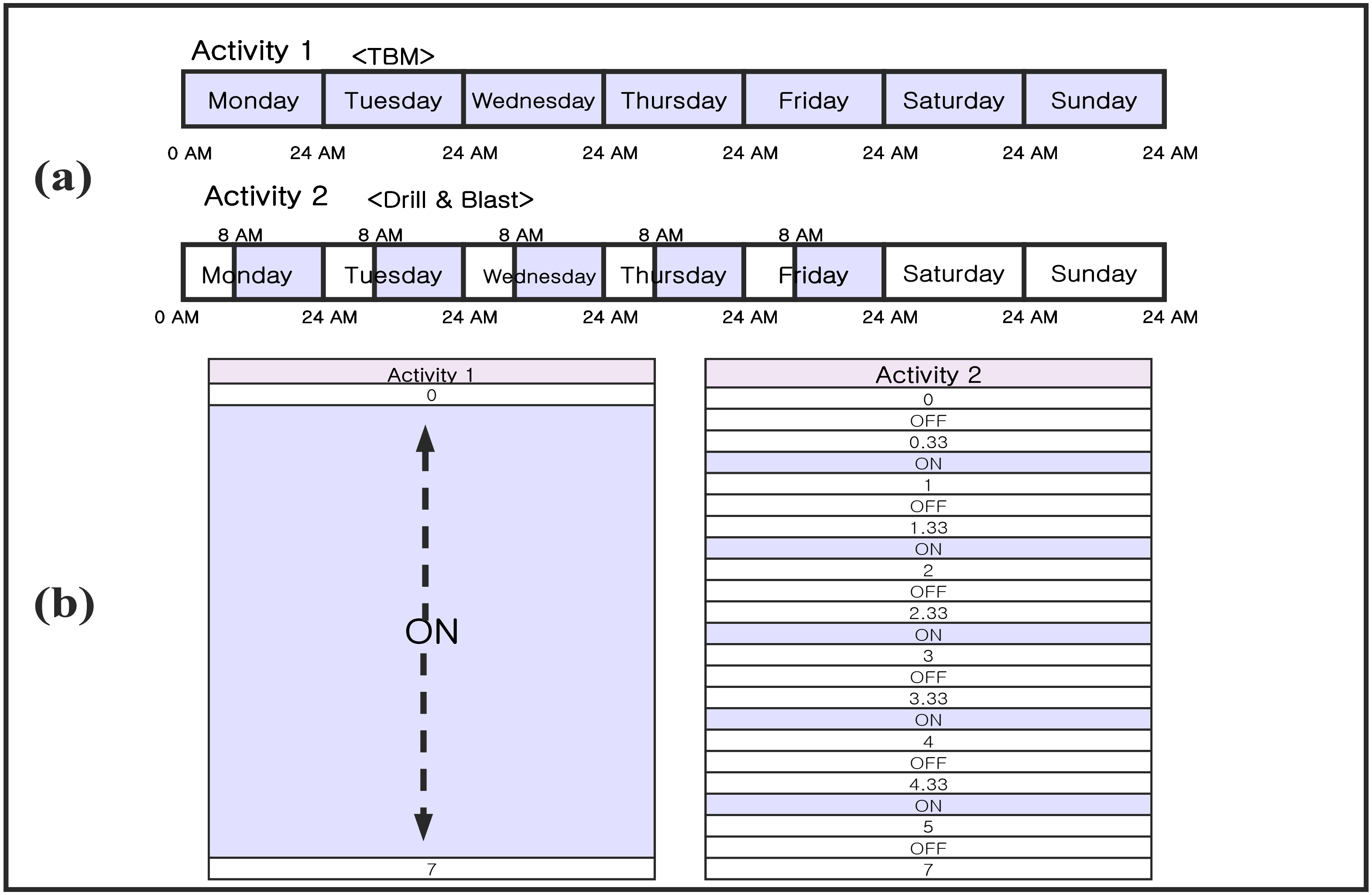


Figure 34. Structure of calendars

Since the total construction time can be obtained by defining time equations for each activity, calendar data need to be specified for each activity and one needs to specify which activity has which calendar data. Figure 35 shows how each activity is related to each set of calendar data. The example shown in Figure 35 indicates that activity 2 and activity n share the same calendar ("Calendar 1").

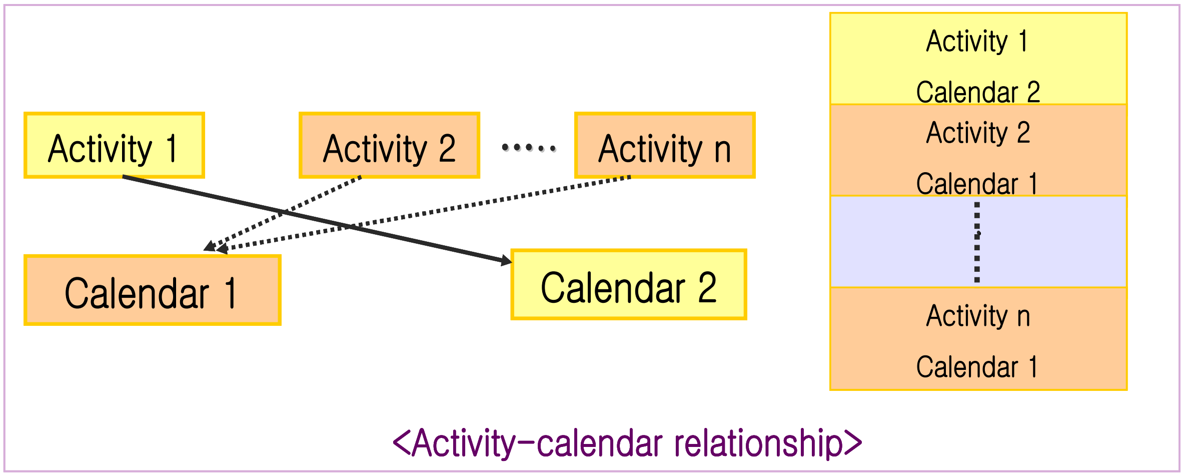


Figure 35. Relationship between calendars and activities

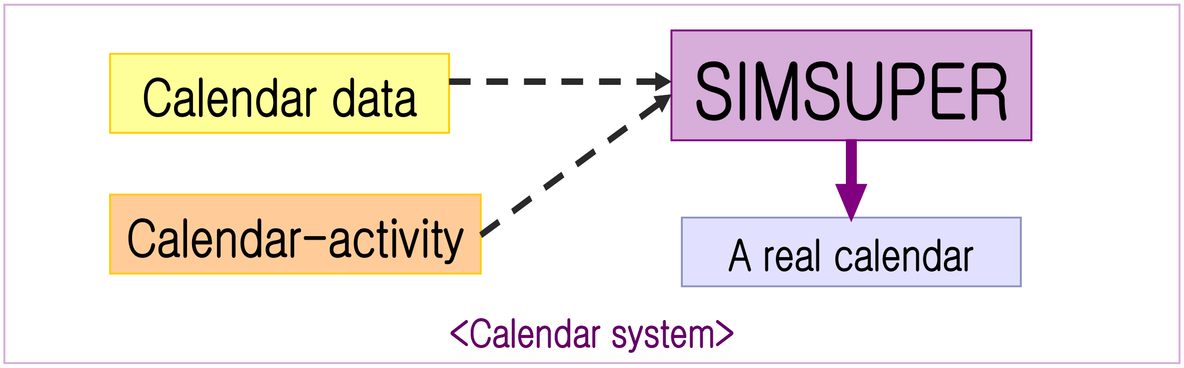


Figure 36. Calendar system

At the end, the results of simulations need to be transferred into a real calendar, which will give one the real dates for a given tunnel. The structure of the entire calendar system is shown in Figure 36.

5-3. Calendar entries

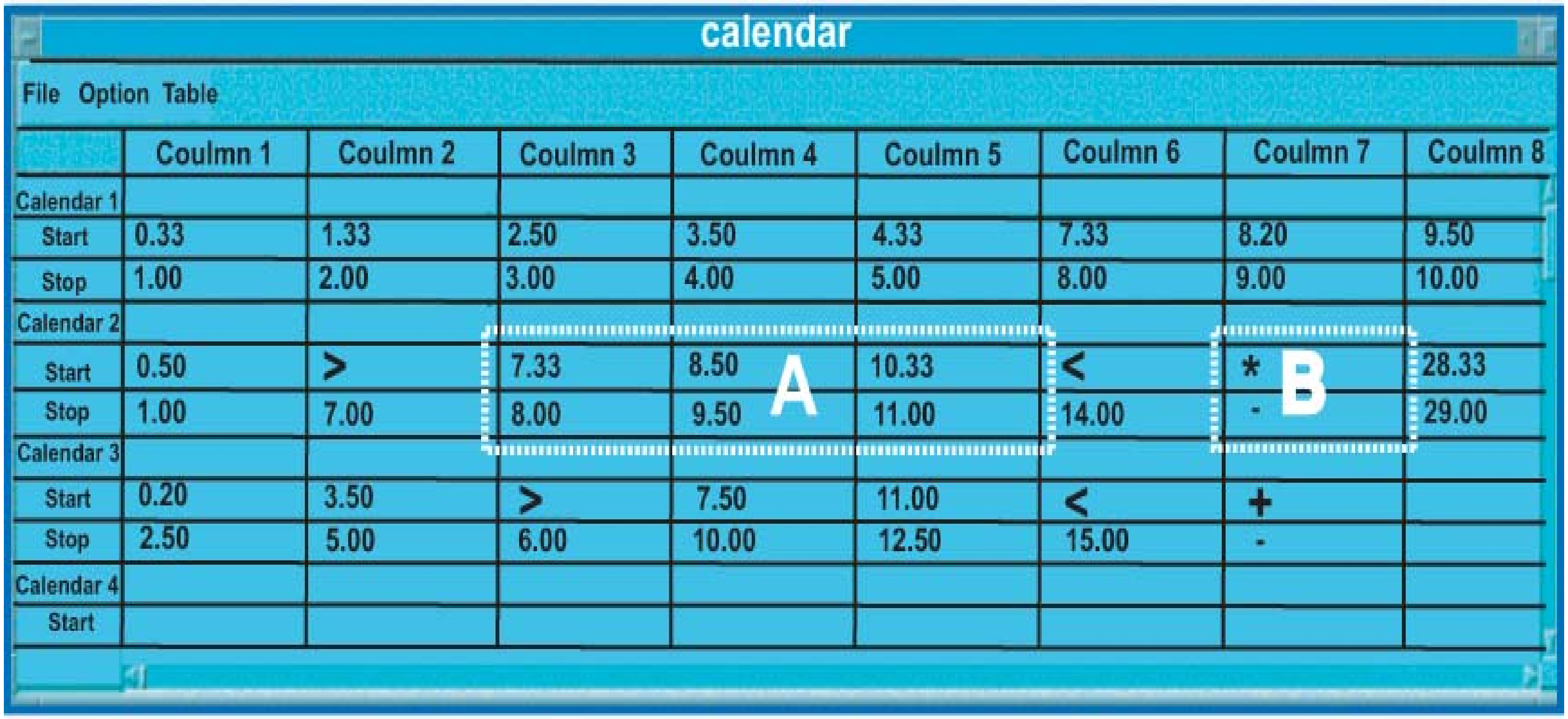
Users can define start and stop times directly in a calendar table as shown in Figure 37. The following four signs are used for defining calendar data in the calendar table. The user can use these signs to avoid defining the working schedules for the entire construction duration.

- *****: copies the data previously defined between ">" and "<".
- **>**: indicates where the calendar data to repeat begins
- **<**: indicates where the calendar data to repeat ends
- **+**: repeats the previously defined data between ">" and "<" until a given activity finishes

The typical way of input is done with the calendar spreadsheet shown in Figure 37. The start and stop times are expressed in decimal format. The way of inputting data can be understood with the following descriptions that include sets of different calendar data.

A unit time is one day for our example shown in Figure 37. The first column of "Calendar 1" shows that an activity starts at 0.33 unit day (Monday 1st, 8 AM) and stops at 1.00 unit day (Monday 1st, 24 AM or Tuesday 2nd, 0 AM). Then this activity will have time off between 1.00 (Tuesday 2nd, 0 AM) and 1.33 (Tuesday 2nd, 8 AM). The rest of the columns of "Calendar 1" are defined in the same way as in the first column; the activity will restart 1.33 (Tuesday 2nd, 8 AM) and stop 2.00 (Wednesday 3rd, 0 AM) and so on.

In this particular example, activities associated with this calendar (“Calendar 1”) will have the “weekend days-off” from 5.00 to 7.33 (from Saturday 6th, 0 AM to Monday 8th, 8 AM). The second example (“Calendar 2”) in Figure 37 shows the case in which an activity has repeated-calendar data. For this case, several symbols are used in order to input calendar data in an efficient way. For example, a column which contains “>/beginning date” indicates the beginning of the calendar date to repeat and a column which contains “<end date” represents the end of the calendar date to repeat. An asterisk, “*” copies the previously defined calendar data to repeat between two columns (“>/beginning date” and “</end date”). And the interval enclosed by two symbols (the “>” and the “<”) are copied as well. In “Calendar 2”, the second column “>/7.00” indicates that the data to repeat start at 7.00 (Monday 8th, 0 AM) and the sixth column indicates that the data to repeat end at 14.00 (Monday 15th, 0 AM). The area “A” (a white rectangle shown in Figure 37) is thus a set of values to repeat with a duration of seven days. The asterisk, “*” in column 7 indicates one repetition of the “A” (defined between “>/7.00” and “</14.00”) starting at 14.00 (Monday 15th, 0 AM). Hence, the asterisk actually represents a new area “B” (Figure 37) which defines the calendar data between “>/14.00” and “</21.00” which are a copy of the values of “A”. Each value in “B” is equal to the data of “A” plus the length or duration of “A” (7 days). The values of “B” will then be “14.33/15.00”, “15.50/16.50” and “17.33/18.00”.



	Coulmn 1	Coulmn 2	Coulmn 3	Coulmn 4	Coulmn 5	Coulmn 6	Coulmn 7	Coulmn 8
Calendar 1								
Start	0.33	1.33	2.50	3.50	4.33	7.33	8.20	9.50
Stop	1.00	2.00	3.00	4.00	5.00	8.00	9.00	10.00
Calendar 2								
Start	0.50	>	7.33	8.50	10.33	<	*	28.33
Stop	1.00	7.00	8.00	9.50	11.00	14.00	-	29.00
Calendar 3								
Start	0.20	3.50	>	7.50	11.00	<	+	
Stop	2.50	5.00	6.00	10.00	12.50	15.00	-	
Calendar 4								
Start								

Figure 37. Calendar input table

The last example (“Calendar 3”) shows the usage of the “+” sign. The “+” sign at the end of the calendar data (column 7) signifies that the program has to keep repeating the last defined calendar data between “>” and “<” (data between “>/6.00” and “</15.00” in “Calendar 3”) until every activity associated with this calendar (“Calendar 3”) finally stops. Since one doesn’t know when each activity finishes, it is not possible to know for how long calendar data have to be defined for a given activity. Therefore the “+” sign is used to not only repeat the last defined calendar data but also terminate every calendar.

For example, if a length of an activity associated with “Calendar 3” (Figure 37) is longer than 15 days, the program will repeat the previously defined calendar data between “>” and “<” (calendar data between the third and sixth columns) until this activity stops.

Every calendar must have a set of data to repeat and must end with a “+” to make sure every calendar finishes (“Calendar 1” and “Calendar 2” in Figure 37 also have to end with “+”, even if this is not shown).

Chapter 6. Conclusions and perspectives

Generally, the DAT can be applied to every tunnel situation and can deal with any condition regarding a particular tunnel. This thesis shows that the DAT can be successfully applied to the Sucheon tunnel project in Korea. Specifically, time-cost distributions and other results reflecting differences in tunnel construction were obtained. In this chapter, the conclusions drawn from this research are presented. Then some perspectives for the future research are developed.

6-1. Conclusions

In study I, the initial information was relatively limited and hence several assumptions regarding unknown data were made for the DAT simulation. Especially, since information on construction costs was not provided the tunnel construction simulation and the analyses of the results could be done only in terms of construction duration. In study I, several investigations were carried out considering several factors such as the effect of the chemical plant, the representation of the lining process and construction of five crossover tunnels.

In study II, additional information such as cost for each construction method, tunnel excavation directions and sequencing of tunnel construction were provided and hence some modifications of the input data were made. With this information, it was possible to obtain not only the construction time distribution but also the construction cost distribution. Due to the fact that the tunnel will be excavated from both ends and faster lining construction, the total construction time was considerably reduced compared to the total construction time obtained from study I.

In study III, there was some new information and feedback from the Korean client. The modification of input data for study III could be done relatively easily due to the previous work that included the preparation of the DAT in studies I and II. In study III, a few sensitivity- and parametric studies were also carried out through many simulations.

For the analyses of the simulation results, two major sources of uncertainty were examined in order to see how they contribute to the overall uncertainty in the time and cost distributions of the Sucheon tunnel.

The generated ground class profiles show that there is a high uncertainty in geology and this uncertainty in geology leads to a greater uncertainty in the cost distribution than in the time distribution. This is because the difference between costs of different construction methods is much greater than the difference between advance rates of different construction methods. On the other hand, uncertainty in the construction methods can lead to a greater uncertainty in the time distribution compared to the uncertainty in the cost distribution. This is so because the range of advance rates is greater than that for costs per length.

The distributions of the total construction time and cost for the Sucheon tunnel, the left and right sides of the main tunnel and the lining tunnel were examined separately.

Since the total construction time of the left side of the main tunnel is much smaller than that of the right side of the main tunnel, the total construction time and time distribution for the entire tunnel are governed by the right side of the main tunnel and the lining tunnel. However, the total construction cost and cost distribution for the entire tunnel is affected by all tunnel components (the left and right sides of the main tunnel, the lining tunnels and crossover tunnels).

The trend of the time-cost scattergrams for the Sucheon tunnel does not show a strong relation between time and cost. This is so because only the right side of the main tunnel has a strong time-cost dependence in that the time increases with the cost while this relation is weaker for the left side of the main tunnel.

From a practical point of view, applicability and suitability of the DAT to the real tunnel project in Korea are demonstrated. This study can be a model for future DAT applications and this will also lead and accelerate further applications of the DAT to other tunnel projects.

6-2. Critique and future extensions

Some further developments of the DAT are needed:

With the current version of SIMSUPER, construction methods are determined by a combination of the tunnel geometry and the ground class profiles. However, even if the Dolsan and the Sucheon tunnels have same geologic profiles and geometries, different construction methods are required to be applied to a specific part of each tunnel due to the existence of the chemical plant. The current model handles this situation by assigning a different “geometry” to each tunnel although the real geometry is the same. However, if new types of parameters, which can for instance represent the environmental effects on a given tunnel, are developed, one can directly consider the effect of external conditions on a given tunnel. The construction methods can then be determined by the combination of ground class, tunnel geometry and environmental parameters.

Generally, the most efficient way of the DAT application is when this tool is used in the design stage of tunnel construction. At this stage, tunnel simulations can be run considering different tunnel alignments and construction methods before the actual tunnel construction begins. The results of simulations can then be used for the tunnel design and construction management.

In addition, the usefulness and applicability of the DAT during tunnel construction needs to be further developed. The updating process and resource modeling can be approaches to do this.

The most critical issue for the application of the DAT during tunnel construction is to find a way by which the total construction cost could be cut down using DAT simulations. This promising future research should be closely studied.

Bibliography

1. Ang, Alfredo H-S.; Tang, Wilson H.; “Probability Concepts in Engineering Planning and Design”; John Wiley & Sons, Inc., 1975

2. Einstein, H.H.; Indermitte, C.A.; et al.; “Creating the Basis for Risk Assessment in Tunneling – The Decision Aids for Tunneling (DAT)”; Conference on Reducing Risk in Tunnel Design and Construction, Basel, Dec. 1988

3. Einstein, H.H.; “The Decision Aids for Tunnelling (DAT) – a Brief Review”; Korea Tunnelling Assoc., Vol. 3.

4. Haas, C.; “Updating in the Decision Aids for Tunneling”; M.Sc. Thesis submitted at the Massachusetts Institute of Technology, 1998

5. Halabe, V.B.; “Resource Modeling for DAT”; Ph.D. Thesis submitted at the Massachusetts Institute of Technology, 1995

6. Indermitte, C.A.; Einstein, H.H.; “Decision Aids for Tunneling, SIMSUPER (User’s Manual)”; Massachusetts Institute of Technology, Mar. 2000

7. Kollarou Christina; “Excavation Materials Handling in the Loetschberg Base Tunnel using Decision Aids for Tunneling (DAT)”; M.Sc. Thesis submitted at the Massachusetts Institute of Technology, 2000

8. Marzer C.; “Decision Aids for Tunneling: Development of the Resource Model (Final report)”; Massachusetts Institute of Technology, 2002

9. Sinfield, J. V.; Einstein, H.H.; “Evaluation of Tunneling Technology Using the Decision Aids for Tunneling”; Tunnelling and Underground Space Technology, Vol.11, No.4, 1996

Appendix (Input data for DAT simulations)

A. Definition of Areas and Zones

The “Area” is the uppermost level of the organization for input in geology. An “Area” is a linear domain and typically represents a part of the tunnel system. It consists of a set of consecutive “Zones”. The “Zone” is the basic unit of geology for input. A “Zone” is a geologic section in the “Area” and considered to be statistically homogeneous. It is related to a set of ground parameters and their probability of occurrence in the region. The geology of the Sucheon tunnel is divided into 8 “Areas”. The 8 areas in turn are subdivided into 23 zones considering geology. In this study, the extent of each zone is defined deterministically.

The lengths of each zone will be generated based either on the estimated zone length or on the estimated end point location (generation mode).

Area: **Begin**			Length of Area: 85.0		Parameter Set: None			
Zone #	Zone name	Generation mode	Pro. Min	Min	Mode	Max	Pro. Max	Parameter Set
0	**szbegin**	End position	0.00	65.0	65.0	65.0	0.00	0
1	**natmbegin**	End position	0.00	85.0	85.0	85.0	0.00	1
Area: **co1_p**			Length of Area: 18.2		Parameter Set: None			
Zone #	Zone name	Generation mode	Pro. Min	Min	Mode	Max	Pro. Max	Parameter Set
18	**co1_p**	End position	0.00	18.2	18.2	18.2	0.00	18

Area: **co2_p**			Length of Area: 17.6		Parameter Set: None			
Zone #	Zone name	Generation mode	Pro. Min	Min	Mode	Max	Pro. Max	Parameter Set
19	**co2_p**	End position	0.00	17.6	17.6	17.6	0.00	19
Area: **co3_p**			Length of Area: 18.2		Parameter Set: None			
Zone #	Zone name	Generation mode	Pro. Min	Min	Mode	Max	Pro. Max	Parameter Set
20	**co3_p**	End position	0.00	18.2	18.2	18.2	0.00	20
Area: **co4_p**			Length of Area: 17.6		Parameter Set: None			
Zone #	Zone name	Generation mode	Pro. Min	Min	Mode	Max	Pro. Max	Parameter Set
21	**co4_p**	End position	0.00	17.6	17.6	17.6	0.00	21
Area: **co5_p**			Length of Area: 18.2		Parameter Set: None			
Zone #	Zone name	Generation mode	Pro. Min	Min	Mode	Max	Pro. Max	Parameter Set
22	**co5_p**	End position	0.00	18.2	18.2	18.2	0.00	22
Area: **end**			Length of Area: 50.0		Parameter Set: None			
Zone #	Zone name	Generation mode	Pro. Min	Min	Mode	Max	Pro. Max	Parameter Set
17	**natmend**	End position	0.00	50.0	50.0	50.0	0.00	17

Area: **Soonchon-Dolsan**			Length of Area: 1,835.0		Parameter Set: None			
Zone #	Zone name	Generation mode	Pro. Min	Min	Mode	Max	Pro. Max	Parameter Set
2	**sz1**	End position	0.00	57.0	57.0	57.0	0.00	2
3	**sz2**	End position	0.00	97.0	97.0	97.0	0.00	3
4	**sz3**	End position	0.00	217.0	217.0	217.0	0.00	4
5	**sz4**	End position	0.00	258.0	258.0	258.0	0.00	5
6	**sz5**	End position	0.00	354.0	354.0	354.0	0.00	6
7	**sz6**	End position	0.00	458.0	458.0	458.0	0.00	7
8	**sz7**	End position	0.00	1,044.0	1,044.0	1,044.0	0.00	8
9	**sz8**	End position	0.00	1,150.0	1,150.0	1,150.0	0.00	9
10	**sz9**	End position	0.00	1,217.0	1,217.0	1,217.0	0.00	10
11	**sz10**	End position	0.00	1,384.0	1,384.0	1,384.0	0.00	11
12	**sz11**	End position	0.00	1,420.0	1,420.0	1,420.0	0.00	12
13	**sz12**	End position	0.00	1,494.0	1,494.0	1,494.0	0.00	13
14	**sz13**	End position	0.00	1,537.0	1,537.0	1,537.0	0.00	14
15	**sz14**	End position	0.00	1,647.0	1,647.0	1,647.0	0.00	15
16	**sz15**	End position	0.00	1,835.0	1,835.0	1,835.0	0.00	16

B. Input for Parameter Sets and Parameters

The parameters describe particular geologic conditions in a section (usually a zone) of the ground. A parameter has several parameter states. In this study, two parameters are defined namely “overburden” and “rock classification”.

Ground parameter sets are used to define the occurrence of parameters and parameter states, and their association with ground classes. They are usually associated with “Zones”. The generation mode consists of three options; Markov, Deterministic and semi-deterministic to determine the formation of segments. Details on these options will be explained in Appendices C and D. In this study, the parameter sets, which have “rock classification” as a ground parameter; are defined using the Markov mode and the parameter sets with “overburden” are defined using the Deterministic mode.

Starting probability has two options; “User input” and “Automatic”. The “User input” option allows one to specify explicitly the starting probability for each parameter state. If the “Automatic” option is used, the starting probability doesn’t need to be specified and the program automatically defines the starting probability of each parameter state based on the transition probabilities and length of each state.

Parameters	Parameter States
overburden	high low moderate
Rock classification	I II III IV V

Param. Set	**Parameter**	**generation mode**	**start. prob.**
0	**Rock classification**	Markov	Automatic
	overburden	Deterministic	User Input
1	**Rock classification**	Markov	Automatic
	overburden	Deterministic	User Input
2	**Rock classification**	Markov	Automatic
	overburden	Deterministic	User Input
3	**Rock classification**	Markov	Automatic
	overburden	Deterministic	User Input
4	**Rock classification**	Markov	Automatic
	overburden	Deterministic	User Input
5	**Rock classification**	Markov	Automatic
	overburden	Deterministic	User Input
6	**Rock classification**	Markov	Automatic
	overburden	Deterministic	User Input
7	**Rock classification**	Markov	Automatic
	overburden	Deterministic	User Input
8	**Rock classification**	Markov	Automatic
	overburden	Deterministic	User Input
9	**Rock classification**	Markov	Automatic
	overburden	Deterministic	User Input
10	**Rock classification**	Markov	Automatic
	overburden	Deterministic	User Input
11	**Rock classification**	Markov	Automatic
	overburden	Deterministic	User Input

Param. Set	**Parameter**	**generation mode**	**start. prob.**
12	**Rock classification**	Markov	Automatic
	overburden	Deterministic	User Input
13	**Rock classification**	Markov	Automatic
	overburden	Deterministic	User Input
14	**Rock classification**	Markov	Automatic
	overburden	Deterministic	User Input
15	**Rock classification**	Markov	Automatic
	overburden	Deterministic	User Input
16	**Rock classification**	Markov	Automatic
	overburden	Deterministic	User Input
17	**Rock classification**	Markov	Automatic
	overburden	Deterministic	User Input
18	**Rock classification**	Deterministic	User Input
	overburden	Deterministic	User Input
19	**Rock classification**	Deterministic	User Input
	overburden	Deterministic	User Input
20	**Rock classification**	Deterministic	User Input
	overburden	Deterministic	User Input
21	**Rock classification**	Deterministic	User Input
	overburden	Deterministic	User Input
22	**Rock classification**	Deterministic	User Input
	overburden	Deterministic	User Input

C. Input for Deterministic Generation Mode

The Deterministic mode allows one to deterministically specify the length and state of each segment.

Parameter Set: 0 **Parameter: overburden**

Deterministic Segments

parameter state	end position
low	65.0

Parameter Set: 1 **Parameter: overburden**

Deterministic Segments

parameter state	end position
low	85.0

Parameter Set: 2 **Parameter: overburden**

Deterministic Segments

parameter state	end position
low	57.0

Parameter Set: 3 **Parameter: overburden**

Deterministic Segments

parameter state	end position
low	97.0

Parameter Set: 4 **Parameter: overburden**

Deterministic Segments

parameter state	end position
low	217.0

Parameter Set: 5 Parameter: overburden

Deterministic Segments

parameter state	end position
low	258.0

Parameter Set: 6 Parameter: overburden

Deterministic Segments

parameter state	end position
moderate	354.0

Parameter Set: 7 Parameter: overburden

Deterministic Segments

parameter state	end position
moderate	458.0

Parameter Set: 8 Parameter: overburden

Deterministic Segments

parameter state	end position
high	1,044.0

Parameter Set: 9 Parameter: overburden

Deterministic Segments

parameter state	end position
high	1,150.0

Parameter Set: 10 Parameter: overburden

Deterministic Segments

parameter state	end position
high	1,217.0

Parameter Set: 11 Parameter: overburden

Deterministic Segments

parameter state	end position
moderate	1,384.0

Parameter Set: 12 **Parameter: overburden**

Deterministic Segments

parameter state	end position
moderate	1,420.0

Parameter Set: 13 **Parameter: overburden**

Deterministic Segments

parameter state	end position
moderate	1,494.0

Parameter Set: 14 **Parameter: overburden**

Deterministic Segments

parameter state	end position
moderate	1,537.0

Parameter Set: 15 **Parameter: overburden**

Deterministic Segments

parameter state	end position
moderate	1,647.0

Parameter Set: 16 **Parameter: overburden**

Deterministic Segments

parameter state	end position
low	1,835.0

Parameter Set: 17 **Parameter: overburden**

Deterministic Segments

parameter state	end position
low	50.0

Parameter Set: 18 **Parameter: Rock classification**

Deterministic Segments

parameter state	end position
II	18.2

Parameter Set: 18 Parameter: overburden

Deterministic Segments

parameter state	end position
low	18.2

Parameter Set: 19 Parameter: Rock classification

Deterministic Segments

parameter state	end position
I	17.6

Parameter Set: 19 Parameter: overburden

Deterministic Segments

parameter state	end position
high	17.6

Parameter Set: 20 Parameter: Rock classification

Deterministic Segments

parameter state	end position
II	18.2

Parameter Set: 20 Parameter: overburden

Deterministic Segments

parameter state	end position
high	18.2

Parameter Set: 21 Parameter: Rock classification

Deterministic Segments

parameter state	end position
I	17.6

Parameter Set: 21 Parameter: overburden

Deterministic Segments

parameter state	end position
moderate	17.6

Parameter Set: 22 **Parameter: Rock classification**

Deterministic Segments

parameter state	end position
II	18.2

Parameter Set: 22 **Parameter: overburden**

Deterministic Segments

parameter state	end position
moderate	18.2

D. Input for Markov Generation Mode

Markov mode indicates that the parameter states are probabilistically defined using the Markov process. This allows the program to generate certain parameters based on the estimated mean length and the transition probability. The transition probability describes the probability that any one parameter state becomes any of the other parameter states.

Parameter Set: 0 Parameter: Rock classification Start Prob**.: Automatic**

Mean Lengths	min	mode	max	start prob
I	10.0	10.0	10.0	0.00
II	10.0	10.0	10.0	0.00
III	0.0	0.0	0.0	0.00
IV	0.0	0.0	0.0	0.00
V	0.0	0.0	0.0	0.00

Transition Probabilities			from param. state	to param. state	prob
I	I	0.00	I	II	1.00
I	III	0.00	I	IV	0.00
I	V	0.00	II	I	1.00
II	II	0.00	II	III	0.00
II	IV	0.00	II	V	0.00
III	I	1.00	III	II	0.00
III	III	0.00	III	IV	0.00
III	V	0.00	IV	I	1.00
IV	II	0.00	IV	III	0.00
IV	IV	0.00	IV	V	0.00
V	I	1.00	V	II	0.00

V	III	0.00	V	IV	0.00
V	V	0.00			

Parameter Set: **1** **Parameter:** **Rock classification** Start Prob.: **Automatic**

Mean Lengths	min	mode	max	start prob
I	2.0	2.0	2.0	0.00
II	4.0	4.0	4.0	0.00
III	4.0	4.0	4.0	0.00
IV	0.0	0.0	0.0	0.00
V	0.0	0.0	0.0	0.00

Transition Probabilities			from param. state	to param. state	prob
I	I	0.00	I	II	0.66
I	III	0.34	I	IV	0.00
I	V	0.00	II	I	0.34
II	II	0.00	II	III	0.66
II	IV	0.00	II	V	0.00
III	I	0.34	III	II	0.66
III	III	0.00	III	IV	0.00
III	V	0.00	IV	I	1.00
IV	II	0.00	IV	III	0.00
IV	IV	0.00	IV	V	0.00
V	I	1.00	V	II	0.00
V	III	0.00	V	IV	0.00
V	V	0.00			

Parameter Set: 2 **Parameter:** **Rock classification** Start Prob.: **Atomatic**

Mean Lengths	min	mode	max	start prob
I	10.0	10.0	10.0	0.00
II	10.0	10.0	10.0	0.00
III	5.0	5.0	5.0	0.00
IV	0.0	0.0	0.0	0.00
V	0.0	0.0	0.0	0.00

Transition Probabilities			from param. state	to param. state	prob
I	I	0.00	I	II	0.66
I	III	0.34	I	IV	0.00
I	V	0.00	II	I	0.66
II	II	0.00	II	III	0.34
II	IV	0.00	II	V	0.00
III	I	0.34	III	II	0.66
III	III	0.00	III	IV	0.00
III	V	0.00	IV	I	1.00
IV	II	0.00	IV	III	0.00
IV	IV	0.00	IV	V	0.00
V	I	1.00	V	II	0.00
V	III	0.00	V	IV	0.00
V	V	0.00			

Parameter Set: **3** **Parameter: Rock classification** Start Prob.: **Automatic**

Mean Lengths	min	mode	max	start prob
I	0.0	0.0	0.0	0.00
II	0.0	0.0	0.0	0.00
III	10.0	10.0	10.0	0.00
IV	10.0	10.0	10.0	0.00
V	0.0	0.0	0.0	0.00

Transition Probabilities			from param. state	to param. state	prob
I	I	0.00	I	II	0.00
I	III	0.50	I	IV	0.50
I	V	0.00	II	I	1.00
II	II	0.00	II	III	0.00
II	IV	0.00	II	V	0.00
III	I	0.00	III	II	0.00
III	III	0.00	III	IV	1.00
III	V	0.00	IV	I	0.00
IV	II	0.00	IV	III	1.00
IV	IV	0.00	IV	V	0.00
V	I	1.00	V	II	0.00
V	III	0.00	V	IV	0.00
V	V	0.00			

Parameter Set: 4 **Parameter:** **Rock classification** Start Prob.: **Automatic**

Mean Lengths	min	mode	max	start prob
I	0.0	0.0	0.0	0.00
II	9.0	9.0	9.0	0.00
III	18.0	18.0	18.0	0.00
IV	3.0	3.0	3.0	0.00
V	0.0	0.0	0.0	0.00

Transition Probabilities			from param. state	to param. state	prob
I	I	0.00	I	II	1.00
I	III	0.00	I	IV	0.00
I	V	0.00	II	I	0.00
II	II	0.00	II	III	0.66
II	IV	0.34	II	V	0.00
III	I	0.00	III	II	0.66
III	III	0.00	III	IV	0.34
III	V	0.00	IV	I	0.00
IV	II	0.34	IV	III	0.66
IV	IV	0.00	IV	V	0.00
V	I	0.00	V	II	1.00
V	III	0.00	V	IV	0.00
V	V	0.00			

Parameter Set: 5 Parameter: Rock classification Start Prob.: **Automatic**

Mean Lengths	min	mode	max	start prob
I	3.0	3.0	3.0	0.00
II	3.0	3.0	3.0	0.00
III	7.0	7.0	7.0	0.00
IV	1.5	1.5	1.5	0.00
V	0.0	0.0	0.0	0.00

Transition Probabilities			from param. state	to param. state	prob
I	I	0.00	I	II	0.50
I	III	0.30	I	IV	0.20
I	V	0.00	II	I	0.30
II	II	0.00	II	III	0.50
II	IV	0.20	II	V	0.00
III	I	0.20	III	II	0.50
III	III	0.00	III	IV	0.30
III	V	0.00	IV	I	0.20
IV	II	0.30	IV	III	0.50
IV	IV	0.00	IV	V	0.00
V	I	0.00	V	II	1.00
V	III	0.00	V	IV	0.00
V	V	0.00			

Parameter Set: 6 **Parameter:** **Rock classification** Start Prob.: **Automatic**

Mean Lengths	min	mode	max	start prob
I	7.0	7.0	7.0	0.00
II	7.0	7.0	7.0	0.00
III	18.0	18.0	18.0	0.00
IV	3.0	3.0	3.0	0.00
V	0.0	0.0	0.0	0.00

Transition Probabilities			from param. state	to param. state	prob
I	I	0.00	I	II	0.50
I	III	0.30	I	IV	0.20
I	V	0.00	II	I	0.30
II	II	0.00	II	III	0.50
II	IV	0.20	II	V	0.00
III	I	0.20	III	II	0.50
III	III	0.00	III	IV	0.30
III	V	0.00	IV	I	0.20
IV	II	0.30	IV	III	0.50
IV	IV	0.00	IV	V	0.00
V	I	1.00	V	II	0.00
V	III	0.00	V	IV	0.00
V	V	0.00			

Parameter Set: 7 Parameter: Rock classification Start Prob.: **Automatic**

Mean Lengths	min	mode	max	start prob
I	8.0	8.0	8.0	0.00
II	6.0	6.0	6.0	0.00
III	2.0	2.0	2.0	0.00
IV	0.0	0.0	0.0	0.00
V	0.0	0.0	0.0	0.00

Transition Probabilities

			from param. state	to param. state	prob
I	I	0.00	I	II	0.66
I	III	0.34	I	IV	0.00
I	V	0.00	II	I	0.66
II	II	0.00	II	III	0.34
II	IV	0.00	II	V	0.00
III	I	0.34	III	II	0.66
III	III	0.00	III	IV	0.00
III	V	0.00	IV	I	1.00
IV	II	0.00	IV	III	0.00
IV	IV	0.00	IV	V	0.00
V	I	1.00	V	II	0.00
V	III	0.00	V	IV	0.00
V	V	0.00			

Parameter Set: 8 **Parameter:** **Rock classification** Start Prob.: **Automatic**

Mean Lengths	min	mode	max	start prob
I	43.0	43.0	43.0	0.00
II	35.0	35.0	35.0	0.00
III	9.0	9.0	9.0	0.00
IV	0.0	0.0	0.0	0.00
V	0.0	0.0	0.0	0.00

Transition Probabilities			from param. state	to param. state	prob
I	I	0.00	I	II	0.66
I	III	0.34	I	IV	0.00
I	V	0.00	II	I	0.66
II	II	0.00	II	III	0.34
II	IV	0.00	II	V	0.00
III	I	0.34	III	II	0.66
III	III	0.00	III	IV	0.00
III	V	0.00	IV	I	1.00
IV	II	0.00	IV	III	0.00
IV	IV	0.00	IV	V	0.00
V	I	1.00	V	II	0.00
V	III	0.00	V	IV	0.00
V	V	0.00			

Parameter Set: 9 **Parameter: Rock classification** Start Prob.: **Automatic**

Mean Lengths	min	mode	max	start prob
I	20.0	20.0	20.0	0.00
II	20.0	20.0	20.0	0.00
III	0.0	0.0	0.0	0.00
IV	0.0	0.0	0.0	0.00
V	0.0	0.0	0.0	0.00

Transition Probabilities			from param. state	to param. state	prob
I	I	0.00	I	II	1.00
I	III	0.00	I	IV	0.00
I	V	0.00	II	I	1.00
II	II	0.00	II	III	0.00
II	IV	0.00	II	V	0.00
III	I	1.00	III	II	0.00
III	III	0.00	III	IV	0.00
III	V	0.00	IV	I	1.00
IV	II	0.00	IV	III	0.00
IV	IV	0.00	IV	V	0.00
V	I	1.00	V	II	0.00
V	III	0.00	V	IV	0.00
V	V	0.00			

Parameter Set: 10	**Parameter:**	**Rock classification**	Start Prob.:	**Automatic**

Mean Lengths	min	mode	max	start prob
I	12.0	12.0	12.0	0.00
II	12.0	12.0	12.0	0.00
III	0.0	0.0	0.0	0.00
IV	0.0	0.0	0.0	0.00
V	0.0	0.0	0.0	0.00

Transition Probabilities			from param. state	to param. state	prob
I	I	0.00	I	II	1.00
I	III	0.00	I	IV	0.00
I	V	0.00	II	I	1.00
II	II	0.00	II	III	0.00
II	IV	0.00	II	V	0.00
III	I	1.00	III	II	0.00
III	III	0.00	III	IV	0.00
III	V	0.00	IV	I	1.00
IV	II	0.00	IV	III	0.00
IV	IV	0.00	IV	V	0.00
V	I	1.00	V	II	0.00
V	III	0.00	V	IV	0.00
V	V	0.00			

Parameter Set: **11** **Parameter: Rock classification** Start Prob.: **Automatic**

Mean Lengths	min	mode	max	start prob
I	25.0	25.0	25.0	0.00
II	25.0	25.0	25.0	0.00
III	0.0	0.0	0.0	0.00
IV	0.0	0.0	0.0	0.00
V	0.0	0.0	0.0	0.00

Transition Probabilities			from param. state	to param. state	prob
I	I	0.00	I	II	1.00
I	III	0.00	I	IV	0.00
I	V	0.00	II	I	1.00
II	II	0.00	II	III	0.00
II	IV	0.00	II	V	0.00
III	I	1.00	III	II	0.00
III	III	0.00	III	IV	0.00
III	V	0.00	IV	I	1.00
IV	II	0.00	IV	III	0.00
IV	IV	0.00	IV	V	0.00
V	I	1.00	V	II	0.00
V	III	0.00	V	IV	0.00
V	V	0.00			

Parameter Set: 12 **Parameter:** **Rock classification** Start Prob.: **Automatic**

Mean Lengths	min	mode	max	start prob
I	12.0	12.0	12.0	0.00
II	3.0	3.0	3.0	0.00
III	0.0	0.0	0.0	0.00
IV	0.0	0.0	0.0	0.00
V	0.0	0.0	0.0	0.00

Transition Probabilities			from param. state	to param. state	prob
I	I	0.00	I	II	1.00
I	III	0.00	I	IV	0.00
I	V	0.00	II	I	1.00
II	II	0.00	II	III	0.00
II	IV	0.00	II	V	0.00
III	I	1.00	III	II	0.00
III	III	0.00	III	IV	0.00
III	V	0.00	IV	I	1.00
IV	II	0.00	IV	III	0.00
IV	IV	0.00	IV	V	0.00
V	I	1.00	V	II	0.00
V	III	0.00	V	IV	0.00
V	V	0.00			

Parameter Set: 13 Parameter: Rock classification Start Prob.: **Automatic**

Mean Lengths	min	mode	max	start prob
I	2.0	2.0	2.0	0.00
II	16.0	16.0	16.0	0.00
III	2.0	2.0	2.0	0.00
IV	0.0	0.0	0.0	0.00
V	0.0	0.0	0.0	0.00

Transition Probabilities

			from param. state	to param. state	prob
I	I	0.00	I	II	0.66
I	III	0.34	I	IV	0.00
I	V	0.00	II	I	0.66
II	II	0.00	II	III	0.34
II	IV	0.00	II	V	0.00
III	I	0.34	III	II	0.66
III	III	0.00	III	IV	0.00
III	V	0.00	IV	I	1.00
IV	II	0.00	IV	III	0.00
IV	IV	0.00	IV	V	0.00
V	I	1.00	V	II	0.00
V	III	0.00	V	IV	0.00
V	V	0.00			

Parameter Set: 14 **Parameter:** **Rock classification** Start Prob.: **Automatic**

Mean Lengths	min	mode	max	start prob
I	3.0	3.0	3.0	0.00
II	12.0	12.0	12.0	0.00
III	0.0	0.0	0.0	0.00
IV	0.0	0.0	0.0	0.00
V	0.0	0.0	0.0	0.00

Transition Probabilities			from param. state	to param. state	prob
I	I	0.00	I	II	1.00
I	III	0.00	I	IV	0.00
I	V	0.00	II	I	1.00
II	II	0.00	II	III	0.00
II	IV	0.00	II	V	0.00
III	I	1.00	III	II	0.00
III	III	0.00	III	IV	0.00
III	V	0.00	IV	I	1.00
IV	II	0.00	IV	III	0.00
IV	IV	0.00	IV	V	0.00
V	I	1.00	V	II	0.00
V	III	0.00	V	IV	0.00
V	V	0.00			

Parameter Set: 15 Parameter: Rock classification Start Prob.: **Automatic**

Mean Lengths	min	mode	max	start prob
I	10.0	10.0	10.0	0.00
II	5.0	5.0	5.0	0.00
III	0.0	0.0	0.0	0.00
IV	0.0	0.0	0.0	0.00
V	0.0	0.0	0.0	0.00

Transition Probabilities			from param. state	to param. state	prob
I	I	0.00	I	II	1.00
I	III	0.00	I	IV	0.00
I	V	0.00	II	I	1.00
II	II	0.00	II	III	0.00
II	IV	0.00	II	V	0.00
III	I	1.00	III	II	0.00
III	III	0.00	III	IV	0.00
III	V	0.00	IV	I	1.00
IV	II	0.00	IV	III	0.00
IV	IV	0.00	IV	V	0.00
V	I	1.00	V	II	0.00
V	III	0.00	V	IV	0.00
V	V	0.00			

Parameter Set: 16 **Parameter:** **Rock classification** Start Prob.: **Automatic**

Mean Lengths	min	mode	max	start prob
I	40.0	40.0	40.0	0.00
II	7.0	7.0	7.0	0.00
III	0.0	0.0	0.0	0.00
IV	0.0	0.0	0.0	0.00
V	0.0	0.0	0.0	0.00

Transition Probabilities			from param. state	to param. state	prob
I	I	0.00	I	II	1.00
I	III	0.00	I	IV	0.00
I	V	0.00	II	I	1.00
II	II	0.00	II	III	0.00
II	IV	0.00	II	V	0.00
III	I	1.00	III	II	0.00
III	III	0.00	III	IV	0.00
III	V	0.00	IV	I	1.00
IV	II	0.00	IV	III	0.00
IV	IV	0.00	IV	V	0.00
V	I	1.00	V	II	0.00
V	III	0.00	V	IV	0.00
V	V	0.00			

Parameter Set: **17** **Parameter: Rock classification** Start Prob.: **Automatic**

Mean Lengths	min	mode	max	start prob
I	3.0	3.0	3.0	0.00
II	5.0	5.0	5.0	0.00
III	10.0	10.0	10.0	0.00
IV	0.0	0.0	0.0	0.00
V	0.0	0.0	0.0	0.00

Transition Probabilities			from param. state	to param. state	prob
I	I	0.00	I	II	0.66
I	III	0.34	I	IV	0.00
I	V	0.00	II	I	0.34
II	II	0.00	II	III	0.66
II	IV	0.00	II	V	0.00
III	I	0.34	III	II	0.66
III	III	0.00	III	IV	0.00
III	V	0.00	IV	I	1.00
IV	II	0.00	IV	III	0.00
IV	IV	0.00	IV	V	0.00
V	I	1.00	V	II	0.00
V	III	0.00	V	IV	0.00
V	V	0.00			

E. Ground Class Distributions

The ground classes describe the ground conditions along the tunnel and are a particular combination of the parameter states. These ground classes will ultimately be used to determine the construction methods used to construct a tunnel (details on the selection of the construction methods will be explained in Appendix F).

One can obtain the ground class distributions from the geologic simulations. The tables below show the possible percentages of ground classes in each "Zone". The percentage is given with a min, mean, max and standard deviation.

Zone 1 (szbegin)

	min	mean	max	std.dev
Length	65	65	65	0
L-I	25.00%	45.83%	75.00%	16.9
L-II	25.00%	54.17%	75.00%	16.9

Zone 2 (natmbegin)

	min	mean	max	std.dev
Length	20	20	20	0
L-I	0.00%	15.50%	50.00%	16.41
L-II	2.50%	50.00%	72.50%	19.9
L-III	15.00%	34.50%	80.00%	19.99

Zone 3 (sz1)

	min	mean	max	std.dev
Length	57	57	57	0
L-I	22.73%	48.64%	79.55%	18.35
L-II	11.36%	32.27%	61.36%	15.37
L-III	0.00%	19.09%	56.82%	17.22

Zone 4 (sz2)

	min	mean	max	std.dev
Length	40	40	40	0
L-III	25.00%	50.62%	75.00%	16.52
L-IV	25.00%	49.38%	75.00%	16.52

Zone 5 (sz3)

	min	mean	max	std.dev
Length	120	120	120	0
L-II	16.25%	30.88%	44.38%	8.84
L-III	50.00%	61.88%	74.38%	6.88
L-IV	0.00%	7.25%	10.00%	3.16

Zone 6 (sz4)

	min	mean	max	std.dev
Length	41	41	41	0
L-I	0.00%	11.02%	35.19%	12.24
L-II	5.56%	30.28%	49.07%	14.51
L-III	20.37%	53.61%	82.41%	19.79
L-IV	0.00%	5.09%	12.04%	4.75

Zone 7 (sz5)

	min	mean	max	std.dev
Length	96	96	96	0
M-I	0.78%	20.08%	43.75%	15.57
M-II	0.00%	25.23%	67.19%	19.96
M-III	13.28%	48.36%	85.16%	23.89
M-IV	0.00%	6.33%	10.94%	3.89

Zone 8 (sz6)

	min	mean	max	std.dev
Length	104	104	104	0
M-I	15.38%	44.86%	64.90%	15.17
M-II	21.63%	44.18%	72.12%	14.33
M-III	5.29%	10.96%	21.63%	4.67

Zone 9 (sz7)

	min	mean	max	std.dev
Length	586	586	586	0
H-I	23.46%	47.46%	63.85%	11.34
H-II	33.85%	47.15%	73.08%	10.25
H-III	1.54%	5.38%	15.77%	4.58

Zone 10 (sz8)

	min	mean	max	std.dev
Length	106	106	106	0
H-I	5.00%	43.00%	85.00%	23.94
H-II	15.00%	57.00%	95.00%	23.94

Zone 11 (sz9)

	min	mean	max	std.dev
Length	67	67	67	0
H-I	35.00%	64.50%	90.00%	17.39
H-II	10.00%	35.50%	65.00%	17.39

Zone 12 (sz10)

	min	mean	max	std.dev
Length	167	167	167	0
M-I	4.17%	47.08%	87.50%	25.23
M-II	12.50%	52.92%	95.83%	25.23

Zone 13 (sz11)

	min	mean	max	std.dev
Length	36	36	36	0
M-I	45.83%	79.37%	100.00%	14.35
M-II	0.00%	20.63%	54.17%	14.35

Zone 14 (sz12)

	min	mean	max	std.dev
Length	74	74	74	0
M-I	3.38%	11.15%	23.65%	6.46
M-II	75.00%	81.55%	89.86%	5.36
M-III	0.68%	7.30%	20.27%	6.86

Zone 15 (sz13)

	min	mean	max	std.dev
Length	43	43	43	0
M-I	7.14%	13.39%	26.79%	6.95
M-II	73.21%	86.61%	92.86%	6.95

Zone 16 (sz14)

	min	mean	max	std.dev
Length	110	110	110	0
M-I	54.55%	66.36%	76.14%	7.05
M-II	23.86%	33.64%	45.45%	7.05

Zone 17 (sz15)

	min	mean	max	std.dev
Length	188	188	188	0
L-I	57.69%	82.40%	99.04%	12.42
L-II	0.96%	17.60%	42.31%	12.42

Zone 18 (natmend)

	min	mean	max	std.dev
Length	50	50	50	0
L-I	0.00%	10.78%	18.75%	5.68
L-II	9.38%	27.97%	54.69%	14.33
L-III	39.06%	61.25%	78.12%	14.43

Zone 19 (co1_p)

	min	mean	max	std.dev
Length	18.2	18.2	18.2	0
L-II		100.00%		0

Zone 20 (co2_v)

	min	mean	max	std.dev
Length	17.6	17.6	17.6	0
H-I		100.00%		0

Zone 21 (co3_p)

	min	mean	max	std.dev
Length	18.2	18.2	18.2	0
H-II		100.00%		0

Zone 22 (co4_v)

	min	mean	max	std.dev
Length	17.6	17.6	17.6	0
M-I		100.00%		0

Zone 23 (co5_p)

	min	mean	max	std.dev
Length	18.2	18.2	18.2	0
M-II		100.00%		0

F. Association of Geometries, Ground Classes and Methods

A specific construction method is defined for each combination of ground class and tunnel geometry. It is possible to probabilistically specify the construction methods so that each combination of ground class and tunnel geometry can be associated with more than one construction method. (e.g. the “patterns 2-1, 2-2 and 2-3 are defined for combinations of one of the ground classes “L-I ~L-V and M-I ~ M-V” and tunnel geometry 3 by the probabilities of 0.22, 0.32 and 0.46 respectively.)

Ground class	Methods	Prob.
Geometry: 0		
L-I	pattern 4	1.00
L-II	pattern 5	1.00
L-III	pattern 6	1.00
L-IV	pattern 6	1.00
Geometry: 1		
L-I	pattern 1	1.00
L-II	pattern 2	1.00
L-III	pattern 3	1.00
L-IV	pattern 4	1.00
L-V	pattern 4	1.00
M-I	pattern 1	1.00
M-II	pattern 2	1.00
M-III	pattern 3	1.00
M-IV	pattern 4	1.00
M-V	pattern 4	1.00
H-I	pattern 1	1.00
H-II	pattern 2	1.00
H-III	pattern 3	1.00
H-IV	pattern 3	1.00
H-V	pattern 3	1.00

Ground class	**Methods**	**Prob.**
Geometry: 2		
L-I	lining_1	1.00
L-II	lining_2	1.00
L-III	lining_3	1.00
L-IV	lining_4	1.00
L-V	lining_4	1.00
M-I	lining_1	1.00
M-II	lining_2	1.00
M-III	lining_3	1.00
M-IV	lining_4	1.00
M-V	lining_4	1.00
H-I	lining_1	1.00
H-II	lining_2	1.00
H-III	lining_3	1.00
H-IV	lining_3	1.00
H-V	lining_3	1.00

Ground class	**Methods**	**Prob.**
Geometry:	**3**	
L-I	pattern 2-1	0.22
	pattern 2-2	0.32
	pattern 2-3	0.46
L-II	pattern 2-1	0.22
	pattern 2-2	0.32
	pattern 2-3	0.46
L-III	pattern 2-1	0.22
	pattern 2-2	0.32
	pattern 2-3	0.46
L-IV	pattern 2-1	0.22
	pattern 2-2	0.32
	pattern 2-3	0.46
L-V	pattern 2-1	0.22
	pattern 2-2	0.32
	pattern 2-3	0.46
M-I	pattern 2-1	0.22
	pattern 2-2	0.32
	pattern 2-3	0.46

M-II	pattern 2-1	0.22
	pattern 2-2	0.32
	pattern 2-3	0.46
M-III	pattern 2-1	0.22
	pattern 2-2	0.32
	pattern 2-3	0.46
M-IV	pattern 2-1	0.22
	pattern 2-2	0.32
	pattern 2-3	0.46
M-V	pattern 2-1	0.22
	pattern 2-2	0.32
	pattern 2-3	0.46

Ground class	**Methods**	**Prob.**
Geometry:	**4**	
L-I	pattern EPP	1.00
L-II	pattern EPP	1.00
L-III	pattern EPP	1.00
L-IV	pattern EPP	1.00
L-V	pattern EPP	1.00
M-I	pattern EPP	1.00
M-II	pattern EPP	1.00
M-III	pattern EPP	1.00
M-IV	pattern EPP	1.00
M-V	pattern EPP	1.00
H-I	pattern EPP	1.00
H-II	pattern EPP	1.00
H-III	pattern EPP	1.00
H-IV	pattern EPP	1.00
H-V	pattern EPP	1.00

Ground class	Methods	Prob.
Geometry: 5		
L-I	crossover_v	1.00
L-II	crossover_v	1.00
M-I	crossover_v	1.00
M-II	crossover_v	1.00
H-I	crossover_v	1.00
H-II	crossover_v	1.00

Ground class	Methods	Prob.
Geometry: 6		
L-I	lining_2	1.00
L-II	lining_2	1.00
L-III	lining_2	1.00
L-IV	lining_2	1.00
L-V	lining_2	1.00
M-I	lining_2	1.00
M-II	lining_2	1.00
M-III	lining_2	1.00
M-IV	lining_2	1.00
M-V	lining_2	1.00

Ground class	Methods	Prob.
Geometry: 7		
M-I	lining_EPP	1.00
M-II	lining_EPP	1.00
M-III	lining_EPP	1.00
M-IV	lining_EPP	1.00
M-V	lining_EPP	1.00
H-I	lining_EPP	1.00
H-II	lining_EPP	1.00
H-III	lining_EPP	1.00
H-IV	lining_EPP	1.00
H-V	lining_EPP	1.00

Ground class	Methods	Prob.
Geometry: 8		
L-I	crossover_p	1.00
L-II	crossover_p	1.00
M-I	crossover_p	1.00
M-II	crossover_p	1.00
H-I	crossover_p	1.00
H-II	crossover_p	1.00

Ground class	Methods	Prob.
Geometry: 9		
L-I	lining_4	1.00
L-II	lining_5	1.00
L-III	lining_6	1.00
L-IV	lining_6	1.00

G. Definition of Methods

For each construction method, information on the cycle length, method variables, correlation of the method variables and "heading and bench" needs to be specified. The cycle length is the length of tunnel that is excavated in one operation. Method variables such as "advance rate" and "cost" for each construction method can be defined probabilistically. The interaction between multiple headings can be specified by defining the cycle lengths of each heading and the minimum/ maximum distance between headings.

Method name: Pattern 1							
Headings			**Cycle length**				
Number	Min. distance	Max. distance	Pro. min	Min	Mode	Max.	Pro. max
Heading 1	0.0	0.0	0.0	3.50	3.50	3.50	0.0

Variables					
Name	Pro. min	Min	Mode	Max.	Pro. max
adv_rate	0.0	3.42	3.60	4.14	0.0
cost	0.0	6505608.50	6848009.00	7190409.50	0.0

<table>
<tr><th colspan="8">Method name: Pattern 2</th></tr>
<tr><th colspan="3">Headings</th><th colspan="5">Cycle length</th></tr>
<tr><td>Number</td><td>Min. distance</td><td>Max. distance</td><td>Pro. min</td><td>Min</td><td>Mode</td><td>Max.</td><td>Pro. max</td></tr>
<tr><td>Heading 1</td><td>0.0</td><td>0.0</td><td>0.0</td><td>3.50</td><td>3.50</td><td>3.50</td><td>0.0</td></tr>
<tr><th colspan="8">Variables</th></tr>
<tr><td>Name</td><td>Pro. min</td><td>Min</td><td>Mode</td><td>Max.</td><td>Pro. max</td></tr>
<tr><td>adv_rate</td><td>0.0</td><td>3.33</td><td>3.51</td><td>4.04</td><td>0.0</td></tr>
<tr><td>cost</td><td>0.0</td><td>7191885.00</td><td>7570405.00</td><td>7948925.00</td><td>0.0</td></tr>
</table>

<table>
<tr><th colspan="8">Method name: Pattern 2-1</th></tr>
<tr><th colspan="3">Headings</th><th colspan="5">Cycle length</th></tr>
<tr><td>Number</td><td>Min. distance</td><td>Max. distance</td><td>Pro. min</td><td>Min</td><td>Mode</td><td>Max.</td><td>Pro. max</td></tr>
<tr><td>Heading 1</td><td>0.0</td><td>0.0</td><td>0.0</td><td>1.50</td><td>1.50</td><td>1.50</td><td>0.0</td></tr>
<tr><th colspan="8">Variables</th></tr>
<tr><td>Name</td><td>Pro. min</td><td>Min</td><td>Mode</td><td>Max.</td><td>Pro. max</td></tr>
<tr><td>adv_rate</td><td>0.0</td><td>2.96</td><td>3.12</td><td>3.59</td><td>0.0</td></tr>
<tr><td>cost</td><td>0.0</td><td>7191885.00</td><td>7570405.00</td><td>7948925.00</td><td>0.0</td></tr>
</table>

<table>
<tr><th colspan="18">Method name: Pattern 2-2</th></tr>
<tr><th colspan="8">Headings</th><th colspan="10">Cycle length</th></tr>
<tr><td colspan="2">Number</td><td colspan="3">Min. distance</td><td colspan="3">Max. distance</td><td colspan="2">Pro. min</td><td colspan="2">Min</td><td colspan="2">Mode</td><td colspan="2">Max.</td><td colspan="2">Pro. max</td></tr>
<tr><td colspan="2">Heading 1</td><td colspan="3">0.0</td><td colspan="3">0.0</td><td colspan="2">0.0</td><td colspan="2">1.20</td><td colspan="2">1.20</td><td colspan="2">1.20</td><td colspan="2">0.0</td></tr>
<tr><th colspan="18">Variables</th></tr>
<tr><td colspan="3">Name</td><td colspan="3">Pro. min</td><td colspan="3">Min</td><td colspan="3">Mode</td><td colspan="3">Max.</td><td colspan="3">Pro. max</td></tr>
<tr><td colspan="3">adv_rate</td><td colspan="3">0.0</td><td colspan="3">2.79</td><td colspan="3">2.94</td><td colspan="3">3.38</td><td colspan="3">0.0</td></tr>
<tr><td colspan="3">cost</td><td colspan="3">0.0</td><td colspan="3">7191885.00</td><td colspan="3">7570405.00</td><td colspan="3">7948925.00</td><td colspan="3">0.0</td></tr>
</table>

<table>
<tr><th colspan="18">Method name: Pattern 2-3</th></tr>
<tr><th colspan="8">Headings</th><th colspan="10">Cycle length</th></tr>
<tr><td colspan="2">Number</td><td colspan="3">Min. distance</td><td colspan="3">Max. distance</td><td colspan="2">Pro. min</td><td colspan="2">Min</td><td colspan="2">Mode</td><td colspan="2">Max.</td><td colspan="2">Pro. max</td></tr>
<tr><td colspan="2">Heading 1</td><td colspan="3">0.0</td><td colspan="3">0.0</td><td colspan="2">0.0</td><td colspan="2">1.00</td><td colspan="2">1.00</td><td colspan="2">1.00</td><td colspan="2">0.0</td></tr>
<tr><th colspan="18">Variables</th></tr>
<tr><td colspan="3">Name</td><td colspan="3">Pro. min</td><td colspan="3">Min</td><td colspan="3">Mode</td><td colspan="3">Max.</td><td colspan="3">Pro. max</td></tr>
<tr><td colspan="3">adv_rate</td><td colspan="3">0.0</td><td colspan="3">2.64</td><td colspan="3">2.78</td><td colspan="3">3.20</td><td colspan="3">0.0</td></tr>
<tr><td colspan="3">cost</td><td colspan="3">0.0</td><td colspan="3">7191885.00</td><td colspan="3">7570405.00</td><td colspan="3">7948925.00</td><td colspan="3">0.0</td></tr>
</table>

Method name: Pattern 3

Headings			Cycle length				
Number	Min. distance	Max. distance	Pro. min	Min	Mode	Max.	Pro. max
Heading 1	0.0	0.0	0.0	2.00	2.00	2.00	0.0

Variables

Name	Pro. min	Min	Mode	Max.	Pro. max
adv_rate	0.0	2.81	2.96	3.40	0.0
cost	0.0	7571393.50	7969888.00	8368382.50	0.0

Method name: Pattern 4

Headings			Cycle length				
Number	Min. distance	Max. distance	Pro. Min	Min	Mode	Max.	Pro. Max
Heading 1	10.0	30.0	0.0	1.50	1.50	1.50	0.0
Heading 2	10.0	30.0	0.0	3.00	3.00	3.00	0.0

Variables

Name	Pro. min	Min	Mode	Max.	Pro. max
adv_rate1	0.0	2.55	2.68	3.08	0.0
adv_rate2	0.0	6.23	6.56	7.54	0.0
cost	0.0	9633723.00	10140761.00	10647799.00	0.0

<table>
<tr><th colspan="24">Method name: Pattern 5</th></tr>
<tr><th colspan="9">Headings</th><th colspan="15">Cycle length</th></tr>
<tr><td colspan="3">Number</td><td colspan="3">Min. distance</td><td colspan="3">Max. distance</td><td colspan="3">Pro. Min</td><td colspan="3">Min</td><td colspan="3">Mode</td><td colspan="3">Max.</td><td colspan="3">Pro. Max</td></tr>
<tr><td colspan="3">Heading 1</td><td colspan="3">10.0</td><td colspan="3">20.0</td><td colspan="3">0.0</td><td colspan="3">1.20</td><td colspan="3">1.20</td><td colspan="3">1.20</td><td colspan="3">0.0</td></tr>
<tr><td colspan="3">Heading 2</td><td colspan="3">10.0</td><td colspan="3">20.0</td><td colspan="3">0.0</td><td colspan="3">1.20</td><td colspan="3">1.20</td><td colspan="3">1.20</td><td colspan="3">0.0</td></tr>
<tr><th colspan="24">Variables</th></tr>
<tr><td colspan="4">Name</td><td colspan="4">Pro. min</td><td colspan="4">Min</td><td colspan="4">Mode</td><td colspan="4">Max.</td><td colspan="4">Pro. max</td></tr>
<tr><td colspan="4">adv_rate1</td><td colspan="4">0.0</td><td colspan="4">2.28</td><td colspan="4">2.40</td><td colspan="4">2.76</td><td colspan="4">0.0</td></tr>
<tr><td colspan="4">adv_rate2</td><td colspan="4">0.0</td><td colspan="4">4.49</td><td colspan="4">4.73</td><td colspan="4">5.44</td><td colspan="4">0.0</td></tr>
<tr><td colspan="4">cost</td><td colspan="4">0.0</td><td colspan="4">10635206.00</td><td colspan="4">11194954.00</td><td colspan="4">11754702.00</td><td colspan="4">0.0</td></tr>
</table>

<table>
<tr><th colspan="24">Method name: Pattern 6</th></tr>
<tr><th colspan="9">Headings</th><th colspan="15">Cycle length</th></tr>
<tr><td colspan="3">Number</td><td colspan="3">Min. distance</td><td colspan="3">Max. distance</td><td colspan="3">Pro. Min</td><td colspan="3">Min</td><td colspan="3">Mode</td><td colspan="3">Max.</td><td colspan="3">Pro. Max</td></tr>
<tr><td colspan="3">Heading 1</td><td colspan="3">10.0</td><td colspan="3">20.0</td><td colspan="3">0.0</td><td colspan="3">1.00</td><td colspan="3">1.00</td><td colspan="3">1.00</td><td colspan="3">0.0</td></tr>
<tr><td colspan="3">Heading 2</td><td colspan="3">10.0</td><td colspan="3">20.0</td><td colspan="3">0.0</td><td colspan="3">1.00</td><td colspan="3">1.00</td><td colspan="3">1.00</td><td colspan="3">0.0</td></tr>
<tr><th colspan="24">Variables</th></tr>
<tr><td colspan="4">Name</td><td colspan="4">Pro. min</td><td colspan="4">Min</td><td colspan="4">Mode</td><td colspan="4">Max.</td><td colspan="4">Pro. max</td></tr>
<tr><td colspan="4">adv_rate1</td><td colspan="4">0.0</td><td colspan="4">2.07</td><td colspan="4">2.18</td><td colspan="4">2.51</td><td colspan="4">0.0</td></tr>
<tr><td colspan="4">adv_rate2</td><td colspan="4">0.0</td><td colspan="4">4.09</td><td colspan="4">4.31</td><td colspan="4">4.96</td><td colspan="4">0.0</td></tr>
<tr><td colspan="4">cost</td><td colspan="4">0.0</td><td colspan="4">11346911.00</td><td colspan="4">11944117.00</td><td colspan="4">12541323.00</td><td colspan="4">0.0</td></tr>
</table>

<table>
<tr><th colspan="24">Method name: Pattern EPP</th></tr>
<tr><th colspan="12">Headings</th><th colspan="12">Cycle length</th></tr>
<tr><td colspan="4">Number</td><td colspan="4">Min. distance</td><td colspan="4">Max. distance</td><td colspan="3">Pro. min</td><td colspan="3">Min</td><td colspan="3">Mode</td><td colspan="3">Max.</td><td colspan="3">Pro. max</td></tr>
<tr><td colspan="4">Heading 1</td><td colspan="4">0.0</td><td colspan="4">0.0</td><td colspan="3">0.0</td><td colspan="3">3.00</td><td colspan="3">3.00</td><td colspan="3">3.00</td><td colspan="3">0.0</td></tr>
<tr><th colspan="24">Variables</th></tr>
<tr><td colspan="4">Name</td><td colspan="4">Pro. min</td><td colspan="4">Min</td><td colspan="4">Mode</td><td colspan="4">Max.</td><td colspan="4">Pro. max</td></tr>
<tr><td colspan="4">adv_rate</td><td colspan="4">0.0</td><td colspan="4">2.96</td><td colspan="4">3.12</td><td colspan="4">3.59</td><td colspan="4">0.0</td></tr>
<tr><td colspan="4">cost</td><td colspan="4">0.0</td><td colspan="4">6842830.00</td><td colspan="4">7202979.00</td><td colspan="4">7563128.00</td><td colspan="4">0.0</td></tr>
</table>

<table>
<tr><th colspan="24">Method name: lining_1</th></tr>
<tr><th colspan="12">Headings</th><th colspan="12">Cycle length</th></tr>
<tr><td colspan="4">Number</td><td colspan="4">Min. distance</td><td colspan="4">Max. distance</td><td colspan="3">Pro. min</td><td colspan="3">Min</td><td colspan="3">Mode</td><td colspan="3">Max.</td><td colspan="3">Pro. max</td></tr>
<tr><td colspan="4">Heading 1</td><td colspan="4">0.0</td><td colspan="4">0.0</td><td colspan="3">0.0</td><td colspan="3">10.0</td><td colspan="3">10.0</td><td colspan="3">10.0</td><td colspan="3">0.0</td></tr>
<tr><th colspan="24">Variables</th></tr>
<tr><td colspan="4">Name</td><td colspan="4">Pro. min</td><td colspan="4">Min</td><td colspan="4">Mode</td><td colspan="4">Max.</td><td colspan="4">Pro. max</td></tr>
<tr><td colspan="4">adv_rate</td><td colspan="4">0.0</td><td colspan="4">6.33</td><td colspan="4">6.66</td><td colspan="4">7.66</td><td colspan="4">0.0</td></tr>
<tr><td colspan="4">cost</td><td colspan="4">0.0</td><td colspan="4">452773.81</td><td colspan="4">476604.00</td><td colspan="4">500434.19</td><td colspan="4">0.0</td></tr>
</table>

<table>
<tr><th colspan="18">Method name: lining_2</th></tr>
<tr><th colspan="8">Headings</th><th colspan="10">Cycle length</th></tr>
<tr><td colspan="2">Number</td><td colspan="3">Min. distance</td><td colspan="3">Max. distance</td><td colspan="2">Pro. min</td><td colspan="2">Min</td><td colspan="2">Mode</td><td colspan="2">Max.</td><td colspan="2">Pro. max</td></tr>
<tr><td colspan="2">Heading 1</td><td colspan="3">0.0</td><td colspan="3">0.0</td><td colspan="2">0.0</td><td colspan="2">10.0</td><td colspan="2">10.0</td><td colspan="2">10.0</td><td colspan="2">0.0</td></tr>
<tr><th colspan="18">Variables</th></tr>
<tr><td colspan="3">Name</td><td colspan="3">Pro. min</td><td colspan="3">Min</td><td colspan="3">Mode</td><td colspan="3">Max.</td><td colspan="3">Pro. max</td></tr>
<tr><td colspan="3">adv_rate</td><td colspan="3">0.0</td><td colspan="3">6.33</td><td colspan="3">6.66</td><td colspan="3">7.66</td><td colspan="3">0.0</td></tr>
<tr><td colspan="3">cost</td><td colspan="3">0.0</td><td colspan="3">452773.81</td><td colspan="3">476605.00</td><td colspan="3">500435.25</td><td colspan="3">0.0</td></tr>
</table>

<table>
<tr><th colspan="18">Method name: lining_3</th></tr>
<tr><th colspan="8">Headings</th><th colspan="10">Cycle length</th></tr>
<tr><td colspan="2">Number</td><td colspan="3">Min. distance</td><td colspan="3">Max. distance</td><td colspan="2">Pro. min</td><td colspan="2">Min</td><td colspan="2">Mode</td><td colspan="2">Max.</td><td colspan="2">Pro. max</td></tr>
<tr><td colspan="2">Heading 1</td><td colspan="3">0.0</td><td colspan="3">0.0</td><td colspan="2">0.0</td><td colspan="2">10.0</td><td colspan="2">10.0</td><td colspan="2">10.0</td><td colspan="2">0.0</td></tr>
<tr><th colspan="18">Variables</th></tr>
<tr><td colspan="3">Name</td><td colspan="3">Pro. min</td><td colspan="3">Min</td><td colspan="3">Mode</td><td colspan="3">Max.</td><td colspan="3">Pro. max</td></tr>
<tr><td colspan="3">adv_rate</td><td colspan="3">0.0</td><td colspan="3">6.33</td><td colspan="3">6.66</td><td colspan="3">7.66</td><td colspan="3">0.0</td></tr>
<tr><td colspan="3">cost</td><td colspan="3">0.0</td><td colspan="3">452480.25</td><td colspan="3">476295.00</td><td colspan="3">500109.75</td><td colspan="3">0.0</td></tr>
</table>

<table>
<tr><th colspan="18">Method name: lining_4</th></tr>
<tr><th colspan="8">Headings</th><th colspan="10">Cycle length</th></tr>
<tr><td colspan="2">Number</td><td colspan="3">Min. distance</td><td colspan="3">Max. distance</td><td colspan="2">Pro. min</td><td colspan="2">Min</td><td colspan="2">Mode</td><td colspan="2">Max.</td><td colspan="2">Pro. max</td></tr>
<tr><td colspan="2">Heading 1</td><td colspan="3">0.0</td><td colspan="3">0.0</td><td colspan="2">0.0</td><td colspan="2">10.0</td><td colspan="2">10.0</td><td colspan="2">10.0</td><td colspan="2">0.0</td></tr>
<tr><th colspan="18">Variables</th></tr>
<tr><td colspan="3">Name</td><td colspan="3">Pro. min</td><td colspan="3">Min</td><td colspan="3">Mode</td><td colspan="3">Max.</td><td colspan="3">Pro. max</td></tr>
<tr><td colspan="3">adv_rate</td><td colspan="3">0.0</td><td colspan="3">6.33</td><td colspan="3">6.66</td><td colspan="3">7.66</td><td colspan="3">0.0</td></tr>
<tr><td colspan="3">cost</td><td colspan="3">0.0</td><td colspan="3">452657.91</td><td colspan="3">476482.00</td><td colspan="3">500306.09</td><td colspan="3">0.0</td></tr>
</table>

<table>
<tr><th colspan="18">Method name: lining_5</th></tr>
<tr><th colspan="8">Headings</th><th colspan="10">Cycle length</th></tr>
<tr><td colspan="2">Number</td><td colspan="3">Min. distance</td><td colspan="3">Max. distance</td><td colspan="2">Pro. min</td><td colspan="2">Min</td><td colspan="2">Mode</td><td colspan="2">Max.</td><td colspan="2">Pro. max</td></tr>
<tr><td colspan="2">Heading 1</td><td colspan="3">0.0</td><td colspan="3">0.0</td><td colspan="2">0.0</td><td colspan="2">10.0</td><td colspan="2">10.0</td><td colspan="2">10.0</td><td colspan="2">0.0</td></tr>
<tr><th colspan="18">Variables</th></tr>
<tr><td colspan="3">Name</td><td colspan="3">Pro. min</td><td colspan="3">Min</td><td colspan="3">Mode</td><td colspan="3">Max.</td><td colspan="3">Pro. max</td></tr>
<tr><td colspan="3">adv_rate</td><td colspan="3">0.0</td><td colspan="3">6.33</td><td colspan="3">6.66</td><td colspan="3">7.66</td><td colspan="3">0.0</td></tr>
<tr><td colspan="3">cost</td><td colspan="3">0.0</td><td colspan="3">452530.59</td><td colspan="3">476348.00</td><td colspan="3">500165.41</td><td colspan="3">0.0</td></tr>
</table>

Method name: lining_6

Headings			Cycle length				
Number	Min. distance	Max. distance	Pro. min	Min	Mode	Max.	Pro. max
Heading 1	0.0	0.0	0.0	10.0	10.0	10.0	0.0

Variables

Name	Pro. min	Min	Mode	Max.	Pro. max
adv_rate	0.0	6.33	6.66	7.66	0.0
cost	0.0	452068.91	475862.00	499655.09	0.0

Method name: Crossover_v

Headings			Cycle length				
Number	Min. distance	Max. distance	Pro. Min	Min	Mode	Max.	Pro. Max
Heading 1	17.6	17.6	0.0	3.00	3.00	3.00	0.0
Heading 2	17.6	17.6	0.0	10.0	10.0	10.0	0.0

Variables

Name	Pro. min	Min	Mode	Max.	Pro. max
adv_rate	0.0	5.73	6.03	6.93	0.0
adv_rate2	0.0	6.23	6.56	7.54	0.0
cost	0.0	2473673.75	2603867.0	2734060.25	0.0
cost2	0.0	452435.59	476248.00	500060.41	0.0

<table>
<tr><th colspan="8">Method name: Crossover_p</th></tr>
<tr><th colspan="3">Headings</th><th colspan="5">Cycle length</th></tr>
<tr><td>Number</td><td>Min. distance</td><td>Max. distance</td><td>Pro. Min</td><td>Min</td><td>Mode</td><td>Max.</td><td>Pro. Max</td></tr>
<tr><td>Heading 1</td><td>18.2</td><td>18.2</td><td>0.0</td><td>2.00</td><td>2.00</td><td>2.00</td><td>0.0</td></tr>
<tr><td>Heading 2</td><td>18.2</td><td>18.2</td><td>0.0</td><td>10.0</td><td>10.0</td><td>10.0</td><td>0.0</td></tr>
<tr><th colspan="8">Variables</th></tr>
</table>

Name	Pro. min	Min	Mode	Max.	Pro. max
adv_rate	0.0	8.21	8.64	9.94	0.0
adv_rate2	0.0	6.23	6.56	7.54	0.0
cost	0.0	2473673.75	2603867.00	2734060.25	0.0
cost2	0.0	452435.59	476248.00	500060.41	0.0

<table>
<tr><th colspan="8">Method name: lining_EPP</th></tr>
<tr><th colspan="3">Headings</th><th colspan="5">Cycle length</th></tr>
<tr><td>Number</td><td>Min. distance</td><td>Max. distance</td><td>Pro. min</td><td>Min</td><td>Mode</td><td>Max.</td><td>Pro. max</td></tr>
<tr><td>Heading 1</td><td>0.0</td><td>0.0</td><td>0.0</td><td>10.0</td><td>10.0</td><td>10.0</td><td>0.0</td></tr>
<tr><th colspan="8">Variables</th></tr>
</table>

Name	Pro. min	Min	Mode	Max.	Pro. max
adv_rate	0.0	6.33	6.66	7.66	0.0
cost	0.0	452766.19	476596.00	500425.81	0.0

H. Input for Activities

A construction method is a series of activities which advance the tunnel by one cycle.

Every activity is associated with two different types of equations: a time equation and a cost equation.

When construction methods involve multiple headings, separate activities have to be specified for every heading. For example, "Pattern 4" has two headings hence; activities "excp4" and "excp4b" are specified for the leading heading and following heading respectively.

Activities and associated time/cost equations

---

excp1
cost: excp1 = cost*round_length()
time: excp1 = round_length()/adv_rate

excp2
cost: excp2 = cost*round_length()
time: excp2 = round_length()/adv_rate

excp2-1
cost: excp2-1 = cost*round_length()
time: excp2-1 = round_length()/adv_rate

excp2-2
cost: excp2-2= cost*round_length()
time: excp2-2 = round_length()/adv_rate

excp2-3
cost: excp2-3 = cost*round_length()
time: excp2-3 = round_length()/adv_rate

excp3
cost: excp3 = cost*round_length()
time: excp3 = round_length()/adv_rate

excp4
cost: excp4 = cost*round_length()
time: excp4 = round_length()/adv_rate

Activities and associated time/cost equations

---

excp4b
cost: excp4b = cost*round_length()
time: excp4b = round_length()/adv_rate2

excp5
cost: excp5 = cost*round_length()
time: excp5 = round_length()/adv_rate

excp5b
cost: excp5b = cost*round_length()
time: excp5b = round_length()/adv_rate2

excp6
cost: excp6 = cost*round_length()
time: excp6 = round_length()/adv_rate

excp6b
cost: excp6b= cost*round_length()
time: excp6b= round_length()/adv_rate2

excpEPP
cost: excpEPP= cost*round_length()
time: excpEPP= round_length()/adv_rate

lining_1
cost: lining_1 = cost*round_length()
time: lining_1 = round_length()/adv_rate

lining_2
cost: lining_2 = cost*round_length()
time: lining_2 = round_length()/adv_rate

lining_3
cost: lining_3 = cost*round_length()
time: lining_3 = round_length()/adv_rate

lining_4
cost: lining_4 = cost*round_length()
time: lining_4 = round_length()/adv_rate

lining_5
cost: lining_5 = cost*round_length()
time: lining_5 = round_length()/adv_rate

Activities and associated time/cost equations

---

lining_6
cost: lining_6 = cost*round_length()
time: lining_6 = round_length()/adv_rate

lining_EPP
cost: lining_EPP = cost*round_length()
time: lining_EPP = round_length()/adv_rate

crossover_v
cost: crossover_v = cost*round_length()
time: crossover_v = round_length()/adv_rate

crossover_p
cost: crossover_p = cost*round_length()
time: crossover_p = round_length()/adv_rate

lining_cross
cost: lining_cross = cost*round_length()
time: lining_cross = round_length()/adv_rate2

I. DAT tunnel network and tunnel information

Simulations use the DAT tunnel network. The DAT tunnel network consists of many sub-tunnels considering construction sequence, tunnel geometries and areas where a tunnel is driven. An arc shown in Figure I represent each sub-tunnel. Tunnel information such as tunnel names, areas, geometries and lengths of tunnel are specified for each sub-tunnel as shown in Table I. Numbers shown in Figure I represent tunnel numbers which correspond to numbers shown in a Table I.

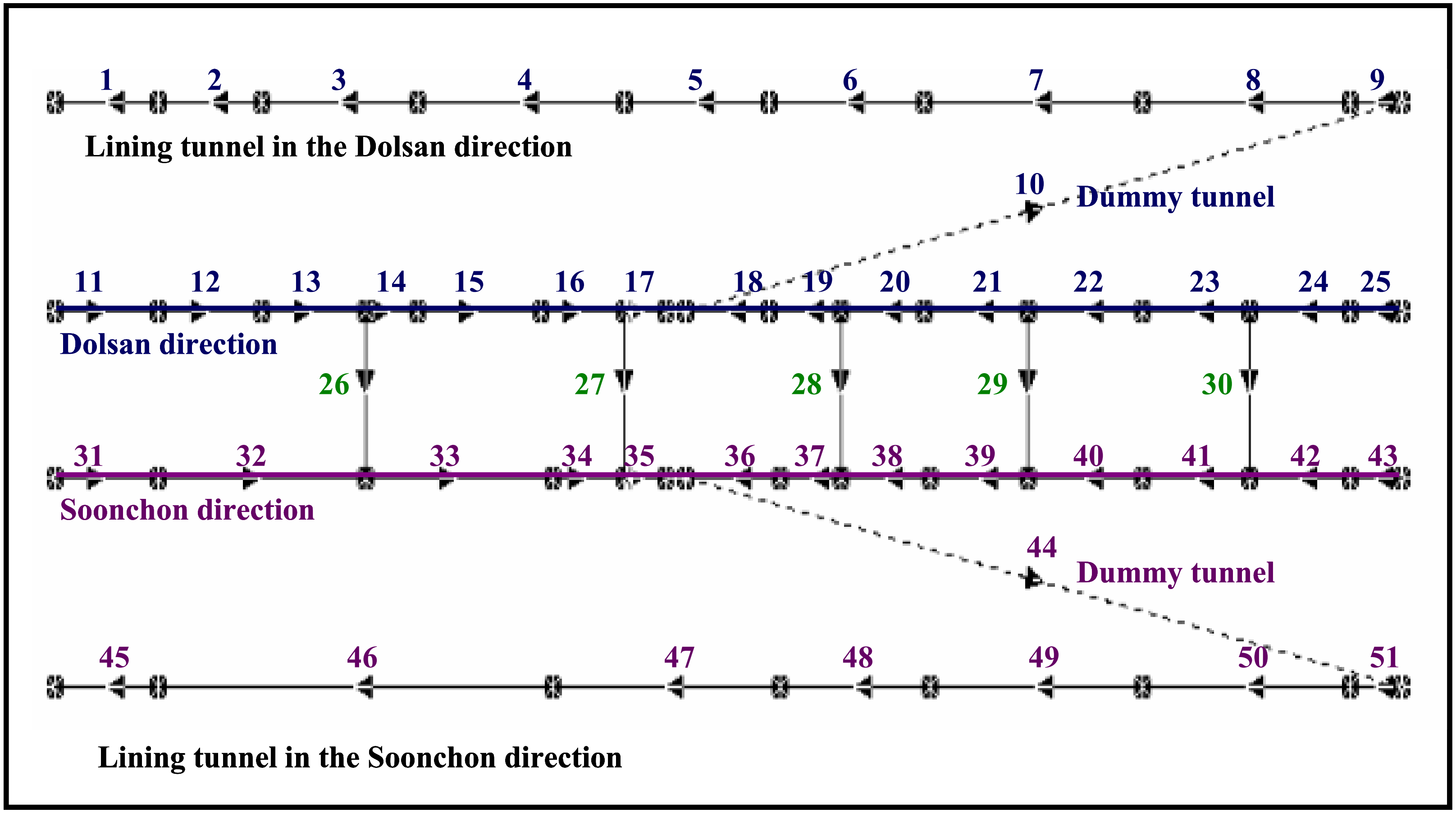


Figure I. DAT tunnel network

Table I. Tunnel information table

	Name	Area	Geometry	Length		Name	Area	Geometry	Length
1	liningbegin_d	begin	10	25	**27**	co_2_v	co2_v	6	17.6
2	lining7_d	S-D	3	117	**28**	co_3_p	co3_p	9	18.2
3	lining6_method2	S-D	7	167	**29**	co_4_v	co4_v	6	17.6
4	lining5_d	S-D	3	254	**30**	co_5_p	co5_p	9	18.2
5	lining4_epp_d	S-D	8	60	**31**	natmbegin_s	begin	1	45
6	lining3_d	S-D	3	600	**32**	soonchon_1	S-D	2	245
7	lining2_epp_d	S-D	8	60	**33**	soonchon_1_2	S-D	2	307
8	lining1_d	S-D	3	577	**34**	epp_1_1	S-D	5	23
9	liningend_d	end	10	40	**35**	epp_1_2	S-D	5	10
10	dummy-d	S-D	2	0	**36**	epp_1_3	S-D	5	27
11	natmbegin_d	begin	1	25	**37**	soonchon_2_1	S-D	2	293
12	dolsan_a	S-D	2	117	**38**	soonchon_2_2	S-D	2	307
13	method2_1	S-D	4	128	**39**	epp_2_1	S-D	5	23
14	method2_2	S-D	4	39	**40**	epp_2_2	S-D	5	37
15	dolsan_2	S-D	2	254	**41**	soonchon_3_1	S-D	2	303
16	epp_3_1	S-D	5	37	**42**	soonchon_3_2	S-D	2	260
17	epp_3-2	S-D	5	10	**43**	natmend_s	end	1	30
18	epp_3_3	S-D	5	13	**44**	dummy_s	S-D	2	0

19	dolsan_3_1	S-D	2	307	**45**	liningbegin_s	begin	10	45
20	dolsan_3_2	S-D	2	293	**46**	lining5_s	S-D	3	552
21	epp_4_1	S-D	5	37	**47**	lining4_epp_s	S-D	8	60
22	epp_4_2	S-D	5	23	**48**	lining3_s	S-D	3	600
23	dolsan_4_1	S-D	2	317	**49**	lining2_epp_s	S-D	8	60
24	dolsan_4_2	S-D	2	260	**50**	lining1_s	S-D	3	563
25	natmend_d	end	1	40	**51**	liningend_s	end	10	30
26	co_1_p	co1_p	9	18.2	**52**				