MEASURED AND PREDICTED PORE PRESSURES IN EARTH DAMS

by

Gregory Paul Matthews

B.S.C.E., Tufts University
(1978)

SUBMITTED IN PARTIAL FULFILLMENT
OF THE REQUIREMENTS FOR THE
DEGREE OF

MASTER OF SCIENCE IN
CIVIL ENGINEERING

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

August 1980

Signature of Author____________________________
Department of Civil Engineering
August 8, 1980

Certified by____________________________
T. William Lambe
Thesis Supervisor

____
W. Allen Marr
Thesis Supervisor

Accepted by____________________________
C. Allin Cornell
Chairman, Departmental Graduate Committee

MEASURED AND PREDICTED PORE PRESSURES IN EARTH DAMS

by

Gregory Paul Matthews

Submitted to the Department of Civil Engineering
on August 8, 1980 in partial fulfillment of the
requirements for the Degree of Master of Science in
Civil Engineering

ABSTRACT

This thesis considers predicted and measured pore pressures, for steady state flow, for four separate earth dams. Each dam is treated as a case study in which initial estimates of soil profile, boundary conditions, and soil permeability are given.

The case studies are then evaluated in more detail to help explain discrepancies between predicted and measured values of pore pressures. Reasons for discrepancies are considered to help determine the accuracy with which an engineer can predict measured pore pressures for steady state flow through earth dams.

Thesis Supervisors:	Dr. T. William Lambe Professor of Civil Engineering
	Dr. W. Allen Marr Research Associate in Civil Engineering

ACKNOWLEDGMENTS

I would like to acknowledge the assistance and cooperation I received from my thesis supervisors, Dr. W.A. Marr and Dr. T.W. Lambe. I would also like to acknowledge the consultations and cooperation of Lambe and Associates; Borden Chemical Inc.; Mr. J. Lowe, Mr. E. Jonas, Mr. I. Fox, and Mr. V. Azooman of TAMS Engineers and Architects; Mr. W. Swiger of the Stone and Webster Engineering Corporation; and W. Hachich, doctoral candidate at M.I.T. This thesis was made possible through the efforts and information made available by these engineers and corporations and their assistance is sincerely appreciated.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF TABLES

INTRODUCTION

This thesis, through the analysis of four case studies, determines the accuracy with which an engineer can predict measured pore pressures for steady state flow through earth dams.

Comparison of measured and predicted performance in this thesis is based on total head. Total head is equal to the sum of pressure head and elevation head at the point where pore pressure is measured.

Lambe (1973) cites three different types of predictions. Type A predictions are those of an event that has not yet occurred; Type B are those made during the event; and Type C are those made after the event. This thesis is primarily concerned with Type A prediction of pore pressure in earth dams.

For the cases considered in this thesis the following assumptions are made.

(1) The flow of water through soils follows Darcy's Law, which states that the amount of flow is linearly proportional to the hydraulic gradient.

(2) Continuity of flowing water exists. This assumes that the water and soil are incompressible and there is no change in degree of saturation.

Combination of the above two assumption yields Laplace's differential equation:

$$k_x \frac{\partial^2 h}{\partial x^2} + k_y \frac{\partial^2 h}{\partial y^2} + k_z \frac{\partial^2 h}{\partial z^2} = 0$$

where h is total head and k is permeability. The scope of this thesis deals with two-dimensional flow for which the equation reduces to:

$$k_x \frac{\partial^2 h}{\partial x^2} + k_z \frac{\partial^2 h}{\partial z^2} = 0$$

Solution of this equation is represented by two families of curves intersecting at right angles. In flow analysis these are known as flow lines and equipotential lines and their plot is called a flow net. Casagrande (1937) contains a derivation of the above equations and gives a thorough explanation of how to solve the flow equation using graphical techniques.

METHODS OF PREDICTION

Flow problems can be solved by different methods. Lambe and Whitman (1969, Chapter 18) discuss soil models, analogy methods and numerical analysis. Soil models can be useful as an instructional tool but are of limited practical use because of scale effects and the difficulty in constructing them. Analogy methods are useful in that Laplace's equation for fluid flow also holds for electrical and heat flow.

Pore pressure predictions in this thesis were made from flow nets which were obtained with the assistance of FEDAR -

a Finite Element analysis based on Darcy flow. FEDAR was developed at UC Berkeley by Taylor and Brown (1967). FEDAR is a numerical method that can handle anisotropy, inhomogeniety, unconfined flow and non-linear soil properties. For unconfined flow problems, as dealt with in this thesis, solution results from successive iterations each yielding improved estimates of the phreatic surface. Output consists of phreatic surface location, equipotentials at specified points in a finite element mesh, and quantity and direction of flow for elements in the mesh.

Methods of prediction just discussed depend on the validity of Darcy's Law and the assumptions that flow is laminar and that there is no flow above the phreatic surface. Leps (1973) and Cedergren (1977, p. 140) discuss approaches for handling non-laminar flow and Walbanke (1975) cites cases of flow above the zero pressure line and approaches that can be used to predict pore pressures in these slopes. For the cases studied in this thesis, flow is considered laminar and the phreatic surface is assumed to be a flow line. Measured pore pressures with time (shown for each case) show each of the cases to be in a steady state condition.

Predictive capability will be evaluated through the analyses of four case studies. Three of the dams studied are located in Florida and one is located in Pakistan. Steady seepage exists in each of the dams and pore pressure predictions are made from flow net constructions. Type A predictions have been made for each dam based on original permeability, geometry, and boundary condition estimates.

Chapter I

PINEY POINT

Piney Point Dam, owned and operated by Borden Chemical Inc., is located near Tampa, Florida. Borden produces acid used for fertilizer at Piney Point and uses the dam for the retention of gypsum wastes. Figure I-1 shows plan and section views of the reservoir and dam. The dam has a total length of approximately 10,000 feet and encloses an area of approximately 110 acres. This study considers predicted and measured performance at Test Section D as shown in Figure I-1.

The solid waste product obtained in the production of acid is transmitted from the plant to the retention system by placing the waste in a water slurry and pumping it into the area enclosed by the dam. Sedimented gypsum is removed from within the reservoir with drag lines and placed on top of the dam. This is schematically shown in Figure I-1b.

Figure I-2a shows the cross-section, piezometer locations and boundary conditions initially used. Figure I-2b shows the cross-section used in flow analysis of Test Section D. Figure I-2b shows less compacted gypsum than Figure I-2a. This is because the location of Material III in Figure I-2b was specially compacted to reduce permeability. Gypsum outside Material III boundaries in Figure I-2b was not considered compacted enough to significantly reduce the permeability.

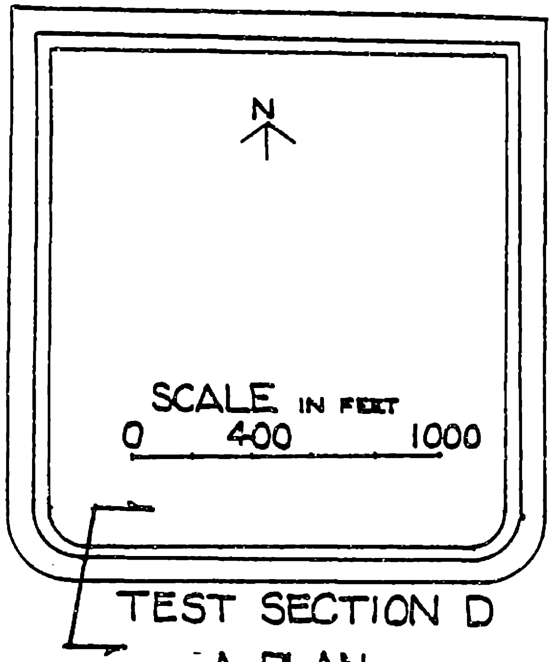
Construction of the dam started in 1966 and in 1968

Lambe and Associates began to investigate seepage and stability conditions within the dam and its foundation.

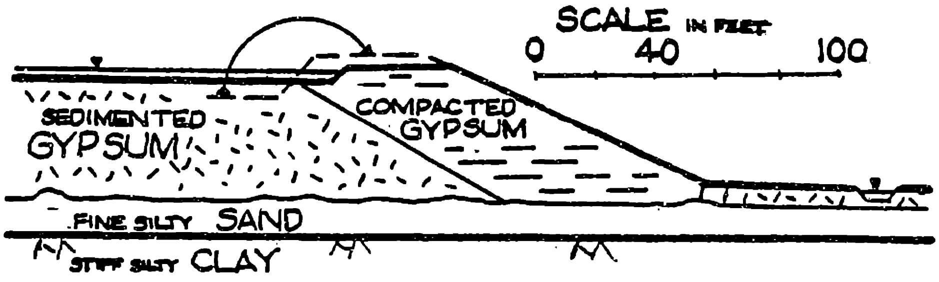
Investigations included field exploration, installation of field instrumentation, and laboratory tests. Table I-1 presents measured properties and properties used in the original seepage analyses. The measured permeabilities were from laboratory tests and field tests on piezometers.

Figure I-3 shows the flow net (constructed by Lambe and Associates) for Test Section D of the dam. This flow net was drawn using the FEDAR output of equipotential values at specified points. Figure I-4 shows pore pressure measurements with varying heights of reservoir and Figure I-5 compares predicted and measured total head.

PINEY POINT-GYPSUM RETENTION RESERVOIR



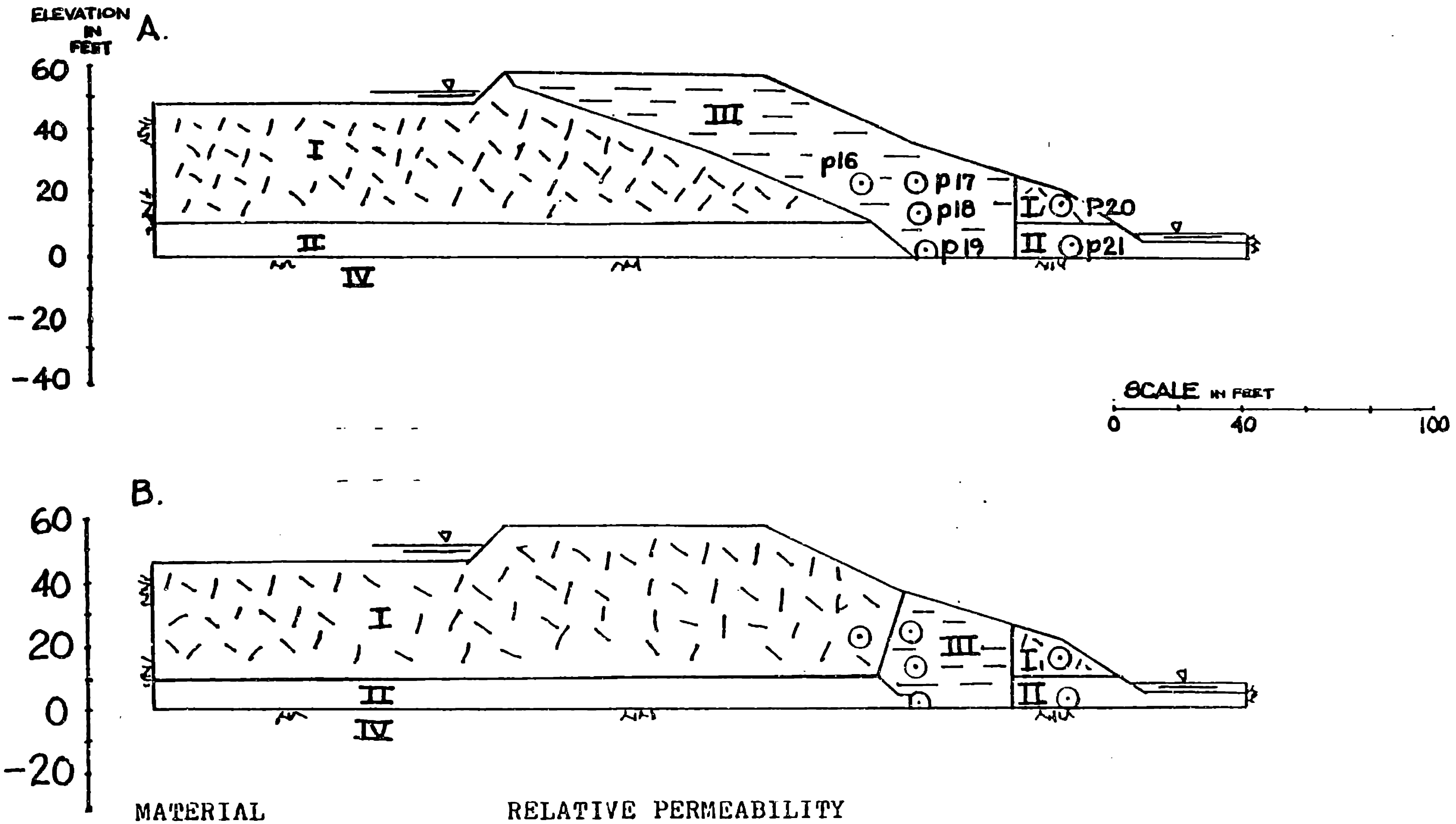
A. PLAN



B. SECTION

FIGURE 1-1

TEST SECTION D



	MATERIAL	RELATIVE PERMEABILITY
I	Sedimented GYPSUM	10
II	Fine Silty SAND	100
III	Compacted GYPSUM	1
IV	CLAY	0

FIGURE 1-2

Table I-1

SOIL PROPERTIES FOR SEEPAGE ANALYSIS OF PINEY POINT GYPSUM DAM

SOIL	PERMEABILITY MEASURED[1] CM/SEC	PERMEABILITY USED CM/SEC
fine silty sand	$10 - 180 \times 10^{-5}$	100×10^{-5}
sedimented Gypsum	$3 - 40 \times 10^{-5}$	10×10^{-5}
compacted Gypsum	$1 - 2 \times 10^{-5}$	1×10^{-5}
foundation Clay	$>1 \times 10^{-6}$	0

[1] range from laboratory tests and field tests on piezometers

FLOW NET-TEST SECTION D

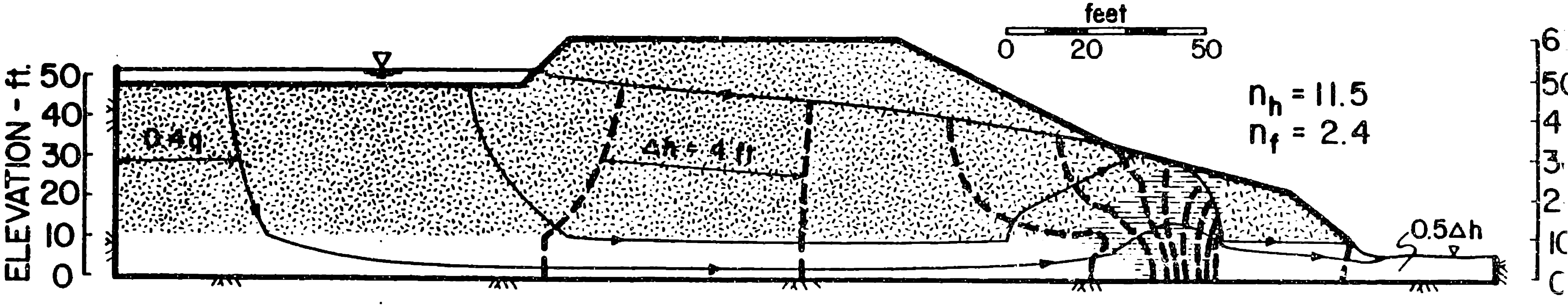
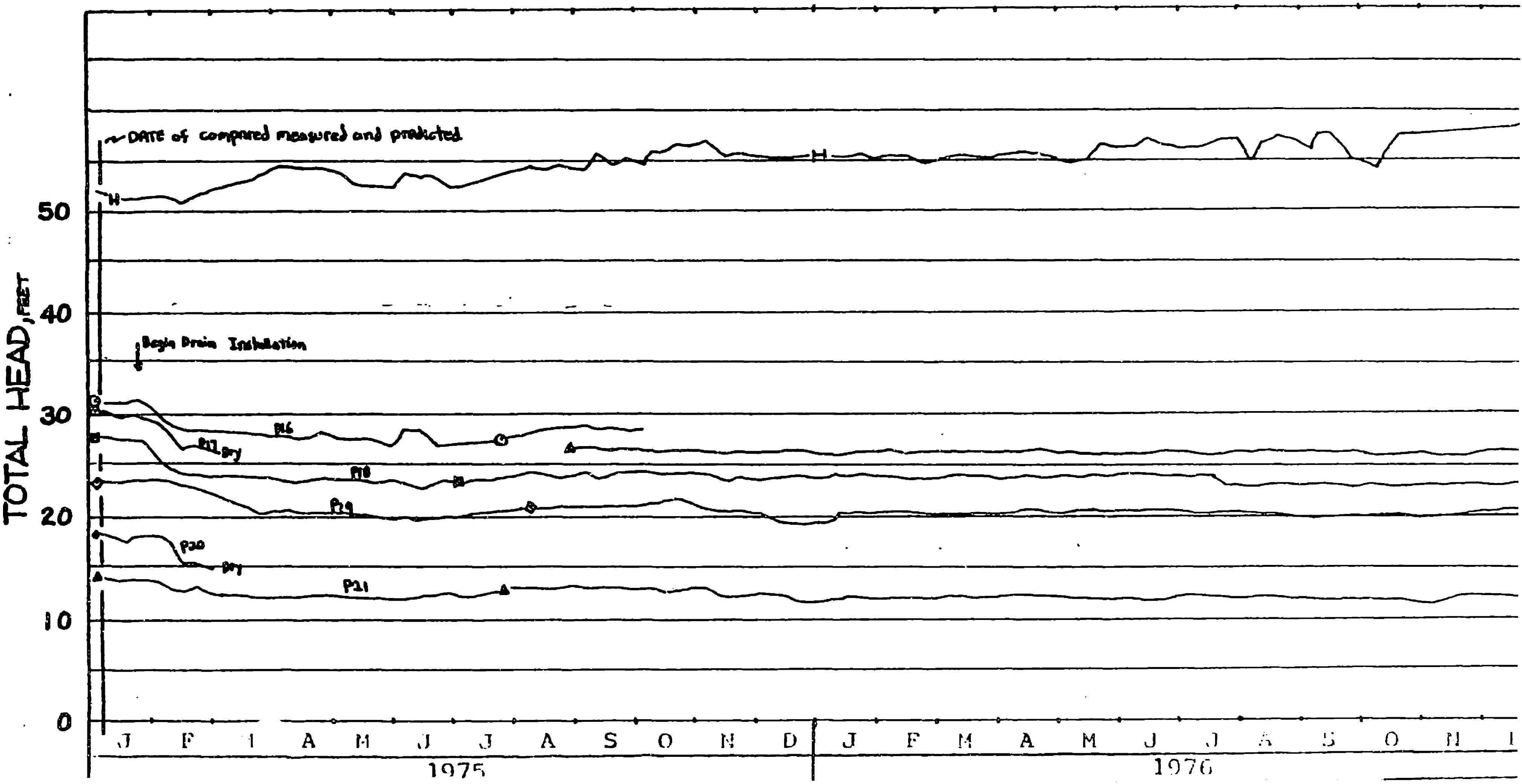


FIGURE 1-3

FIGURE 1-4

MEASURED TOTAL HEAD - TEST SECTION D



MEASURED AND PREDICTED TOTAL HEADS - TEST SECTION D

PIEZOMETER	PREDICTED TOTAL HEAD - FT	MEASURED TOTAL HEAD - FT
P16	38	31.5
P17	34	30.2
P18	35	27.5
P19	39	23.6
P20	dry	18.4
P21	10	13.9

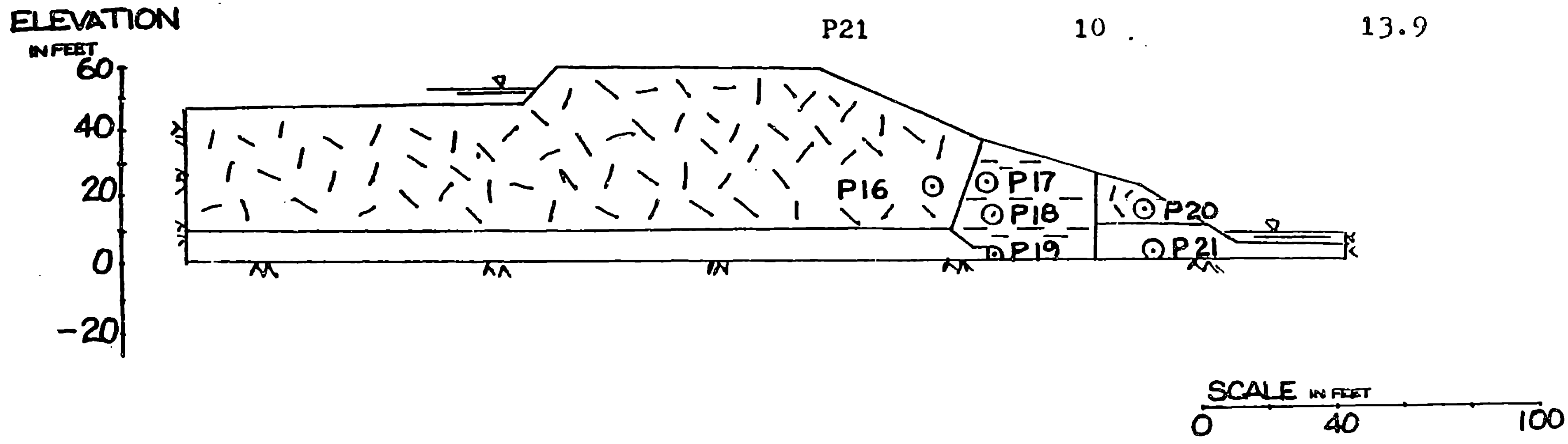


FIGURE I-5

Chapter II

BF-1

Big Four Waste Retention Dam No. 1 (BF-1) is owned by Borden Chemical, Inc. and is located in Florida. Figure II-1 shows a plan view of the dam and locates instrumented sections 162 and 106 along the length of the dam. This zoned earth dam has a total length of approximately 22,000 feet as shown in Figure II-1 and encloses an area of approximately 400 acres.

Figure II-2 shows a cross-section of the dam selected by Bromwell Engineering (Lakeland, Florida) for which soil profile and permeabilities were estimated. This cross-section is shown in Figure II-2 and resembles conditions at Test Section 162 located in Figure II-1. Boundary conditions and piezometer locations are also shown in Figure II-2.

Bromwell Engineers estimated permeabilities for the constructed portion of the dam using lab tests and consideration of placement conditions in the field. Permeability estimates of the foundation soils were made from flow observations during excavation for the core trench. Table II-1 presents original permeabilities used in the seepage analyses.

A FEDAR analysis was made (by the author) for the design section using Bromwell's original permeability estimates and the boundary conditions shown in Figure II-2. Figure II-3 shows the flow net resulting from this analysis.

Figure II-4 shows measured total head at Station 162 and Figure II-5 compares measured and FEDAR predicted total heads at these piezometers.

BIG FOUR WASTE RETENTION DAM NO.1 - BF-1

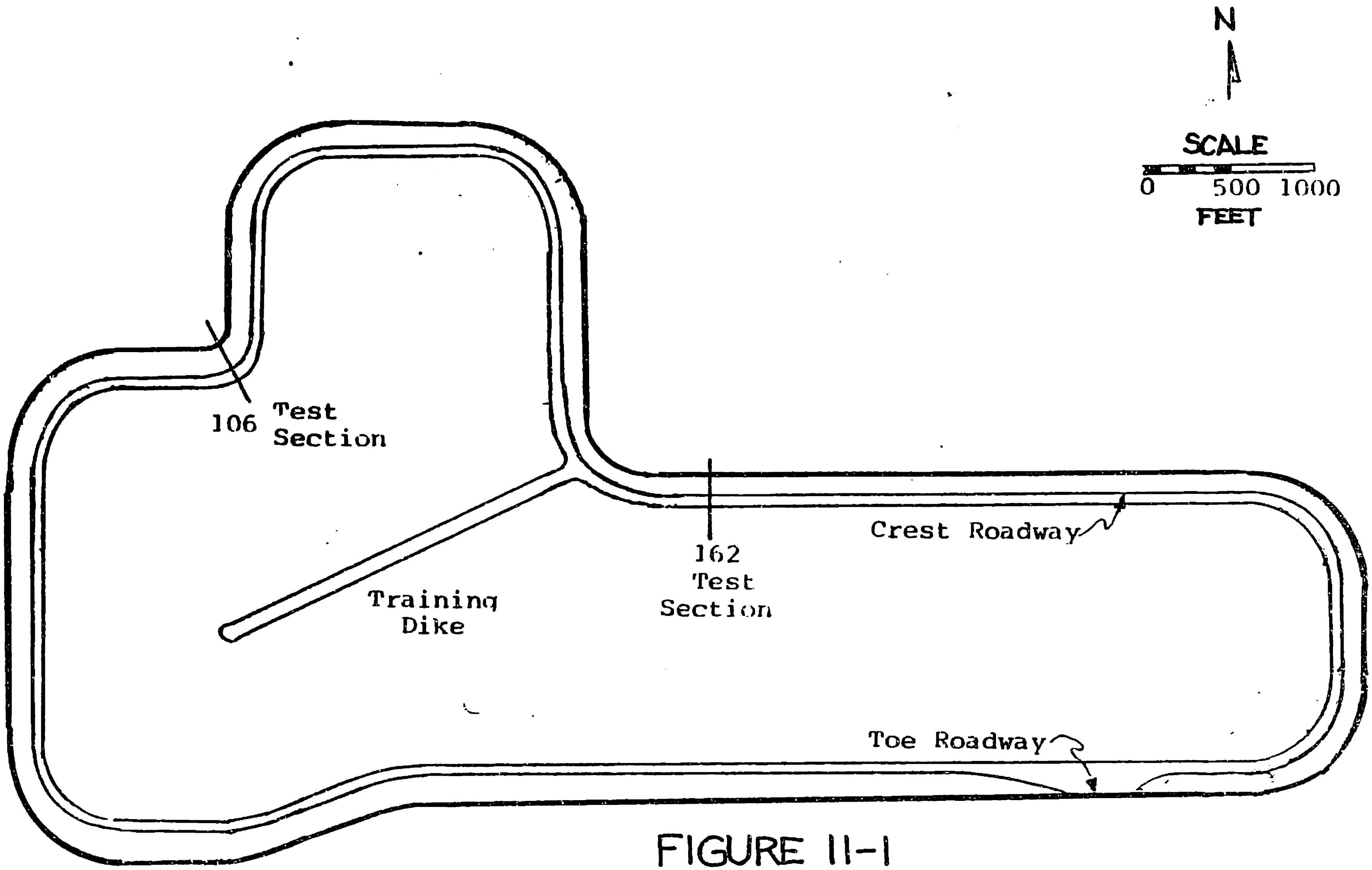
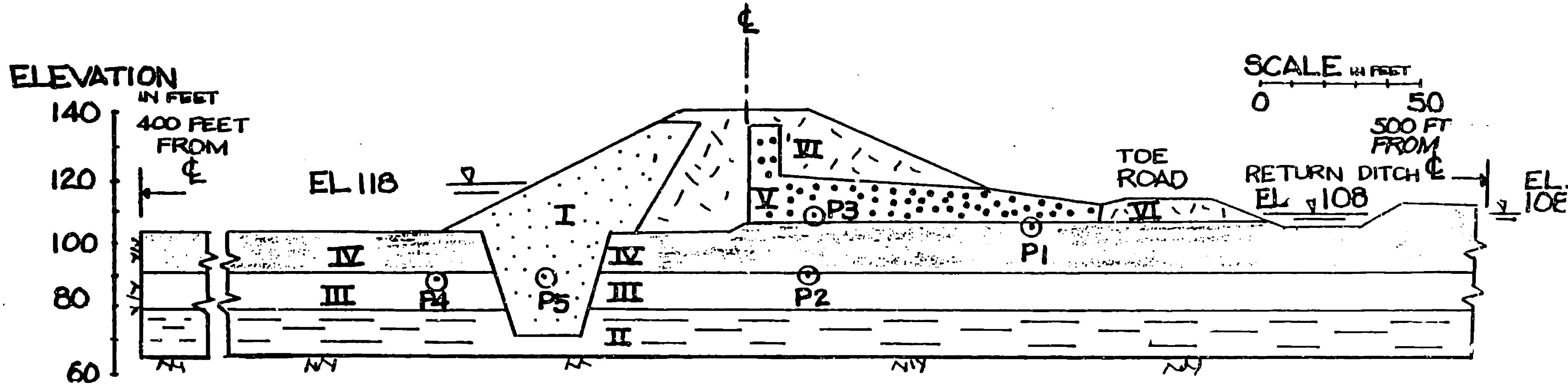


FIGURE II-1

TEST SECTION 162



	MATERIAL	RELATIVE PERMEABILITY
I	CORE	1
II	MATRIX	15
III	SAND	1000
IV	HARDPAN	10
V	DRAIN	25
VI	GENERAL FILL	10

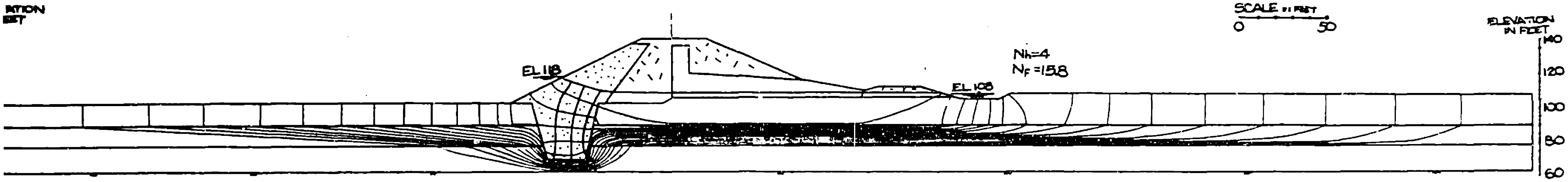
FIGURE 11-2

Table II-1

SOIL PROPERTIES FOR SEEPAGE ANALYSIS OF BF-1 DAM

SOIL	PERMEABILITY CM/SEC
silty Sand - Core	5×10^{-5}
black Sand - HARDPAN	50×10^{-5}
GENERAL FILL	50×10^{-5}
gray Sand with phosphate feed and pebble - MATRIX	75×10^{-5}
Sand - DRAIN	125×10^{-5}
SAND	5000×10^{-5}

FLOW NET - STATION 162



PERMEABILITIES AND BOUNDARY CONDITIONS ARE GIVEN IN FIGURE II-2

FIGURE II-3

MEASURED TOTAL HEAD-TEST SECTION 162

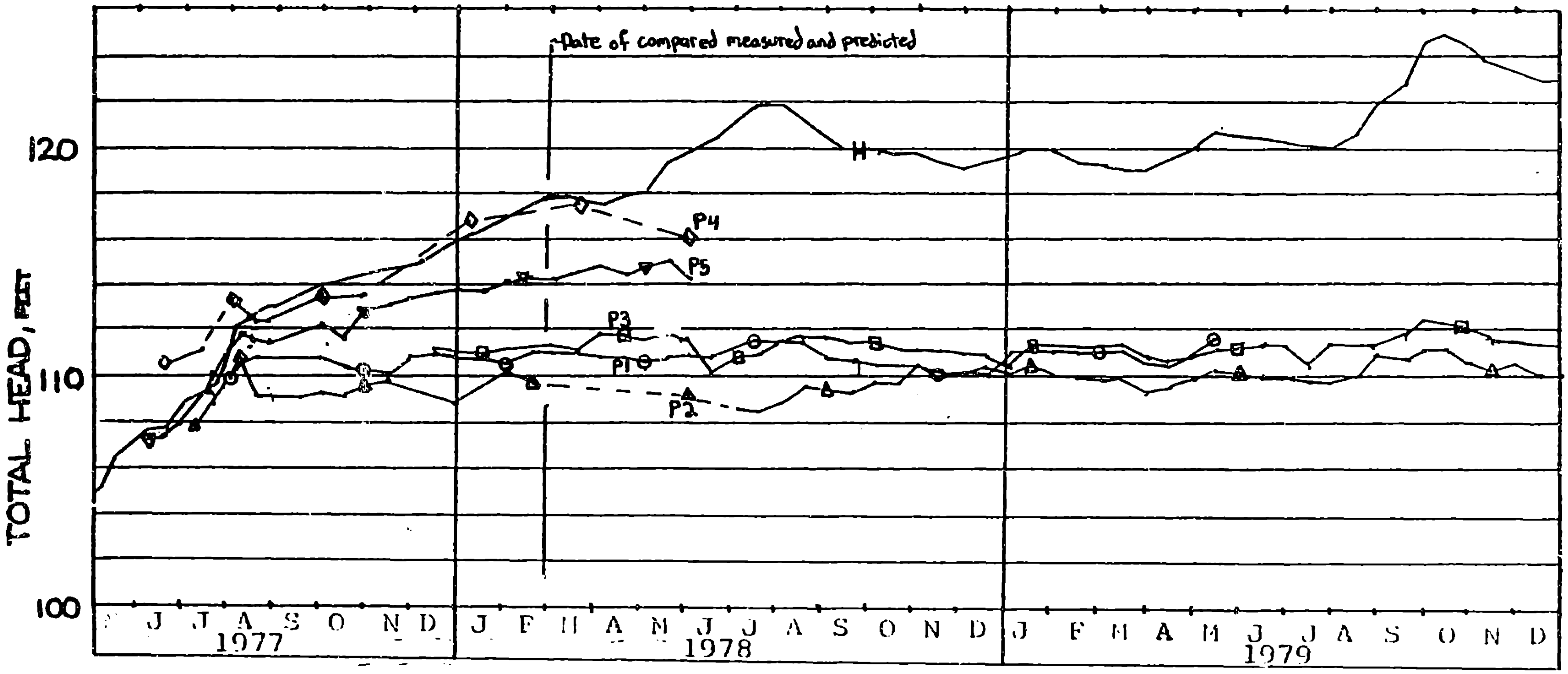


FIGURE 11-4

MEASURED AND PREDICTED TOTAL HEADS - TEST SECTION 162

PIEZOMETER	PREDICTED TOTAL HEAD - FT	MEASURED TOTAL HEAD - FT
P1	108.7	111.1
P2	109.0	109.7
P3	109.0	111.4
P4	117.7	117.4
P5	113.9	114.3

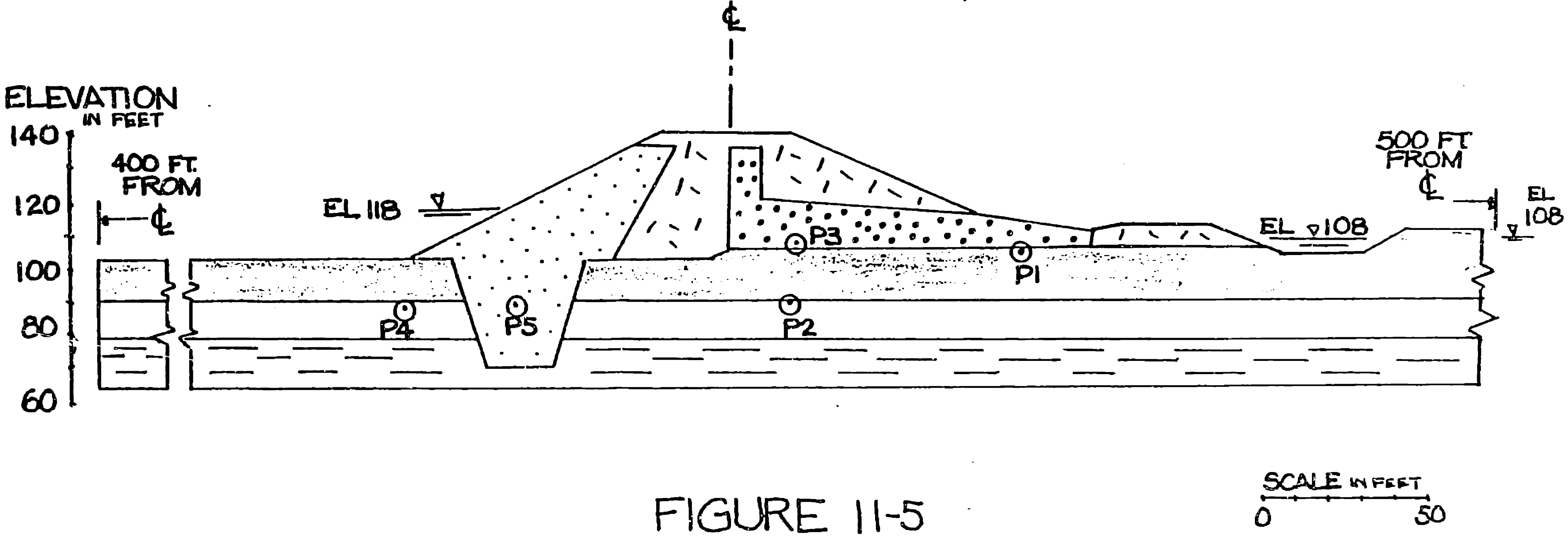


FIGURE 11-5

Chapter III

SWDAM

Figure III-1 shows a cross-section of a dam in Florida for which the Stone and Webster Engineering Corporation has done extensive seepage analyses. It has been requested that the owner, original consultants, and name of the dam not be included in this thesis. For this reason the dam will be referred to as SWDAM.

Figure III-1 shows reservoir level at elevation 37 feet, water elevation in the return ditch at 19 feet and water level at elevation 19 feet in a canal located 650 feet from the toe of the dam. Initial analysis assumed the stratified foundation to be of one permeability and the cemented shell (limestone) to be impervious. Permeability estimates of the embankment and foundation shown in Figure III-1 are the results of field pumping tests and some laboratory tests made by the original consultants on the project.

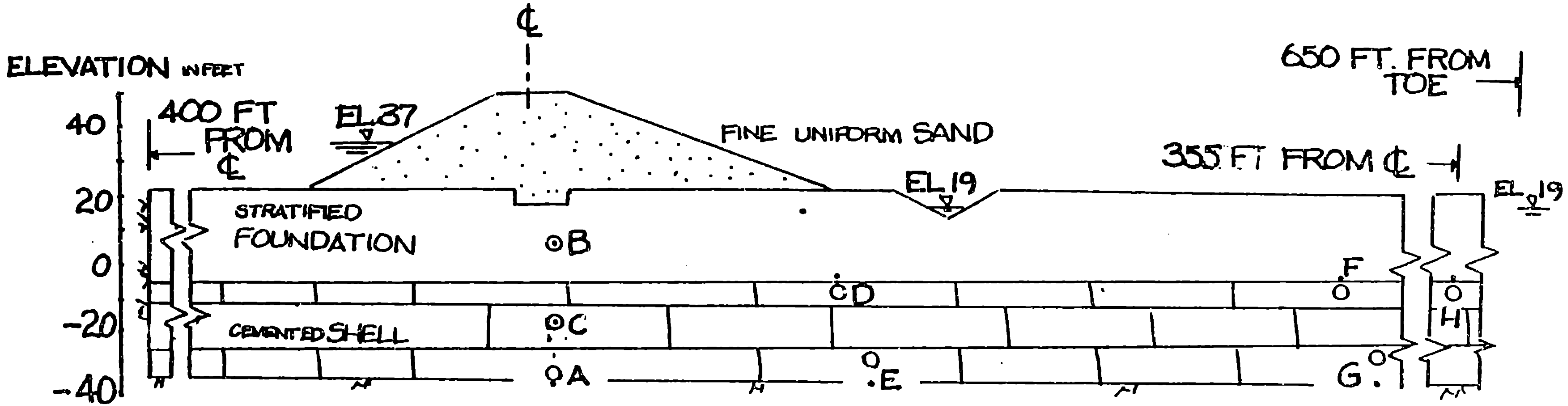
A FEDAR analysis was made (by the author) for the conditions described in Figure III-1. Originally the cemented shell was considered impervious; then a relatively low value of permeability of 10^{-8}cm/sec was used for the layer. FEDAR results showed predicted heads within the cemented shell to be insensitive to the permeability used for the strata as long as it was relatively low (on the order of 10^{-8}cm/sec). The cemented shell layer was continued to elevation -35 feet (the elevation of the deepest piezometer) and below that was considered impervious.

Figure III-1 also shows piezometer locations at two instrumented sections along the length of the dam. These piezometers are at stations 370 and 460 and are located approximately 9000 feet from each other. Note that the only assumed differences between the two stations (for seepage studies) are the vertical locations of some of the piezometers.

Refined estimates of soil profile and permeabilities have evolved through Stone and Webster's seepage analyses. This current profile is shown in Figure III-2 and will be discussed later.

A FEDAR analysis (by the author) was made for permeabilities and boundary conditions shown in Figure III-1. Figure III-3 shows the flow net which resulted from this analysis. Figure III-4 gives total head measurements taken at Stations 370 and 460 and Figure III-5 compares measured and FEDAR predicted total heads at these piezometers.

SWDAM-TEST SECTIONS 370 AND 460



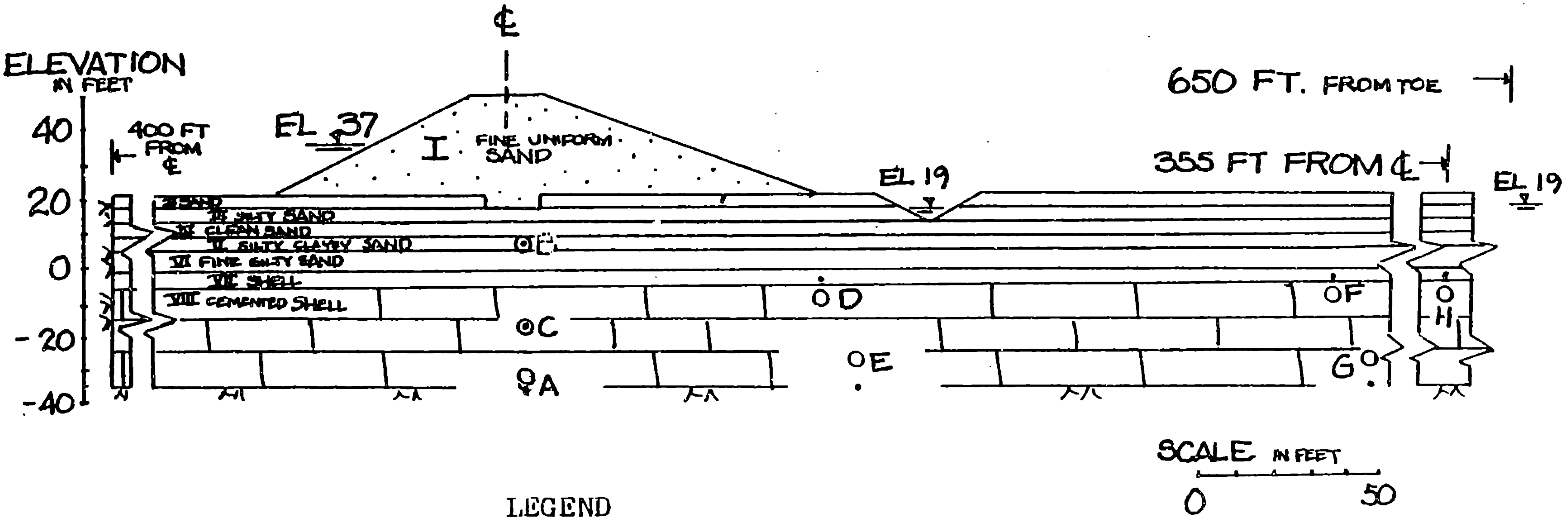
MATERIAL	PERMEABILITY (cm/sec)	
fine uniform SAND	$.0025 \times 10^{-2}$	$k_h = k_v$
stratified FOUNDATION	1.2×10^{-2}	$k_h = 1.6 k_v$
cemented SHELL	1.0×10^{-8}	$k_h = k_v$

LEGEND

- • Piezometer Sta. 370
- O Piezometer Sta. 460

FIGURE III-1

SW DAM - REFINED PROFILE



LEGEND

- • Piezometer Sta. 370
- o Piezometer Sta. 460

FIGURE III-2

FLOW NET - SW DAM

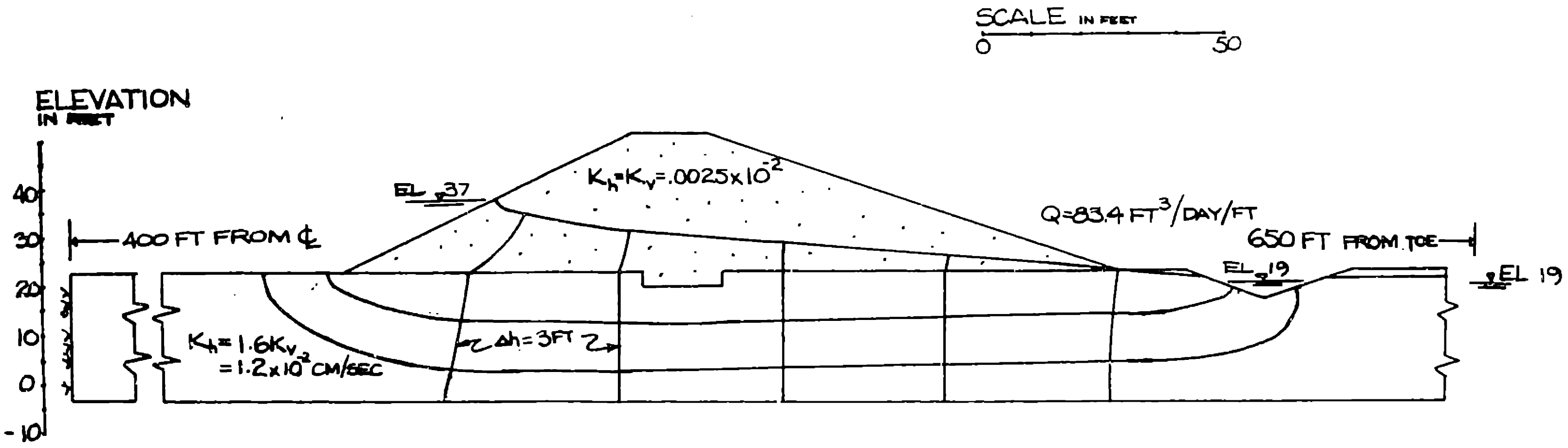
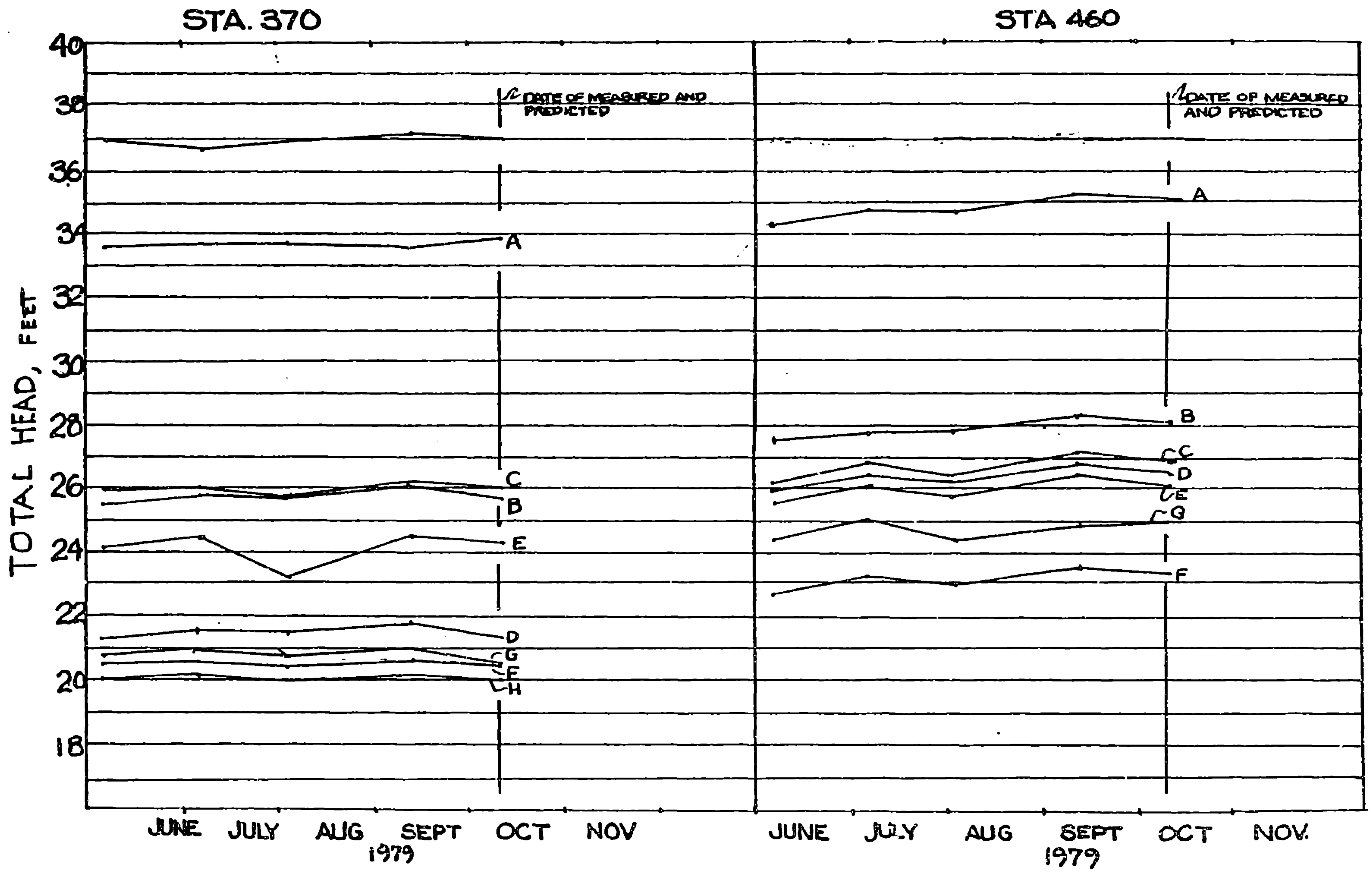


FIGURE III-3

FIGURE III-4

SWDAM - MEASURED TOTAL HEAD - TEST SECTIONS 370 AND 460



MEASURED AND PREDICTED TOTAL HEADS - SW DAM

PIEZOMETER	STATION 370 PREDICTED TOTAL HEAD	STATION 370 MEASURED TOTAL HEAD	STATION 460 PREDICTED TOTAL HEAD	STATION 460 MEASURED TOTAL HEAD
A	29.4	33.9	29.4	35.0
B	29.4	25.7	29.4	28.1
C	29.4	26.0	29.4	26.8
D	21.9	21.4	21.9	26.5
E	21.4	24.4	21.3	26.0
F	19.3	20.5	19.3	23.3
G	19.3	20.6	19.3	24.9
H	19.2	20.0	19.3	

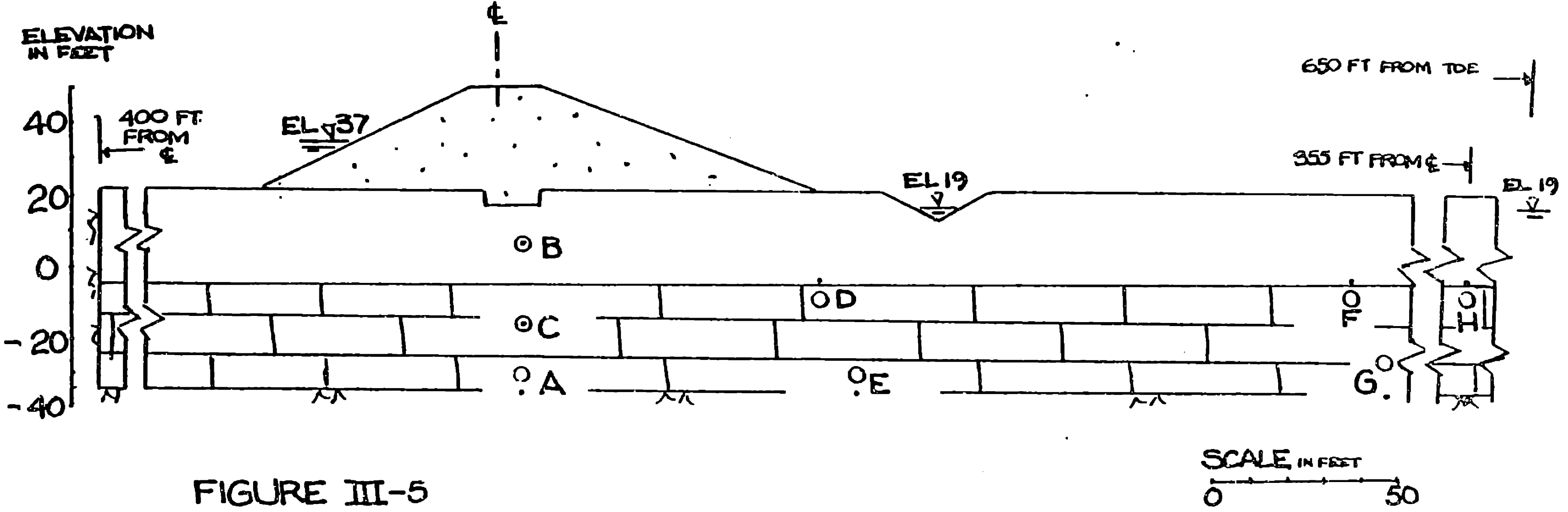


FIGURE III-5

Chapter IV

Tarbela Dam

The Tarbela Dam is located in Pakistan and is operated by the Water and Power Development Authority in Pakistan. TAMS Engineering in New York has done extensive seepage analysis on this project.

The main embankment of the Tarbela Dam has a crest length of approximately 9000 feet. About 6200 feet of this embankment is founded on deep alluvial deposits. Depths of the alluvium generally range from 200 to 350 feet, with local spots as deep as 600 feet. This case study will address pore pressures within the main embankment overlying these alluvial deposits.

TAMS estimated permeabilities of the river deposits from borehole permeability tests, field pumping tests, and estimates from grain size distribution. Water pressure tests were made in most core borings drilled in rock. Permeabilities resulting from these tests decreased with depth. This was attributed to the closing of joints under heavy load.

The core and upstream core extension were built of well-graded angular gravel, sand and silt mixture. Mixtures of core materials containing various percentages of silt were permeability tested in the laboratory. The permeability of plain silt was estimated to be 10^{-7} to 10^{-8}cm/sec. The mixtures of gravel, sand and silt showed permeabilities of

10^{-5} to 10^{-6}cm/sec, depending on percentage of silt contained.

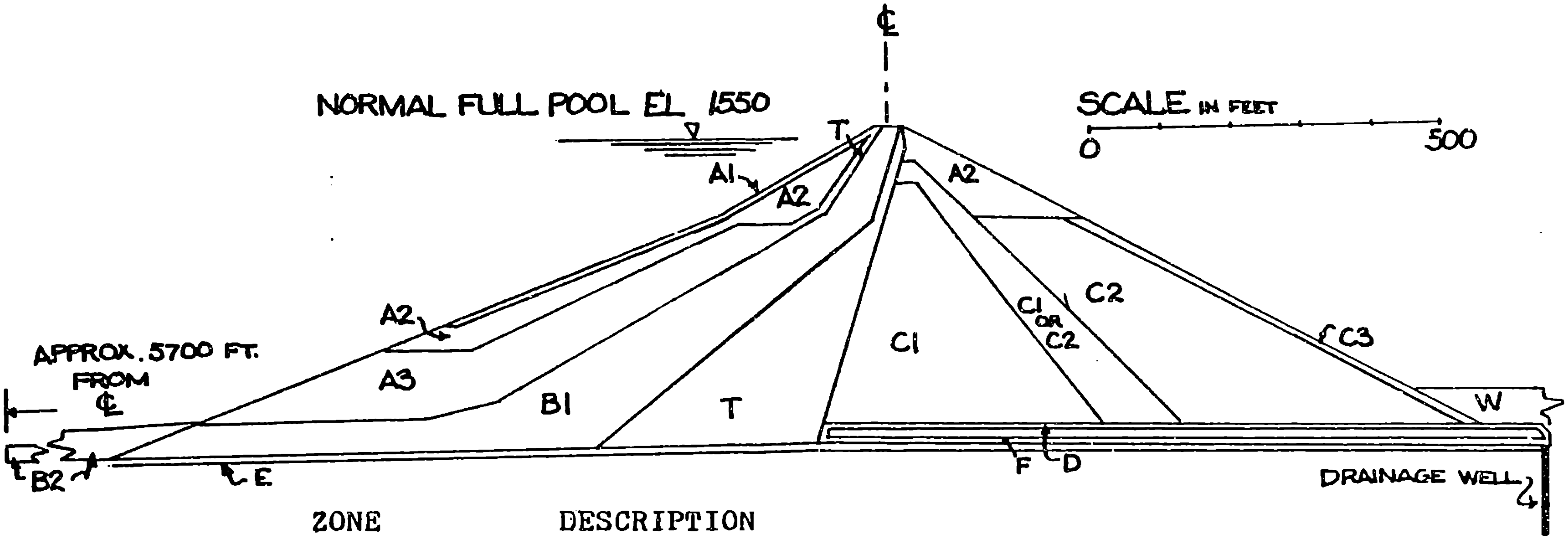
TAMS Engineering constructed several flow nets for different assumptions concerning foundation conditions and permeabilities. Schemes included the foundation as being homogeneous and isotropic, homogeneous and anisotropic ($k_h > k_v$), layered foundations with $k_h = k_v$, and layered foundations with $k_h > k_v$.

TAMS seepage analyses for flow through the embankment, blanket, and foundation were made for four different conditions. Permeability values of $k_c = k_b = 10^{-5}$, 10^{-6}, 10^{-7}, and 10^{-8}cm/sec were used for the core and blanket and $k_f = 2\text{x}10^{-2}$ cm/sec for the foundation. Examination of flow nets drawn by TAMS using the above permeabilities showed that differing values of $k_c = k_b$ and k_f resulted in varied seepage quantities but yielded the same distribution of head loss through the core of the embankment. Therefore, the analyses mentioned above all predicted the same total heads within the core.

Figure IV-1 shows a typical section of the main embankment, Figure IV-2 shows instrumented Section MC with piezometer locations, and Figure IV-3 shows the flow net (based on TAMS' flow nets but redrawn and slightly modified by the author) for $k_c = k_b = 10^{-7}$cm/sec and $k_f = 2\text{x}10^{-2}$cm/sec. TAMS considered the permeability of the core much lower than the permeability of the shell, filter transition, and drainage materials. Thus the shell, filter transition, and drainage materials were neglected for their seepage restricting ability and flow nets were drawn only through the core, blanket, and foundation.

Figure IV-4 shows total head measurements at piezometers at Test Section MC and Figure IV-5 compares these measured heads with those predicted from the flow net in Figure IV-3.

TARBELA DAM - TYPICAL SECTION



ZONE	DESCRIPTION
A1	RIPRAP SLOPE PROTECTION
A2	FREE DRAINING FILL
A3	GRANULAR FILL
B1	IMPERVIOUS CORE
B2	IMPERVIOUS BLANKET
C1	CENTRAL ZONE
C2	DOWNSTREAM SHELL
C3	FREE DRAINING SLOPE PROTECTION
T	TRANSITION
D	DRAINAGE ZONE
E	FOUNDATION FILL
W	WEIGHT BERM

FIGURE IV-1

TEST SECTION MC

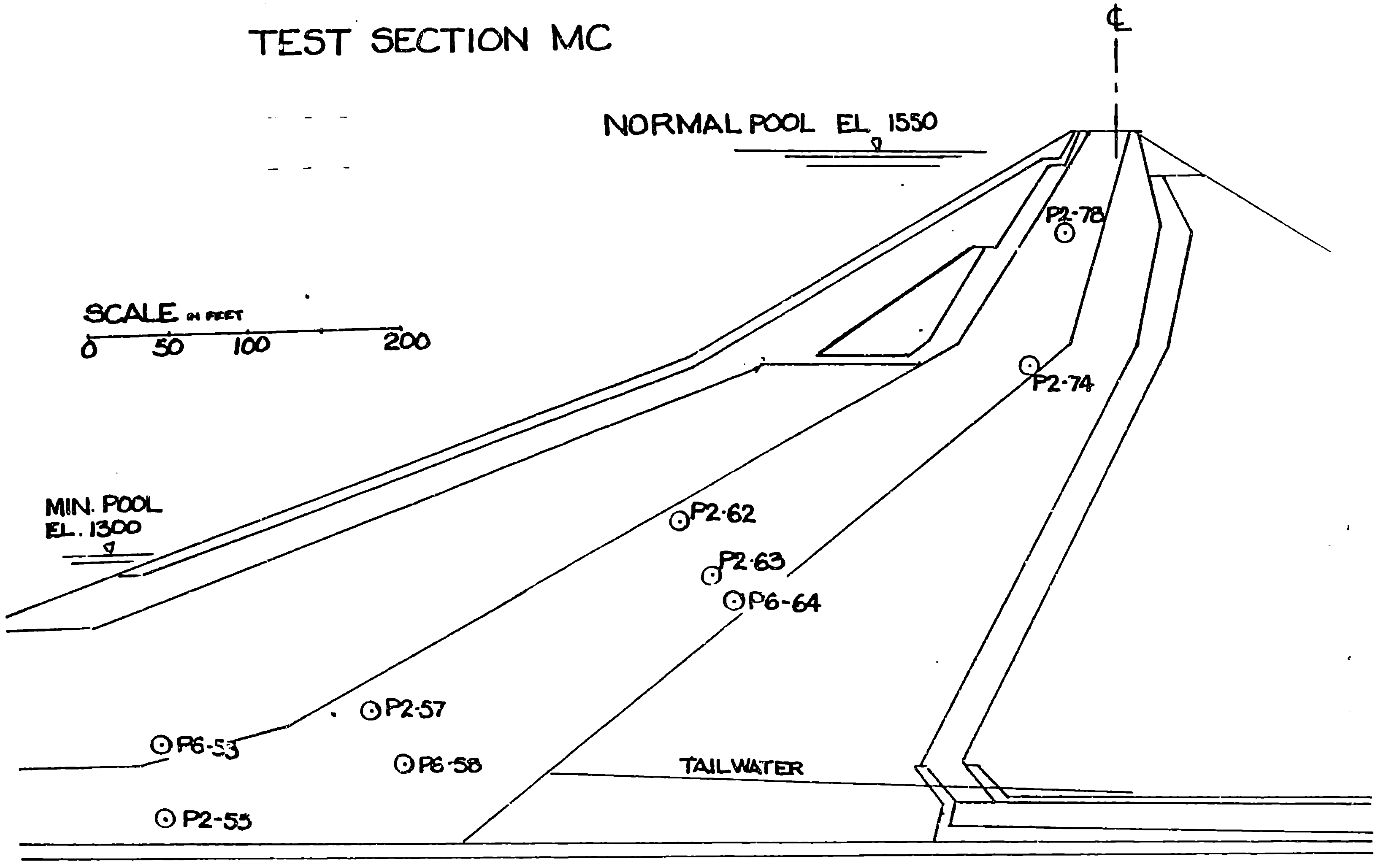
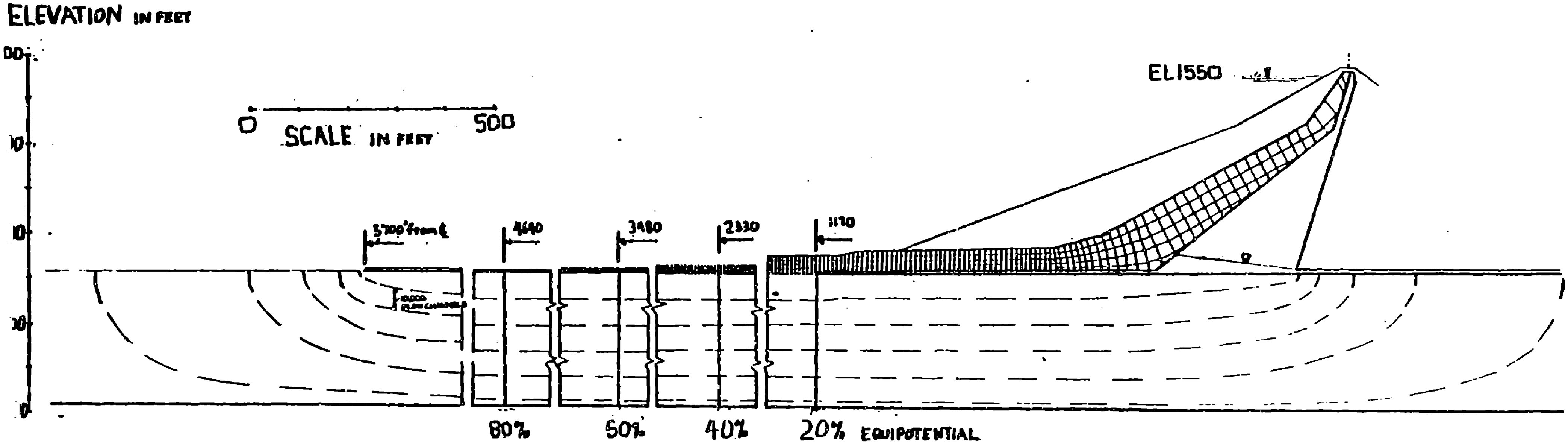


FIGURE IV-2

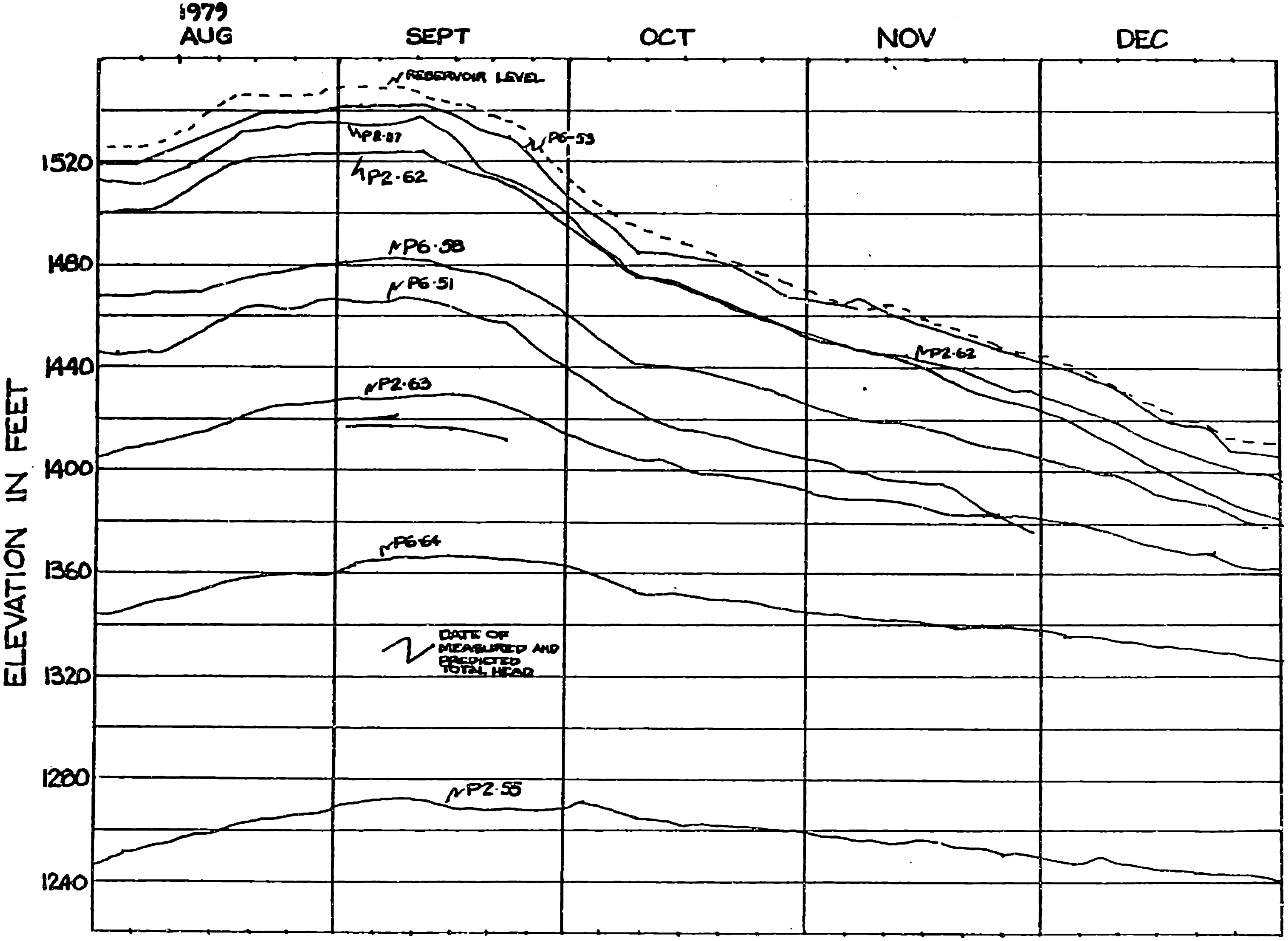
FLOW NET - TARBELA DAM - SECTION MC



$k_b = k_c = 10^{-7}$ cm/sec
$k_f = 2 \times 10^{-2}$ cm/sec

$Q_b = .21 \times 10^{-3}$ cfs
$Q_f = 14.7 \times 10^{-3}$ cfs
$Q_c = .006 \times 10^{-3}$ cfs

FIGURE IV-3



MEASURED TOTAL HEAD-TEST SECTION M.C.

FIGURE IV-4

MEASURED AND PREDICTED TOTAL HEADS-TEST SECTION MC

PIEZOMETER	PREDICTED TOTAL HEAD	MEASURED TOTAL HEAD
P2-78	1540	1535
P2-74	1440	1437
P2-62	1510	1562
P2-63	1375	1430
P6-64	1310	1367
P2-57	1480	1537
P6-58	1325	1484
P6-53	1550	1544
P2-55	1280	1273

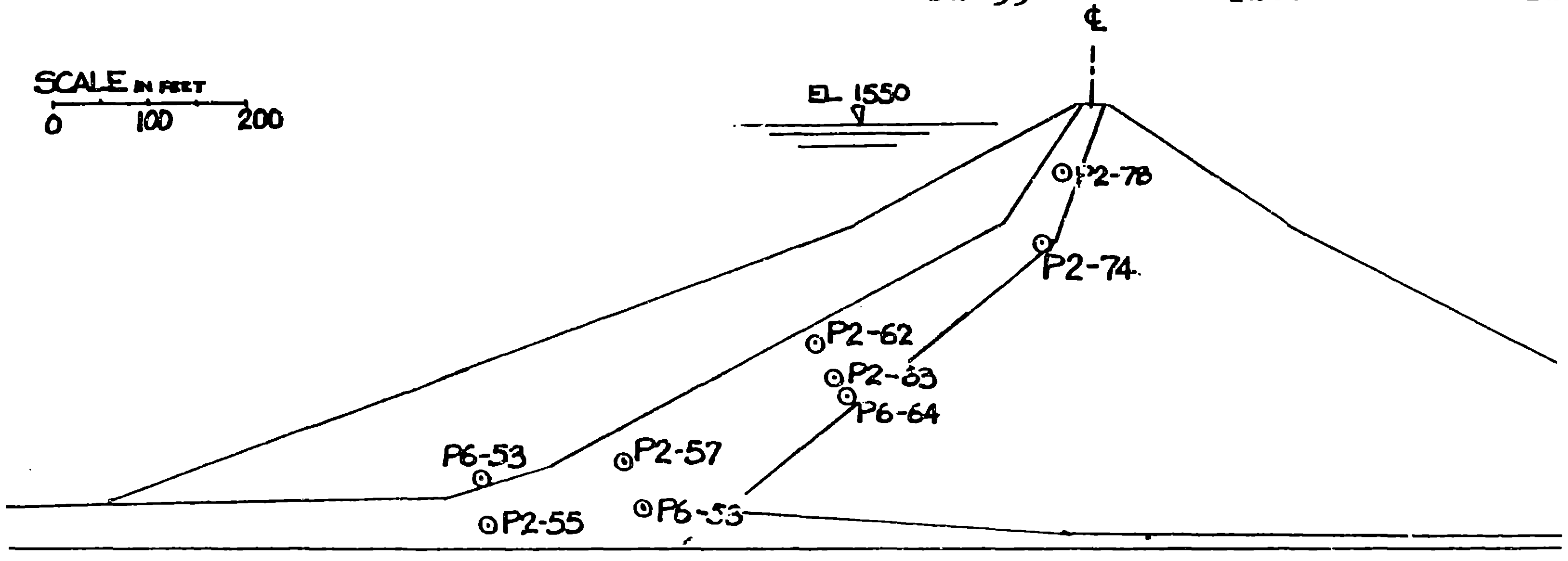


FIGURE IV-5

Chapter V

ACCURACY OF PREDICTIONS

In determining how well pore pressures were predicted, accuracy will be defined as

$$\text{Accuracy} = \frac{\text{Predicted Head - Measured Head}}{\text{Total Head Lost Through the Dam}}$$

A positive result indicates the predicted head is greater than the measured head and a negative result indicates the predicted head is less than the measured head.

Table V-1 lists accuracy as defined above for the predictions in each of the dams analyzed. The results in this table show a large variation in accuracy for each dam which will be discussed in the remainder of this chapter.

This type of data is well represented in histogram form. The shape of a histogram is very sensitive to the length of the interval used to represent the frequency of a range of data points. Benjamin and Cornell (1970) site an empirical rule which is often used to determine the optimum number of intervals for a given number of data points. This rule is

$$K = 1 + 3.3\log n$$

with K = number of intervals

n = number of data points

Table V-1 consists of 36 data points. The above equation suggests 6 intervals for data representation.

Figure V-1 shows the data in Table V-1 in histogram form. Since the purpose of this thesis is to evaluate predictive capability in general, all of the data points are grouped together in this analysis.

Table V-1 shows accuracy to range from -42% to 35%. The mean value of accuracy from these predictions is -7% with a standard deviation (unbiased) of 18.4%. This negative value of mean accuracy along with observation of the histogram in Figure V-1 suggests that pore pressures were generally underpredicted.

Confidence in predictions is very important when considering predicted and measured values of total head in evaluating the performance of a structure. There are probabalistic theorems which relate the mean, standard deviation, and probability distribution of discrete and random variables. For a distribution of data points having a single peak (as Figure V-1 suggests of the accuracy data) the probability of obtaining a value which deviates from the mean by at least k standard deviations is at most $1/2.25k^2$. This relationship is the result of refinements by Camp (Freeman, 1963) to the Bienayme-Chebychev Theorem. Thus, for the cases studied, the probability of predicting total head outside the accuracy range of ± one standard deviation is $1/2.25x1^2$ or less than 44%.

Figure V-2 graphically shows this relationship for the cases studied in this thesis. This figure shows that there is a 76% likelihood of predicting total head to within ±25% of the mean value (i.e., within the range of +18% to -32%) and a 94% likelihood of predicting total head to within ±50% of the mean value (within the range of +43% to -57%).

In analysis of data as in Figure V-1 an important question arises as to the significance of this data in relation to total head predictions in general. It would be useful to know how well the results of these four case studies compare with the results of other cases. There are many published articles which contain measured pore pressures but very few which also contain permeabilities and boundary conditions used in the original analyses. Some articles do give permeabilities and boundary conditions but it is difficult to ascertain if these have been biased as a result of field measurements.

Significance tests can be made on data to determine how well they represent the total population of similar data. This is done by assuming the total population follows a certain probability distribution. More data of this type (Type A total head predictions) are needed to help determine the probability distribution(s) which would best represent data of this kind. It is important to note that all of these data are not independent of each other as required for most common distributions. For example, some of the cases studied showed measured heads to be overpredicted, while others showed measured heads to be underpredicted. As an initial estimate as to the accuracy of Type A predicted total heads it is probably best to initially use data grouped together from different dams. More refined comparisons and estimates might be warranted if certain similarities exist between a dam being studied and one which has already been studied. For example, if a dam with a stratified foundation is encountered, comparisons with results from the SWDAM case study might give some further insight into certain aspects which might yield problems.

In evaluating predictive capability it is important to know what factors are important in limiting accuracy. The next chapter discusses factors which led to discrepancies between measured and predicted total heads in the cases studied.

Table V-1

ACCURACY OF PREDICTED HEADS

DAM	ΔH Total Head Lost (FT)	PIEZOMETER	P Predicted Total Head (FT)	M Measured Total Head (FT)	ACCURACY $\frac{P-M}{\Delta H}$ %
Piney Point	44	P16	38	31.5	15
		P17	34	30.2	9
		P18	35	27.5	17
		P19	39	23.6	35
		P20	dry	18.4	-42
		P21	10	13.9	-9
BF-1	10	P1	108.7	111.1	-24
		P2	109.0	109.7	-7
		P3	109.0	111.4	-24
		P4	117.7	117.4	3
		P5	113.9	114.3	-4
Tarbela	394	P2-78	1540	1535	1
		P2-74	1440	1437	1
		P2-62	1510	1562	-13
		P2-63	1375	1430	-14
		P6-64	1310	1367	-14
		P2-57	1480	1537	-14
		P6-58	1325	1484	-40
		P6-53	1550	1544	2
		P2-55	1280	1273	2

Table V-1 (continued)

ACCURACY OF PREDICTED HEADS

DAM	ΔH Total Head Lost (FT)	PIEZOMETER	P Predicted Total Head (FT)	M Measured Total Head (FT)	ACCURACY $\frac{P-M}{\Delta H}$ %
SWDAM Sta. 370	18	A	29.4	33.9	-25
		B	29.4	25.7	21
		C	29.4	26.0	19
		D	21.9	21.4	3
		E	21.4	24.4	-17
		F	19.3	20.5	-7
		G	19.3	20.6	-7
		H	19.2	20.0	4
SWDAM Sta. 460	18	A	29.4	35.0	-31
		B	29.4	28.1	7
		C	29.4	26.8	14
		D	21.9	26.5	-26
		E	21.3	26.0	-26
		F	19.3	23.3	-22
		G	19.3	24.9	-31
		H	19.3		

FREQUENCY OF PREDICTED ACCURACIES FOR CASES STUDIED

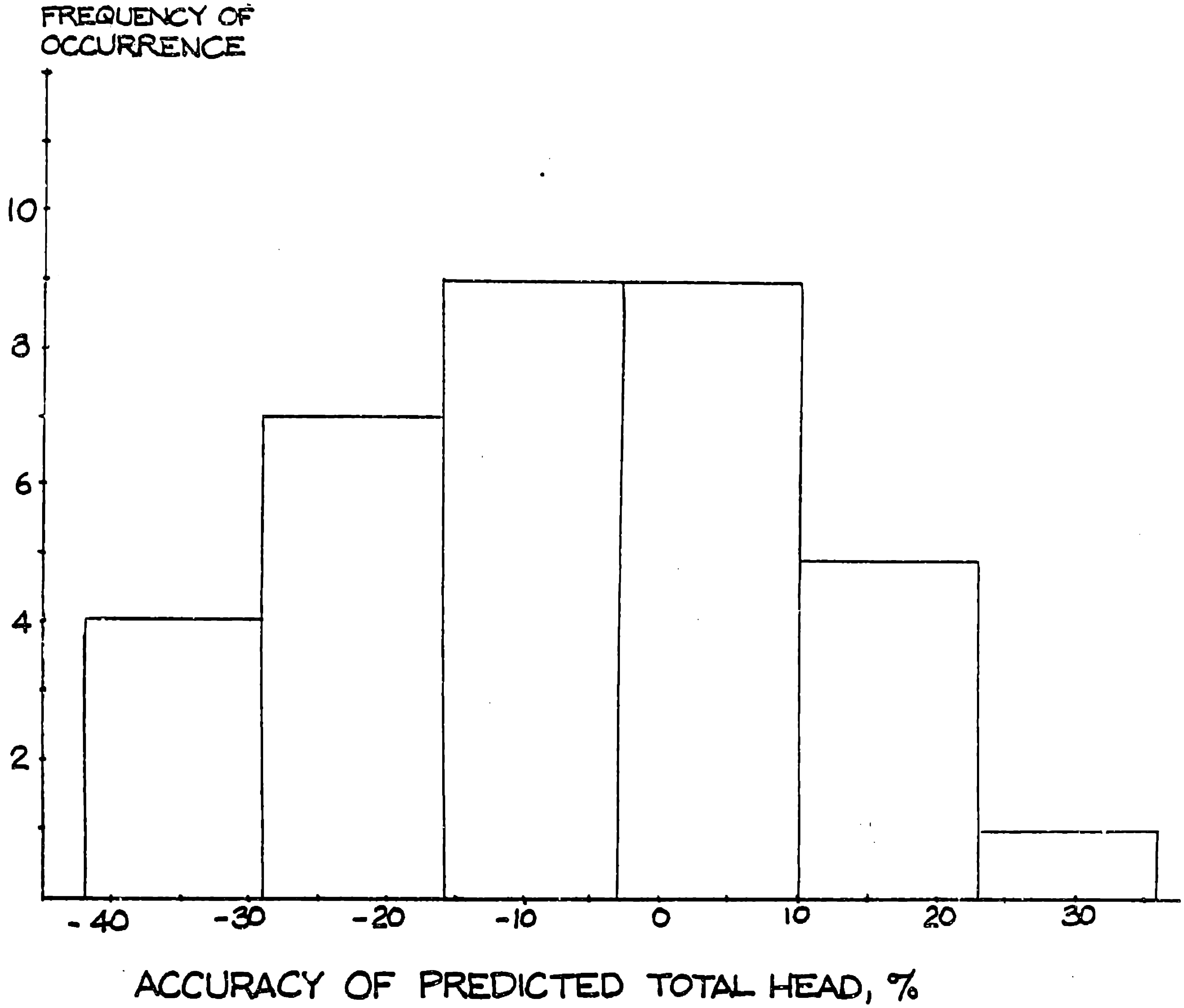
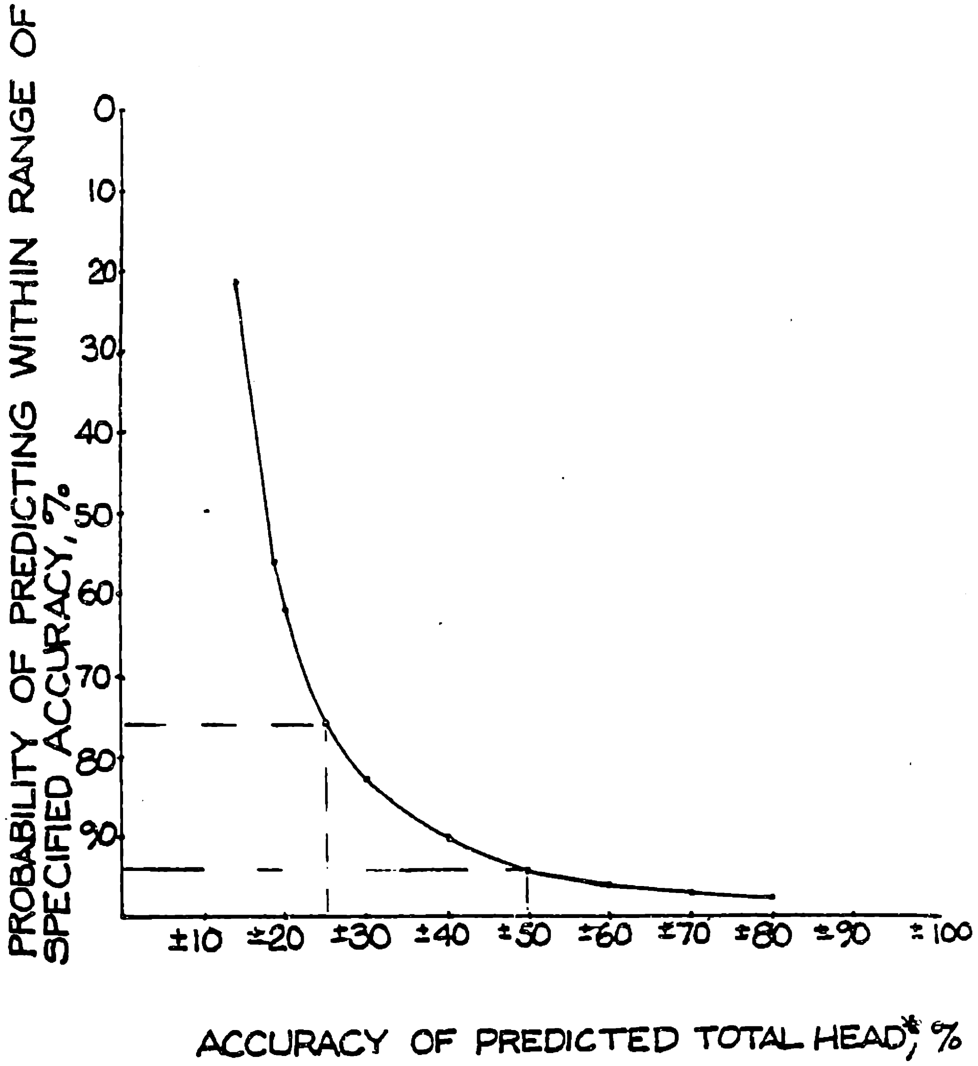


FIGURE V-1

PROBABILITIES OF PREDICTION (BASED ON FOUR CASE STUDIES)



*BASED ON ACCURACY FROM MEAN VALUE OF -7% (IE. ±20% = RANGE FROM +13% TO -27% ACCURACY)

FIGURE V-2

Chapter VI

DISCREPANCIES BETWEEN MEASURED AND PREDICTED HEADS

This chapter considers reasons for discrepancies between measured and predicted total heads. In the cases studied, important factors in predicting total heads were how well assumed boundary conditions, soil profile and soil permeabilities matched actual field conditions.

Boundary Conditions

Small variations in boundary conditions can cause marked changes in quantities of flow and head loss through an earth dam. Boundary conditions used in the cases studied in this thesis are based on estimates of the actual field condition. Comparisons of predicted and measured total heads were made when reservoir levels in the field were the same as those used in the Type A analyses. Water elevations in the return ditches and at specified distances from the embankments were based on engineers' estimates prior to the operation of the structures.

An important boundary condition estimate is how far from within the reservoir water should be assumed as flowing toward the embankment. This is quite important in a case such as the Tarbela Dam. In the section of this dam which was studied comparatively little flow occurs through the blanket and core as opposed to the foundation. Examination of the flow net for this case (Figure IV-3) shows that most of the flow originates beyond the blanket toward the center of the reservoir. If the boundary of no flow toward the embankment were taken closer to the blanket, less flow and a different distribution of head loss would result in the foundation.

An estimate often used for this boundary condition of flow from within the reservoir is to assume that there is no flow across the centerline of the reservoir. The Piney Point case study does not extend this boundary out that far. Observation of the flow net (Figure I-3) shows that most of the head loss is through the compacted gypsum. For this geometry and distribution of head loss, extending the boundary farther within the reservoir would result in insignificant changes in amounts of flow and head loss distribution. FEDAR analyses also showed this to be true for the BF-1 case study. The centerline of the reservoir for this case is more than 4000 feet from the centerline of the dam which was used as the boundary from within the reservoir. FEDAR results showed that extending this boundary farther into the reservoir results in an insignificant increase in flow quantity and no change in head loss distribution. This can be seen by noting most of the flow originates close to the embankment in Figure II-3.

Soil Profile and Permeability

SWDAM

Figure VI-1 shows a cross-section of the SWDAM as presently perceived. As mentioned earlier, this section was not used in the original analysis. The permeabilities on this figure are the result of seepage studies, by the Stone and Webster Engineering Corporation, based on measured heads and gradients throughout the profile.

A FEDAR analysis was made (by the Author) on this refined profile. Figure VI-2 compares the flow net for the homogeneous representation of the foundation with the phreatic surface and equipotentials of the refined profile. Note the difference in shape of the equipotentials. Figure VI-2b shows total head to be quite sensitive to position in relation to the low permeability silty clayey Sand layer. Most of the flow through this dam and foundation will be through the Sand and Shell layers. High gradients result through the silty clayey Sand layer which could yield problems of soil transport and low effective stress, especially downstream of the dam. These potential problems cannot be as easily foreseen if the foundation is treated as homogeneous.

Table VI-1 compares measured and predicted total heads for the homogeneous and stratified foundations. Pore pressure measurements for this particular profile are highly dependent on the geometry and thickness of the soil layers. This can be seen by noting the marked differences in measured total heads at similar locations of Stations 370 and 460. The difference in measurements suggests the geometries to be different at the two stations.

Figure VI-1 and Table VI-1 show that representing a stratified foundation as homogeneous can lead to marked differences in predictions and misleading conclusions as to the performance of the dam.

BF-1 DAM

Upon completion and filling of BF-1 reservoir high pore pressure measurements in the toe at instrumented Station 106 lead to a reassessment of the flow conditions of the dam. These pore pressure measurements were much higher than those predicted in the original analyses. This indicated a difference existed between soil profile and permeabilities used in the analyses and those which actually exist in the field. In fact, close examination showed the silty sand (hardpan) layer upstream was partially removed from inside the reservoir. Re-evaluation also indicated that the core did not reach into the low permeability matrix at some locations.

Observations of exposed soils in the mine cut lead to conclusions that the permeability of the clean sand is lower than that used in the original analysis and the permeability of the matrix is higher than that used. Review of construction drawings lead to uncertainties as to whether the core ties into the matrix at Station 162 and as to whether the hardpan within the reservoir was removed for borrow. Figure VI-3 shows a cross-section at Station 162 with the core tying into the matrix and the hardpan existing within the reservoir. This figure also compares original permeability estimates with the refined estimates from Station 106 and further refinements for Station 162.

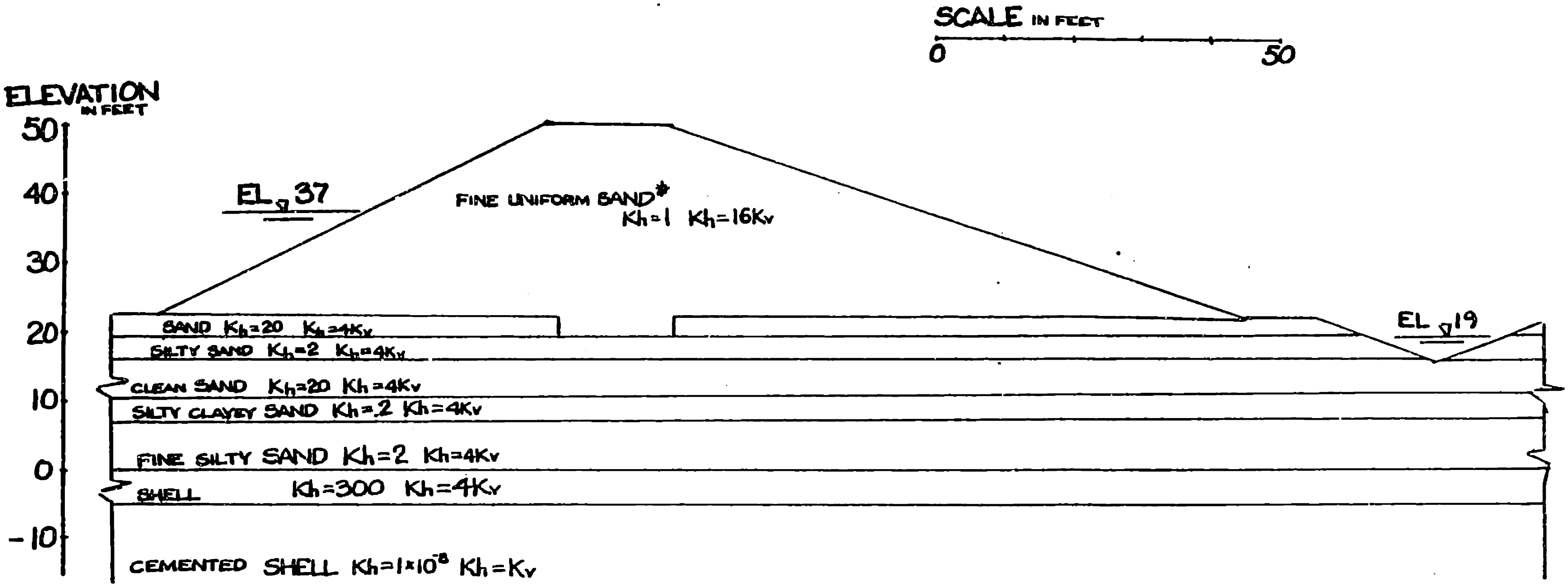
The measured total heads at Station 162 could be reasonably matched with FEDAR predictions by using the permeabilities of Station 106 studies (although the matrix permeability was halved), continuing the core into the matrix, and assuming half of the hardpan thickness upstream was removed. Figure VI-4 compares the phreatic surface and equipotentials for this Type C prediction with the flow net from the original analysis. Table VI-2 compares FEDAR predicted total head from both analyses with measured total head. Better accuracy of the Type C prediction is due to the increased knowledge of geometry and permeabilities. Permeabilities from Station 106 studies greatly facilitated this further study at Station 162.

Different combinations of permeability and soil profile could result in reasonably matched predictions and measurements at a particular instrumented station. In Type C predictions the engineer must be careful to keep perspective on geometry and permeabilities. Assumptions made in this particular case are reasonable in that they have been substantiated by construction records and observations in the field.

Instrument Location

An important point that arises in the prediction of pore pressures and in the significance of these predictions is whether pore pressures can be more accurately predicted at one location in a dam (or its foundation) than at another location. It would seem reasonable that predictions would be most accurate nearer the known boundary conditions. The BF-1 case study shows that this is not necessarily true. Piezometer P1 (located near the return ditch) shows a much larger discrepancy between measured and predicted head than piezometer P2 (located near the centerline of the dam). This is because the pervious sand layer underlying a much less pervious layer can make measured pore pressures quite sensitive to the vertical location of the measuring instrument. This results from a great deal of head loss from flow up through the less pervious hardpan layer.

SWDAM - REFINED SOIL PROFILE

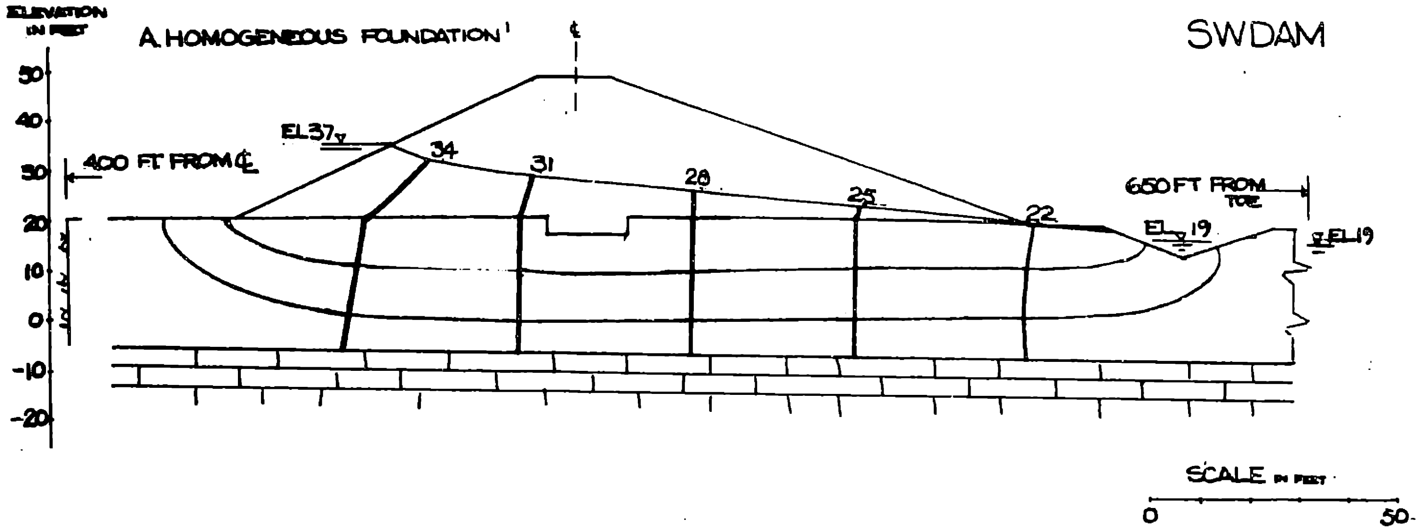


*FINE UNIFORM SAND $K_h = 5 \times 10^{-4}$ CM/SEC = 1

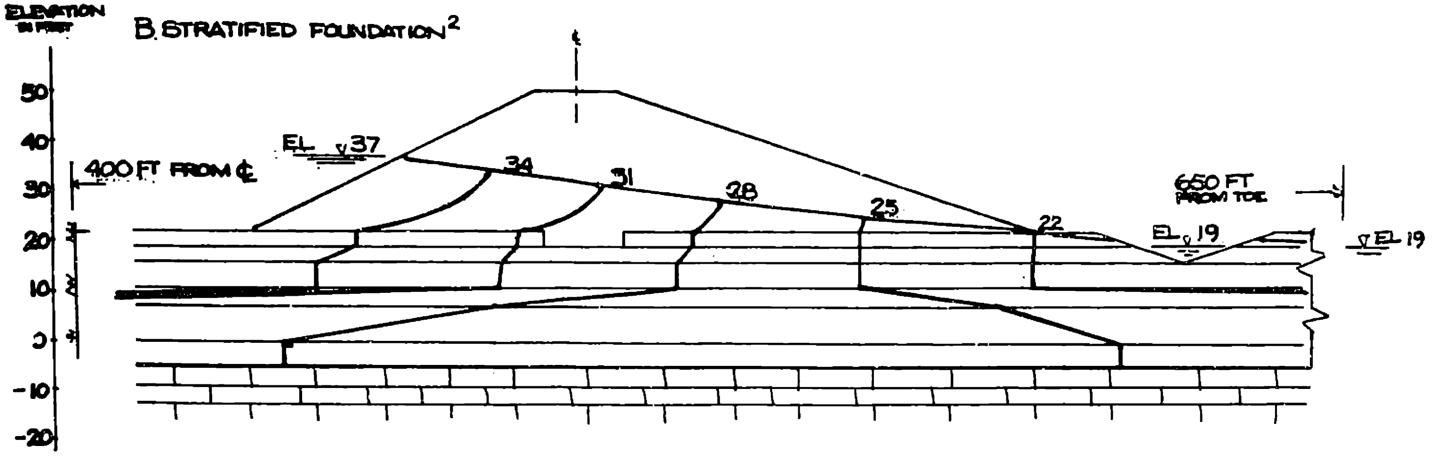
FIGURE VI-1

COMPARED HOMOGENEOUS AND STRATIFIED FOUNDATION–SWDAM

A. HOMOGENEOUS FOUNDATION[1]



B. STRATIFIED FOUNDATION[2]



[1] PERMEABILITIES GIVEN IN FIGURE III-1

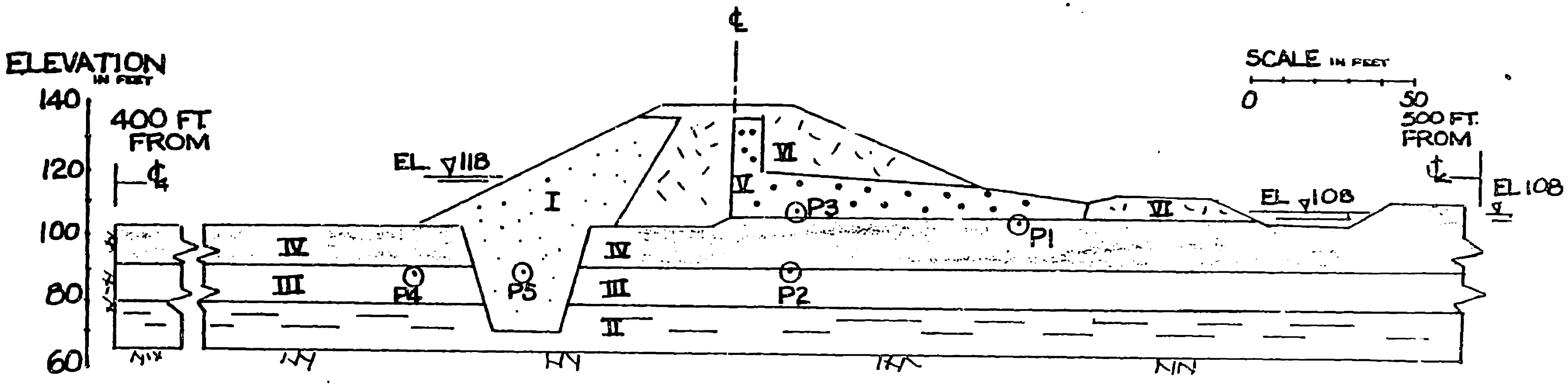
[2] PERMEABILITIES GIVEN IN FIGURE VI-1

FIGURE VI-2

Table VI-1
PREDICTED TOTAL HEADS AT SWDAM

PIEZOMETER	STATION 370			STATION 460		
	Measured Head (FT)	Predicted Head Homogeneous Foundation (FT)	Predicted Head Stratified Foundation (FT)	Measured Head (FT)	Predicted Head Homogeneous Foundation (FT)	Predicted Head Stratified Foundation (FT)
A	33.9	29.4	26.9	35.0	29.4	26.9
B	25.7	29.4	27.7	28.1	29.4	27.7
C	26.0	29.4	26.9	26.8	29.4	26.9
D	21.4	21.9	25.4	26.5	21.9	25.4
E	24.4	21.4	25.2	26.0	21.3	25.2
F	20.5	19.3	23.1	23.3	19.3	23.1
G	20.6	19.3	22.9	24.9	19.3	22.9
H	20.0	19.2	21.5	25.5	19.3	21.5

RELATIVE PERMEABILITY ESTIMATES - STATION 162



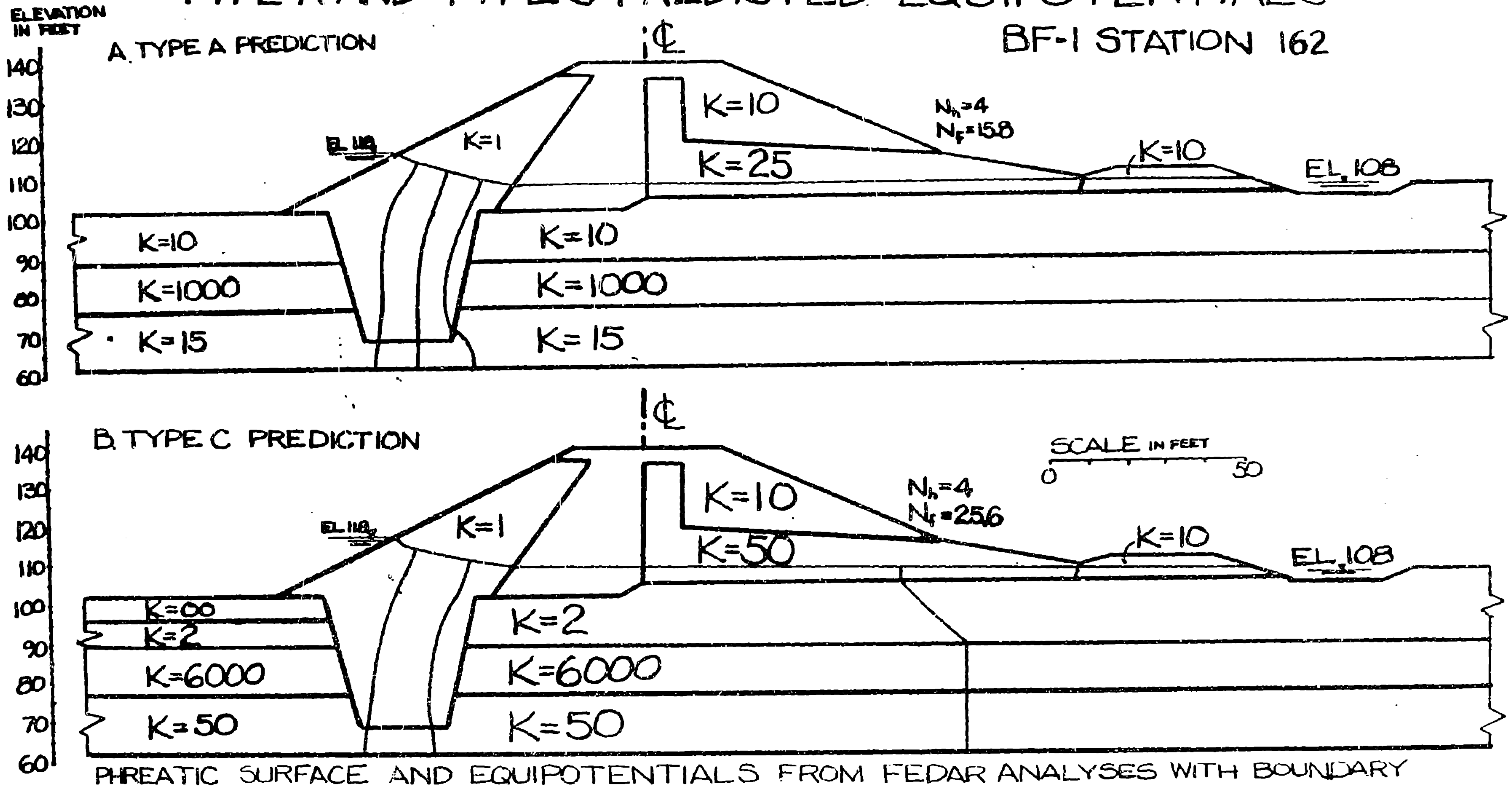
	MATERIAL	RELATIVE PERMEABILITY ESTIMATES Type A Estimates	Station 106 Estimates	Estimates from Sta. 162 Studies
I	CORE	1	1	1
II	MATRIX	15	100	50
III	SAND	1000	6000	6000
IV	HARDPAN*	10	2	2
V	DRAIN	25	50	50
VI	GENERAL FILL	10	10	10

FIGURE VI -3

* Station 162 studies suggest approximately $\frac{1}{2}$ of upstream hardpan layer removed

TYPE A AND TYPE C PREDICTED EQUIPOTENTIALS –

BF-1 STATION 162



PHREATIC SURFACE AND EQUIPOTENTIALS FROM FEDAR ANALYSES WITH BOUNDARY CONDITIONS FROM FIGURE VI-3

FIGURE VI-4

Table VI-2
TYPE A AND TYPE C PREDICTIONS AT BF-1 DAM

PIEZOMETER	MEASURED HEAD (FT)	TYPE A PREDICTION/ACCURACY (FT)	TYPE B PREDICTION/ACCURACY (FT)
P1	111.1	108.7 / -24%	110.3 / -8%
P2	109.7	109.0 / 12%	110.9 / 12%
P3	111.4	109.0 / -24%	110.9 / -5%
P4	117.4	117.7 / 3%	116.9 / -5%
P5	114.3	113.9 / -4%	114.7 / 3%

CONCLUSIONS

The purpose of this thesis was to evaluate the civil engineering profession's predictive ability in regards to steady state pore pressure in earth dams. Four case studies were examined in which Type A predictions were made for each case. The histogram in Figure V-1 illustrates the scatter in these predictions and shows that pore pressures were generally underpredicted. Pore pressure predictions in these four cases had a mean accuracy of -7% and a standard deviation of 18.5%.

Figure V-2 summarizes the accuracy of Type A predictions for the cases studied. Based on the data from these cases there is a 76% liklihood of predicting total head to within ±25% of the mean value of -7% accuracy and a 94% liklihood of predicting total head to within ±50% of the mean value. Data such as those in Figure V-2 can be useful in estimating the accuracy of Type A predicted total head in other dams. The data which are represented by this plot considers all of the dams together. This was done to give a perspective on Type A predictions in general.

More information from other dams would be useful in broadening the data base from which more general statements of predictive capability could be made. Unfortunately very few published articles containing pore pressure measurements also contain the information necessary to assess the Type A predictive accuracy.

In Type A analyses of other dams information such as that contained in Figure V-2 can be useful in estimating ranges in other aspects of performance of earth dams which are related to pore pressure (such as stability). If certain similarities exist between a dam being studied and one which has already been studied then more refined comparisons and estimates might be possible.

Boundary conditions, soil profile, permeability estimates and instrument location were discussed in the cases studied.

Boundary conditions used in the case studies were based on estimates of the actual field condition. An important boundary to be considered is how far from within the reservoir water should be assumed as flowing toward the embankment. Pore pressures can be quite sensitive to this boundary in a case such as the Tarbela Dam where a seepage restricting blanket extends into the reservoir. One estimate for this boundary is to assume there is no flow across the centerline of the reservoir. The Piney Point and BF-1 analyses showed that pore pressures can be insensitive to changes in this boundary after extending it a certain distance out into the reservoir. In the Piney Point case this was attributed to the major source of head loss being well removed from this boundary. In the BF-1 case most of the flow lines originate close to the embankment and extension of this boundary farther toward the center of the reservoir results in insignificant changes in pore pressures and seepage quantity.

Type C analyses of Station 162 (BF-1) showed that measured heads could be reasonably matched using field measurements and observations of the functioning dam. Information from analyses of another station from this dam gave insight into field permeabilities, which were useful in the Type C analysis. Use of these revised permeabilities along with recorded field observations and construction records led to more accurate predictions for the Type C analyses than for the Type A analyses. In Type C predictions the engineer must be careful to keep perspective on geometry and permeabilities. There are many combinations of both which could lead to reasonably matched predictions and measurements.

The SWDAM case study illustrated that representing a stratified foundation as homogeneous can yield misleading results and conclusions as to the performance of the dam. Potential problems such as high gradients leading to soil transport and/or low effective stress can be masked by misrepresenting the stratified layers as homogeneous.

No general statement can be made relating accuracy of prediction in relation to location in a dam or foundation. The BF-1 case study showed that accuracy depends very much on where the major loss of head occurs in the dam and foundation.

The cases studied in this thesis showed that the civil engineering profession is limited in its ability to predict pore pressures in earth dams largely because of limitations in knowing field permeabilities, geometry and boundary conditions. Improvement of predictive capability of pore pressures in earth dams will most likely come about from the profession's improving its ability to determine actual field conditions.

REFERENCES

Benjamin, J.R. and Cornell, C.A. (1970), Probability, Statistics and Decision for Civil Engineers, McGraw-Hill.

Casagrande, A. (1937), "Seepage Through Dams", J. New England Water Works Association, June 1937, pp. 131-170.

Cedergren, H.R. (1977), Seepage, Drainage and Flow Nets, John Wiley and Sons, Inc.

Freeman, H. (1963), Introduction to Statistical Inference, Addison-Wesley Publishing Company, Inc., pp. 30-31.

Harr, M.E. (1962), Groundwater and Seepage, McGraw-Hill.

Lambe, T.W. (1973), "Predictions in Soil Engineering", Geotechnique 23, No. 2, pp. 149-202.

Lambe and Associates (1978), "Flow and Stability Analyses for Big Four Waste Retention Dam No. 1", Report prepared for Borden Chemical, Borden, Inc., January, 1980.

Lambe and Associates (1980), "Performance Evaluation, Big Four Safety Program, January-December 1979", Report prepared for Borden Chemical, Borden, Inc., January 1980.

Lambe and Associates (1976), "Quarterly Report, Piney Point Surveillance, October-December, 1976", Report prepared for Borden Chemical, Borden, Inc.

Lambe, T.M. (1973) and Whitman, R.V. (1969), Soil Mechanics, John Wiley and Sons, Inc.

Leps, T.M. (1973), "Flow Through Rock Fill", in Embankment Dam Engineering - Casagrande Volume, John Wiley and Sons, 1973.

Marr, W.A. and Lambe, T.W. (1977), "Predicted and Measured Pore Pressures in a Dam", Proceedings of Specialty Session on Computers in Soil Mechanics, Ninth International Conference on Soil Mechanics and Foundation Engineering, July 1977.

Miller, I. and Freund, J.E. (1977), Probability and Statistics for Engineers, Prentice-Hall, Inc.

Milligan, V. (1975), "Field Measurement of Permeability in Soil and Rock", ASCE Conference on In Situ Measurement of Soil Properties, June 1-4, 1975, Vol. 11, pp. 3-33.

REFERENCES (continued)

Stone and Webster Engineering Corporation (1980), Personal communication.

TAMS, Tippetts-Abbett-McCarthy-Stratton, Engineers and Architects, Personal communication.

Taylor, R.L. and Brown, C.B. (1967), "Darcy Flow Solutions with a Free Surface", Journal of the Hydraulics Division, ASCE, 93, No. HY2, pp. 25-33.