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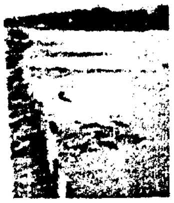

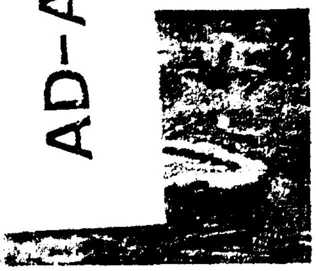

REMR RESEARCH PROGRAM

REPAIR, EVALUATION, MAINTENANCE, AND REHABILITATION RESEARCH PROGRAM

TECHNICAL REPORT REMR-GT-11

LEVEE UNDERSEEPAGE ANALYSIS FOR SPECIAL FOUNDATION CONDITIONS

by

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GT	Geotechnical	EI	Environmental Impacts
HY	Hydraulics	OM	Operations Management
CO	Coastal		

COVER PHOTOS:

TOP - Schematic of levee underseepage.
SECOND - Expedient measures for control of high water.
THIRD - Sand boil ringed with sandbags to control adverse effects of underseepage.
BOTTOM - Levee erosion due to a combination of underseepage and through seepage.

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

This report describes a research study in which techniques were developed for prediction of underseepage conditions for special cases of levee and foundation geometry. The differential equations for levee underseepage were derived and programmed in finite difference form for three special cases of boundary conditions. The developed programs allow analyses that are not restricted to the boundary conditions assumed in the conventional, closed form solution, i.e., two foundation layers of uniform thickness with horizontal boundaries.

The three special cases of foundation conditions that can be analyzed are as follow:

a. Foundations consisting of three layers of uniform thickness with horizontal boundaries and differing horizontal and vertical permeability in each layer.

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A report of the Geotechnical problem area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Programs. Available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

18. SUBJECT TERMS (Continued).

Analyses	Numerical methods
Foundations	Permeability
Geometry evaluation	Rehabilitation
Irregular boundaries	Underseepage
Levees	

19. ABSTRACT (Continued).

b. **Foundations consisting of two layers of nonuniform thickness with irregular boundaries.** and

c. Levee reaches where the levee alignment bends or forms a corner. Capabilities of the techniques and programs are demonstrated by comparing theoretical solutions to observed performance at eight field locations where piezometric data are **available. At each location, the field permeability ratio was estimated by** varying program input and seeking a match between the program output and actual observed performance.

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PREFACE

This study reported herein was performed during the period 18 March 1987 through 30 September 1987 under Contract No. DACW39-87-K-0041 as a research need of Work Unit 32274, "Rehabilitation Alternatives to Control Adverse Effects of Levee Underseepage," of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program being conducted by the US Army Engineer Waterways Experiment Station (WES).

This report was prepared by Dr. Thomas F. Wolff of Michigan State University. The study addresses the prediction of underseepage conditions for special cases of levee and foundation geometry that may not be adequately modeled by traditional procedures. Dr. Wolff was assisted by Messrs. Magdal N. Haji, Hassan Al-Moussawi, Ali F. A. Rassoul, Fritz Klingler, and Shawn Reed.

The study was under the direct supervision of Mr. G. Britt Mitchell, the Problem Area Leader. Mr. Hugh M. Taylor, Jr., was Principal Investigator and Contracting Officer's Representative, Soil Mechanics Division (SMD), during the conduct and publication of the work. General supervision was provided by Mr. Clifford L. McAnear, Chief, SMD, and Dr. William F. Marcuson III, Chief, GL.

Data and technical support for the study were provided by Messrs. George Mech, Sibte A. Zaidi and Donald Baumann of Rock Island District; Bruce H. Moore, George J. Postol, and Patrick J. Conroy of the St. Louis District; Joseph Keithly and John Monroe of the Memphis District; and Bobby Fleming and Wayne Forrest of the Vicksburg District. Partial funding was provided by the Rock Island and Vicksburg Districts.

The Directorate of Research and Development Coordinator for REMR in Headquarters, US Army Corps of Engineers (HQUSACE), was Mr. Jesse A. Pfeiffer, Jr. Members of the REMR Overview Committee in HQUSACE were Mr. James E. Crews and Dr. Tony C. Liu. Mr. Arthur H. Walz was Technical Monitor. The WES REMR Program Manager was Mr. William F. McCleese, WES.

Commander and Director of WES during the preparation of this report was COL Larry B. Fulton, EN. Dr. Robert W. Whalin was Technical Director.

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LEVEE UNDERSEEPAGE ANALYSIS FOR SPECIAL FOUNDATION CONDITIONS

PART I: INTRODUCTION

Background, Purpose, and Scope

1. A Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Levee Underseepage Workshop was held at the US Army Engineer Waterways Experiment Station (WES) on 19 April 1984 to establish research needs related to control of levee underseepage. Representatives from the Rock Island, St. Louis, Memphis, and Vicksburg Corps of Engineers (CE) Districts attended the workshop. One of the research tasks established was comparing predicted levee underseepage conditions to observed performance. In September 1986, a critical review of underseepage analysis procedures was prepared by this author (Wolff 1986) under an Interagency Personnel Agreement with the WES Geotechnical Laboratory. The workshop and the critical review both indicated that levee and foundation geometry may significantly affect seepage conditions, and the method of modeling geometry in analysis may affect performance predictions.

2. The focus of underseepage analysis is to estimate or predict the residual head, h_o, and exit gradient, i, at the landside levee toe or berm toe during high water. Where the predicted gradient exceeds some critical value, typically 0.85, control measures such as relief wells or seepage berms are provided. The analysis procedure presently used by the CE WES 1956a; US Army, Office, Chief of Engineers 1978) assumes two-dimensional (2-D) flow and models the subsurface profile as two horizontal layers of uniform thickness. In the Mississippi River Valley, the upper layer, or semipervious top stratum, is typically 2 to 20 ft* thick and consists of clays, silts, silty sands, or combinations thereof. The lower layer, or pervious substratum, is typically 50 to 150 ft thick and consists of clean sand, gravelly sand, or silty sand. The analysis procedure is based on a solution obtained by Bennett

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* A table of factors for converting non-SI units of measurement to SI (metric) units is presented on page 7.

CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745329	radians
feet	0.3048	metres
feet per minute	0.5080	centimetres per second
inches	2.54	centimetres
miles (US statute)	1.609347	kilometres

6. Use of the developed computer programs is described in Appendices A, B, and C; the programs LEVEE3L, LEVEEIRR, LEVEECOR and the conventional method are compared in Appendix D; the notation is documented in Appendix E.

Previous Studies

Infinitely long foundations

7. Bennett (1946) derived a solution for steady-state flow through a two-layer foundation consisting of a semipervious top blanket of thickness z overlying a pervious substratum of thickness d, both of infinite lateral extent. In Bennett's analysis, flow is assumed downward vertical in the riverside top blanket, landward horizontal in the substratum, and upward vertical in the landside top blanket. Bennett stated that the substratum must be at least 10 times as pervious as the top blanket for these assumptions to be reasonable; this is almost always the case for levees in the Mississippi Valley. Bennett's analysis is summarized in Figure 1. To calculate the residual head, h_o, at the landside levee toe where the foundations layers are of infinite length, the pervious substratum and semi pervious top blanket are replaced by finite "effective" lengths of pervious substratum and impervious top stratum. These effective lengths are designated x_1 on the riverside and x_3 on the landside and are a function of the thicknesses and permeabilities of the two materials. The base width of the levee is designated x_2. With the top stratum now impervious, the head in the substratum varies linearly with distance, and the head at the levee toe, h_o, can be found by simple interpolation:

$$h_o = \frac{Hx_3}{x_1 + x_2 + x_3} \tag{1}$$

where H is the net head on the levee (difference between river stage and landside ground or tailwater).

Foundations of finite length

8. Solutions for effective entrance and exit distances for finite foundation lengths were presented by Bennett and extended and summarized in Technical Memorandum (TM 3-424 (WES 1964)). The semipervious top blanket and pervious substratum extend for distances of L_1 riverward of the riverside

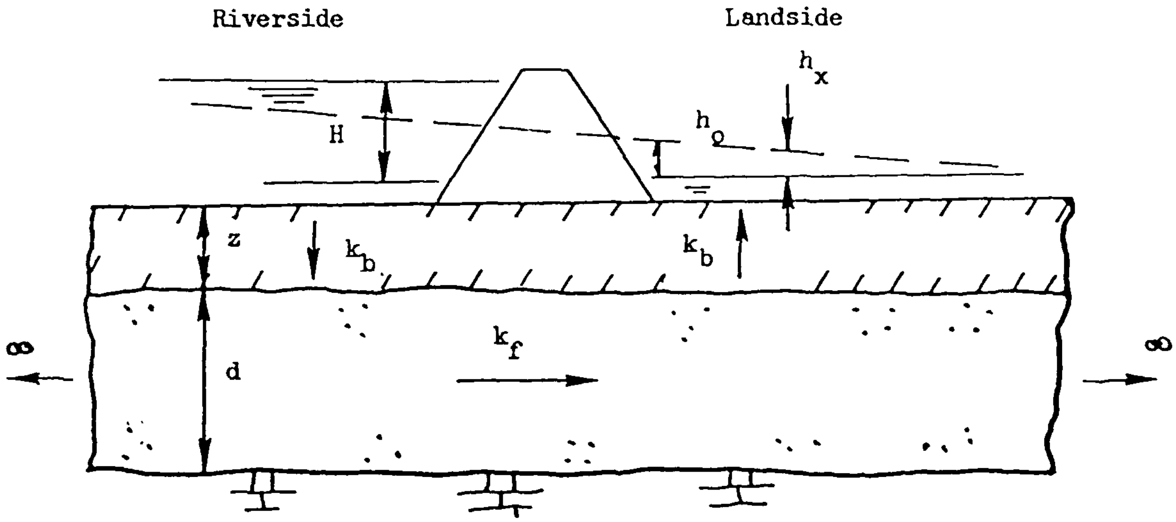
(1946), which was extended and summarized in WES Technical Memorandum 3-424 (WES 1956a). It is referred to herein as the "conventional analysis." Although actual foundation conditions may be highly irregular, the conventional analysis requires the foundation geometry to be transformed into an "equivalent" system of two horizontal layers of uniform thickness. Development of the equivalent foundation may involve changing both the thickness and permeability of the top blanket. As this transformation process can be highly subjective, performance predictions for irregular foundation conditions are often difficult to make and are unreliable.

3. The "conventional analysis" assumptions allow a closed-form solution to the differential equation for the piezometric head at the interface between the top blanket and the substratum. The residual head and gradient could readily be calculated using 1950's techniques such as slide rules and charts. Digital computers and numerical methods now allow solution of the flow equation for very complex conditions. Finite element programs are available that can model any conceivable seepage problem (e.g. Tracy 1973); however, they are seldom used for levee underseepage analysis because the effort required for problem description and coding is usually undesirable for routine calculations. For levee underseepage problems, an analysis technique is desired wherein the heads and gradients can be obtained as a function of relatively few parameters, facilitating repetitive calculations for numerous foundation sections along the length of a levee.

4. The purpose of this research was to develop analysis procedures that are not constrained by some of the assumptions in the conventional procedure. A second purpose was to investigate whether improved performance predictions could be made using the developed procedures. As part of the research, three computer programs were developed to perform underseepage analysis for three special but relatively common geometric conditions. These are:

- a. Program LEVEE3L for analysis of foundations consisting of three layers of uniform thickness.
- b. Program LEVEEIRR for analysis of foundations consisting of two layers of irregular shape (nonuniform thickness).
- c. Program LEVEECOR for analysis of underseepage at angles or "corners" in levee alignment.

5. For each of the three types of special foundation conditions, two to four prototype reaches were analyzed and the results compared to actual performance data (piezometer readings during flood).



Dashed line is piezometric head at base of top blanket.

For a vertical section on the land side:

$$q_{in} = q_{up} + q_{out}$$

$$q_{in} = k_f \left(\frac{dh}{dx}\right)_x d$$

$$q_{out} = k_f \left(\frac{dh}{dx}\right)_{x+dx} d$$

$$q_{up} = k_b \left(\frac{h}{z}\right)_{x+\frac{dx}{2}} dx$$

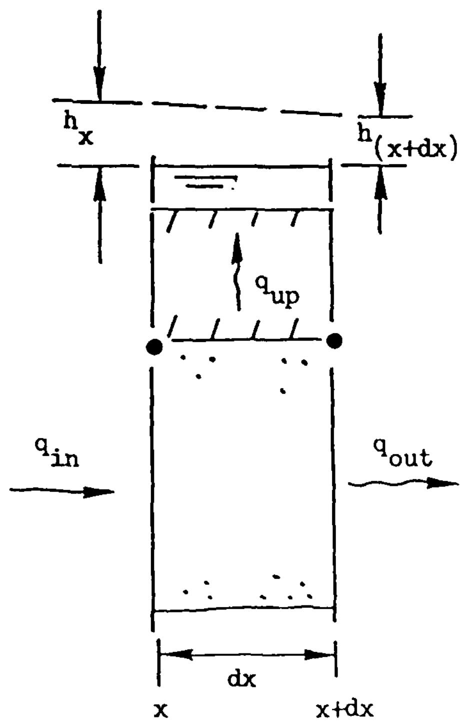


Figure 1. Bennett's analysis

levee toe and L_3 landward of the landside levee toe, respectively. the effective lengths x_1 and x_3 are functions of L_1 and L_3. The pervious substratum may be modeled as either open or blocked at the entrance and exit points. The analyses for open entrance and exit conditions are illustrated in Figure 2.

Back-Calculation of Parameters

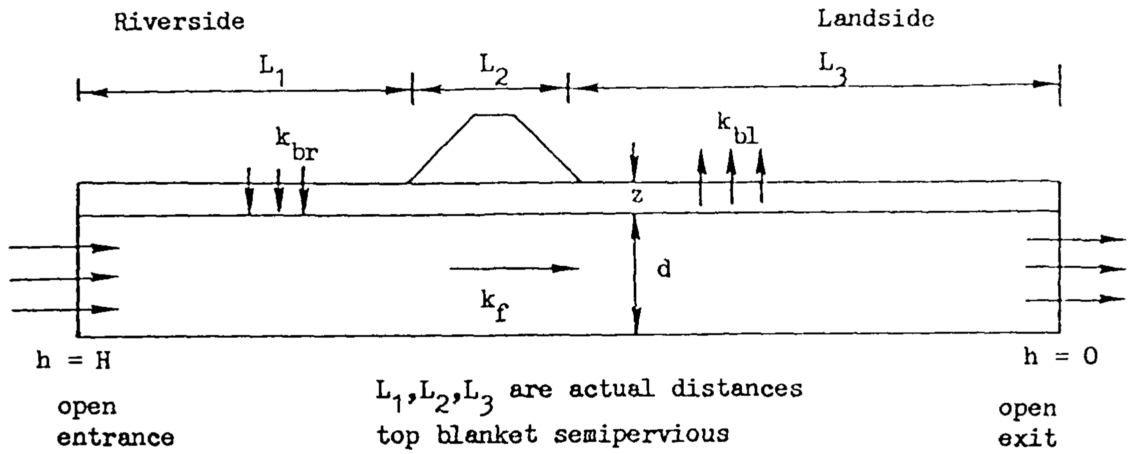
9. A number of studies have been made where residual heads and gradients observed during high water have been compared to design calculations (e.g. WES 1964; US Army Engineer District (USAED), St. Louis 1976; Cunny 1980; McClelland Engineers 1985). Some of the findings from these studies have been summarized by Wolff (1986). Much of this effort has been directed towards the back-calculation of appropriate values for the analysis parameters, in order to verify the adequacy of the levees as well as the adequacy of design criteria for future levees. To back-calculate any parameter, the remaining parameters must be known or assumed; back-calculated parameters can only be as accurate as the assumptions made for the "constrained" parameters. For conditions that fit the assumptions of the conventional analysis, the relationship between piezometric elevation at the levee toe and the river stage will be linear and of the form

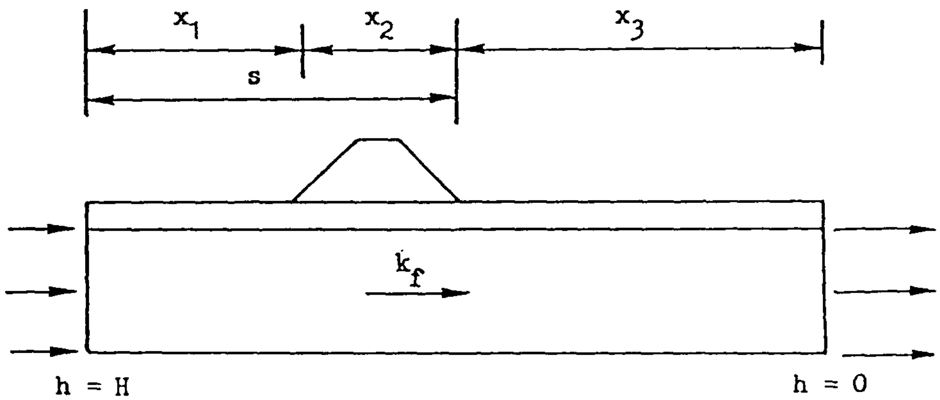
$$y = mx + b \tag{2}$$

or

$$\text{Piez. el} = (h_o/H)(\text{river stage} - \text{ground el}) + \text{ground el} \tag{3}$$

The slope of the relationship, h_o/H, is a function of the foundation geometry (lengths and thicknesses) and permeability ratio (k_f/K_b). The intercept depends on the ground elevation (or elevation of landside water). Where the geometry and ground elevations assumed in the analysis match those in the field, then the field permeability ratio can be determined by trial and error; the correct ratio will yield a straight line plot through the observed data. Where the real ground profile is complex, assessment of the field permeability ratio is uncertain because of the uncertainty regarding the appropriate





x_1,x_2,x_3 are effective distances for impervious tcp blanket

$$x_1 = \frac{\tanh(cL_1)}{c}$$

$$c = \sqrt{\frac{k_{br}}{k_f \; z \; d}}$$

$$x_2 = L_2$$

$$x_3 = \frac{\tanh(cL_3)}{c}$$

$$c = \sqrt{\frac{k_{bl}}{k_f \; z \; d}}$$

$$\text{if } L_3 = \infty \quad x_3 = \frac{1}{c} = \sqrt{\frac{k_f}{k_{bl}} \; z \; d}$$

Figure 2. TM 3-424 solutions for finite foundation lengths

"effective values" of the layer thicknesses and ground elevations. Different permeability ratios will be back-calculated for different (although reasonable) assumptions of effective layer thicknesses and elevations.

10. By using the programs developed herein, the foundation geometry is more completely described, and fewer assumptions are required to make the problem tractable. Thus, back-calculated permeability ratios should be more reliable and less uncertain than those obtained from conventional analysis.

PART II: SPECIAL CASES OF FOUNDATION CONDITIONS

11. As previously stated, the conventional assumptions of 2-D flow and a foundation profile of two uniform horizontal layers are not always consistent with actual foundation conditions. For this research, three alternate sets of assumptions have been identified and a computer program for the finite difference solution of steady state laminar flow in porous incompressible saturated media was developed for each. These special cases are representative of many prototype locations. In many cases, the relevant deficiencies of the conventional method can be circumvented by selecting an appropriate alternative. These alternate of "special" conditions are described in detail below.

Foundations Characterized by Three Layers

12. The special condition considered is the case of a foundation consisting of three materials deposited in horizontal layers. The pervious materials immediately below a clay top blanket are often fine sand or silty sand, while those at greater depth are typically medium or coarse clean sand. Such layering is consistent with the geologic environment of a meandering stream, where the expected grain size distribution is fining upward. In the developed analysis, each of three layers may have different thicknesses and different horizontal and vertical permeabilities. The layers are herein referred to as the semipervious top blanket, moderately pervious middle stratum, and pervious substratum. In such deposits, the top blanket may be a backswamp deposit, the middle stratum may be a point-bar deposit of relatively uniform fine sands or silts, and the pervious substratum is representative of a lower section in the point bar or a "channel lag" deposit. Figure 3 illustrates a three-layer foundation. Use of the conventional analysis requires that the analyst either convert the middle stratum to a relatively thin equivalent layer of top blanket, or consider it part of the substratum and average its relatively low permeability with higher permeability values farther down the profile. Neither of these approaches may adequately model flow conditions along the base of the top blanket. If the horizontal permeability of the middle stratum exceeds the vertical permeability of the substratum, residual heads at the

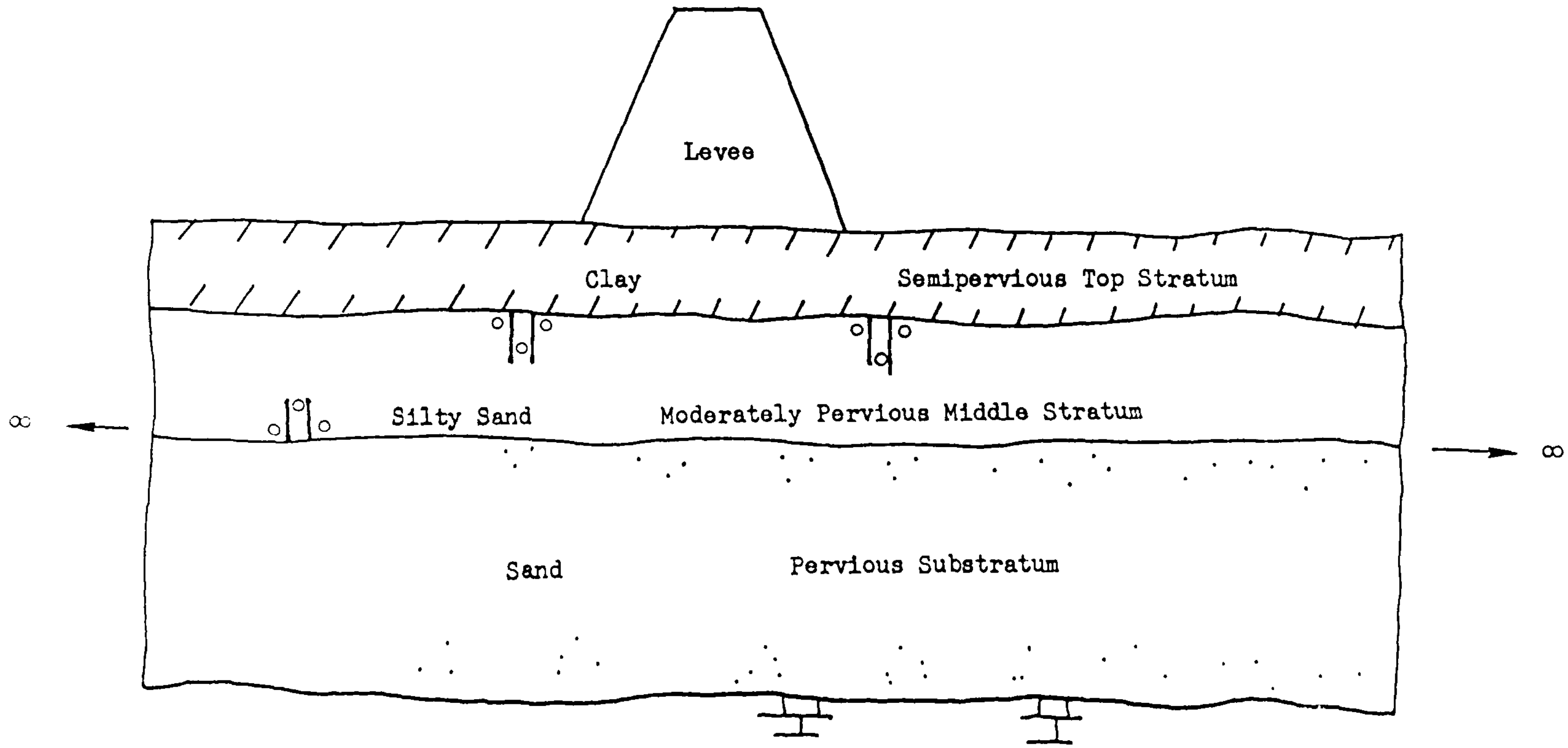


Figure 3. Example of a three-layer foundation

base of the top blanket may be quite dependent on the properties of the middle stratum, and less dependent on properties of the substratum.

Foundations Characterized by Two Layers of Irregular Shape

13. The top blanket thickness and the ground surface elevation are not always uniform. In most cases, prevailing "average" values can be used for analysis. However, in certain cases, foundation conditions cannot be reasonably modeled using such averages. The landside ground surface may slope downward away from the levee; this is commonly the case where flood-control levees are built over natural levees. Ridge and swale topography may be presented landward of the levee. Borrow pits and ditches interrupt the ground surface and form significant discontinuities in the top blanket. The occurrence of sand boils is highly related to the presence of discontinuities such as those listed above (WES 1956a). Where clay-filled channel plug deposits run parallel the levee, the top blanket may be locally quite thick, and seepage will be concentrated at the edges of the plug. Some of the factors causing irregularities in the top blanket are illustrated in Figure 4. The lower Mississippi River Valley exhibits markedly irregular top blanket conditions because of the high degree of stream meandering that has occurred. Irregularities in the bedrock surface elevation may also be present, due to features such as preglacial channels; however, seepage conditions are usually more affected by variations in top stratum thickness than variations in substratum thickness.

Angles or "Corners" in Levee Alignment

14. Where levees parallel major river bends or where mainline riverfront levees meet tributary or flank levees, the levee alignment may bend and form an angle or corner. In such cases, the area of the levee toe may be subjected to concentrations of seepage because the flow regime is not 2-D. Such conditions are illustrated in a plan view in Figure 5. Although such conditions can be found throughout the Mississippi River Valley, the best piezometric data for such conditions were found in the St. Louis District. In other areas, it appears that straight reaches of levee have been deliberately selected for piezometer locations to simplify analysis.

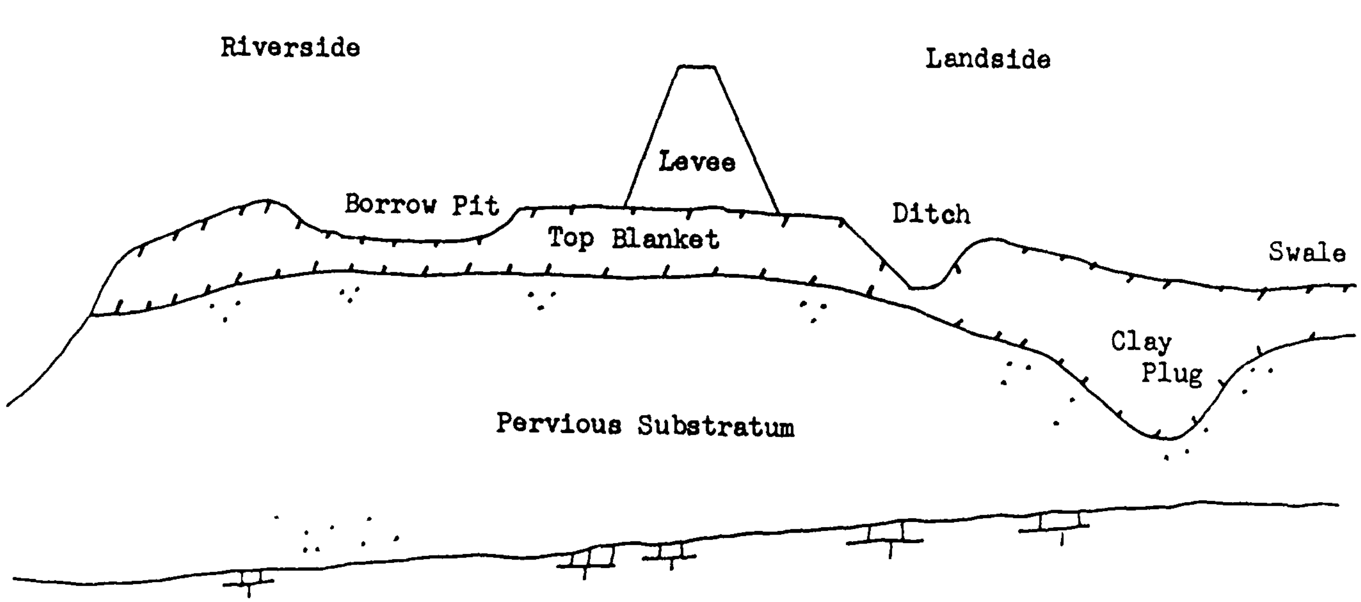


Figure 4. Example of irregular foundation

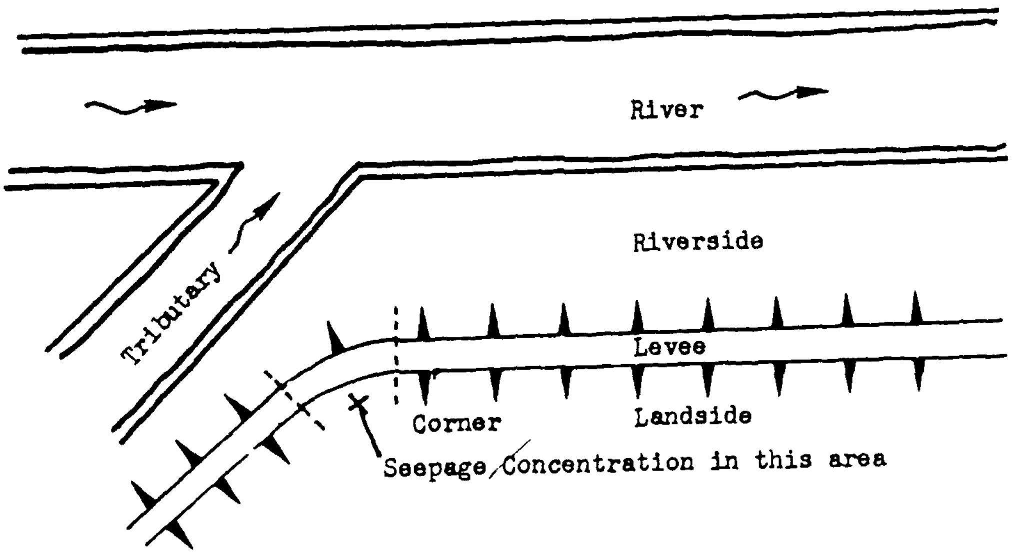


Figure 5. Example of angle in levee alignment

PART III: SELECTION OF LEVEE REACHES FOR STUDY

Selection Criteria

15. Levee reaches in the Rock Island, St. Louis, Memphis, and Vicksburg Districts were screened to identify reaches where actual performance could be compared to predicted performance using the three developed computer programs. Two criteria were considered: first, the reach must fit the particular foundation conditions of interest (three layer, irregular, or corner) and second, sufficient and reliable performance data must be available. The most well-documented performance data are for those levee reaches reported by Cunny (1980) for the Rock Island District, those reported by the St. Louis District (USAED, St. Louis 1976), those reported by WES (WES 1956a and b, 1964) for the Memphis and Vicksburg Districts, and those reported by McClelland Engineers, Inc. (1985) for the Vicksburg District. Even from these sources, significant amounts of data are missing or have been identified by the original analyst as having questionable reliability.

Selected Reaches

16. The following reaches were identified in the preliminary screening as fitting the conditions of interest and having reasonably accurate and complete data. Those identified by an asterisk have been analyzed for this report and are discussed in detail in Parts IV through VI. Locations of the reaches analyzed are shown in Figure 6.

Foundations Characterized by Three Layers

* Rock Island District, Sny Island "F"
  Memphis District, Caruthersville
  Memphis District, Commerce
  Vicksburg District, Upper Francis
* Vicksburg District, Eutaw

Foundations Characterized by Two Layers of Irregular Shape

  Rock Island District, Sny Island, Range "G"
* Rock Island District, Hunt, Range "B"
  Rock Island District, South Quincy, Range "SQ"
  Rock Island District, South River, Range "SRC"

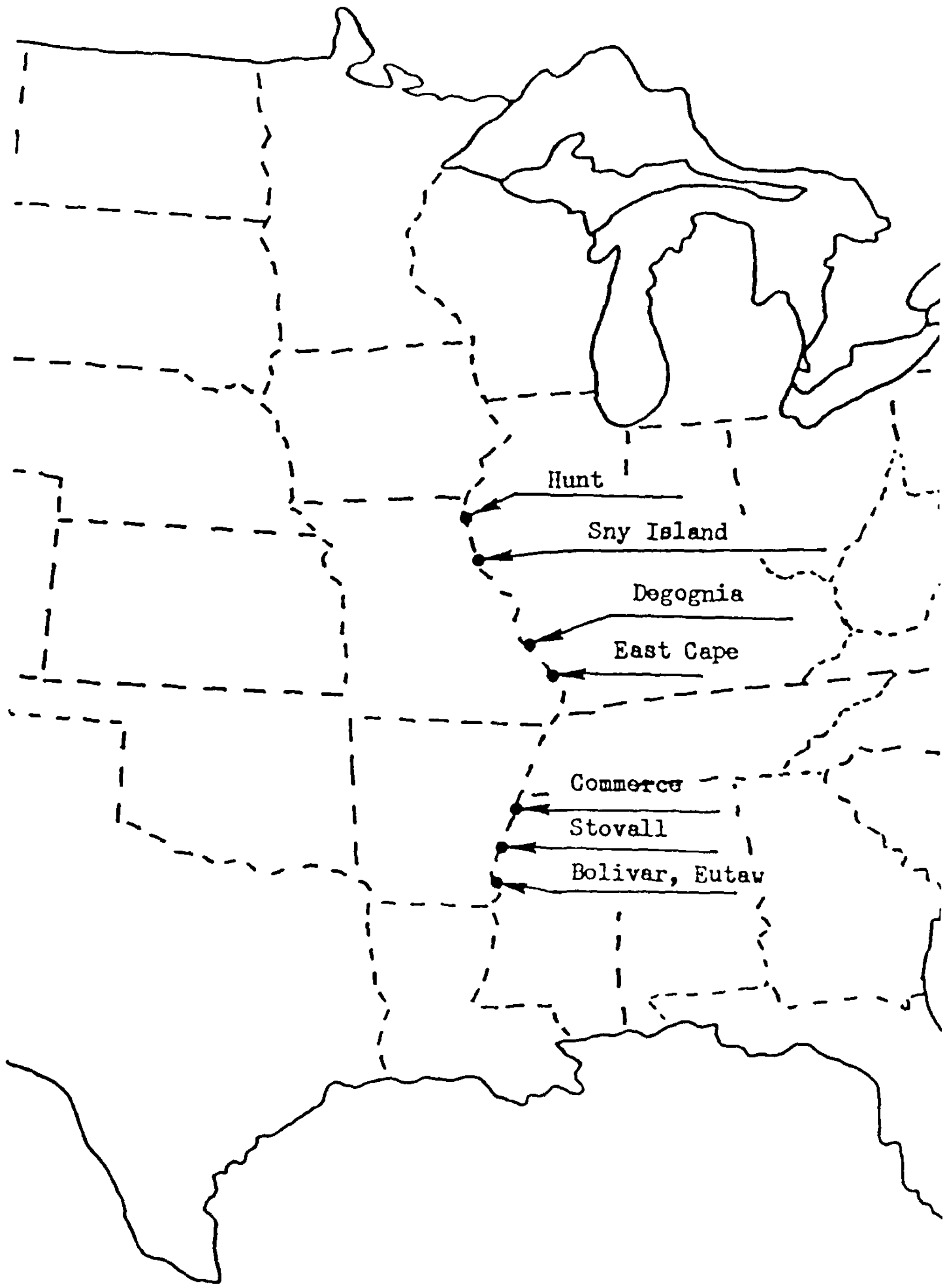


Figure 6. Locations of analyzed levee reaches

Foundations Characterized by Two Layers of Irregular Shape (Continued)

St. Louis District, Perry County, Sta 329+85

Memphis District, Gammon

* Memphis District, Commerce

* Memphis District, Stovall

* Vicksburg District, Bolivar, Range "D"

Angles or "Corners" in Levee Alignment

Rock Island District, Bay Island, Range C

St. Louis District, Columbia Sta. 653

* St. Louis District, Degognia Sta. 260-290

St. Louis District, Grand Tower Sta. 430

* St. Louis District, East Cape Sta. 94

St. Louis District, East Cape Sta. 309

Memphis District, Farrell

Memphis District, Stovall

Vicksburg District, Bolivar, Range "D"

PART IV: FOUNDATIONS CHARACTERIZED BY THREE LAYERS

Numerical Modeling Technique

17. To analyze underseepage conditions for foundations consisting of three layers, a computer program named LEVEE3L was written. Given the thicknesses and effective lengths of the layers, LEVEE3L generates a grid of 96 points or nodes (8 rows by 12 columns) and solves the differential equation for 2-D flow at each node using the finite difference method. The spacing between the nodes varies in both the x- and y-directions and is a function of the specified geometry. Figure 7 defines the variables used by LEVEE3L to describe the problem geometry and illustrates the generated grid. The ground surface coincides with Row 1, the base of the top blanket coincides with Row 3, the base of the middle stratum coincides with Row 5, and the base of the substratum coincides with Row 8. Column 1 corresponds to an open entrance, and Column 12 corresponds to an open exit. Infinite L_1 or L_3 distances are modeled by specifying very large values, as is traditionally done in finite element modeling. The landside levee toe is at Column 7. The exit gradient is obtained by dividing the excess head at node (3,7) by the thickness of the top blanket. The finite difference equation for flow at an interior node is shown in Figure 8. Use of the program LEVEE3L is described in Appendix A. Results of the program are compared to the other programs in Appendix D.

Effect of Moderately Pervious Middle Stratum

18. The effect of a middle stratum was initially investigated by using the program to perform a series of parametric studies. Results of these studies are illustrated in Figures 9 through 11. For all parametric studies, the base width of the levee was arbitrarily taken as 50 ft and the differential head was taken as 20 ft. Most real levees of 20-ft height would have a wider base width; this would tend to reduce the calculated gradients somewhat. In the first study, constant foundation geometry was assumed, and the ratio of the vertical permeability in the top blanket (k_{1v}) to the horizontal permeability in the substratum (k_{3h}) was assumed to be 1,000. Then the exit gradient through the top blanket, i , was evaluated at point 1, 7 in Figure 7

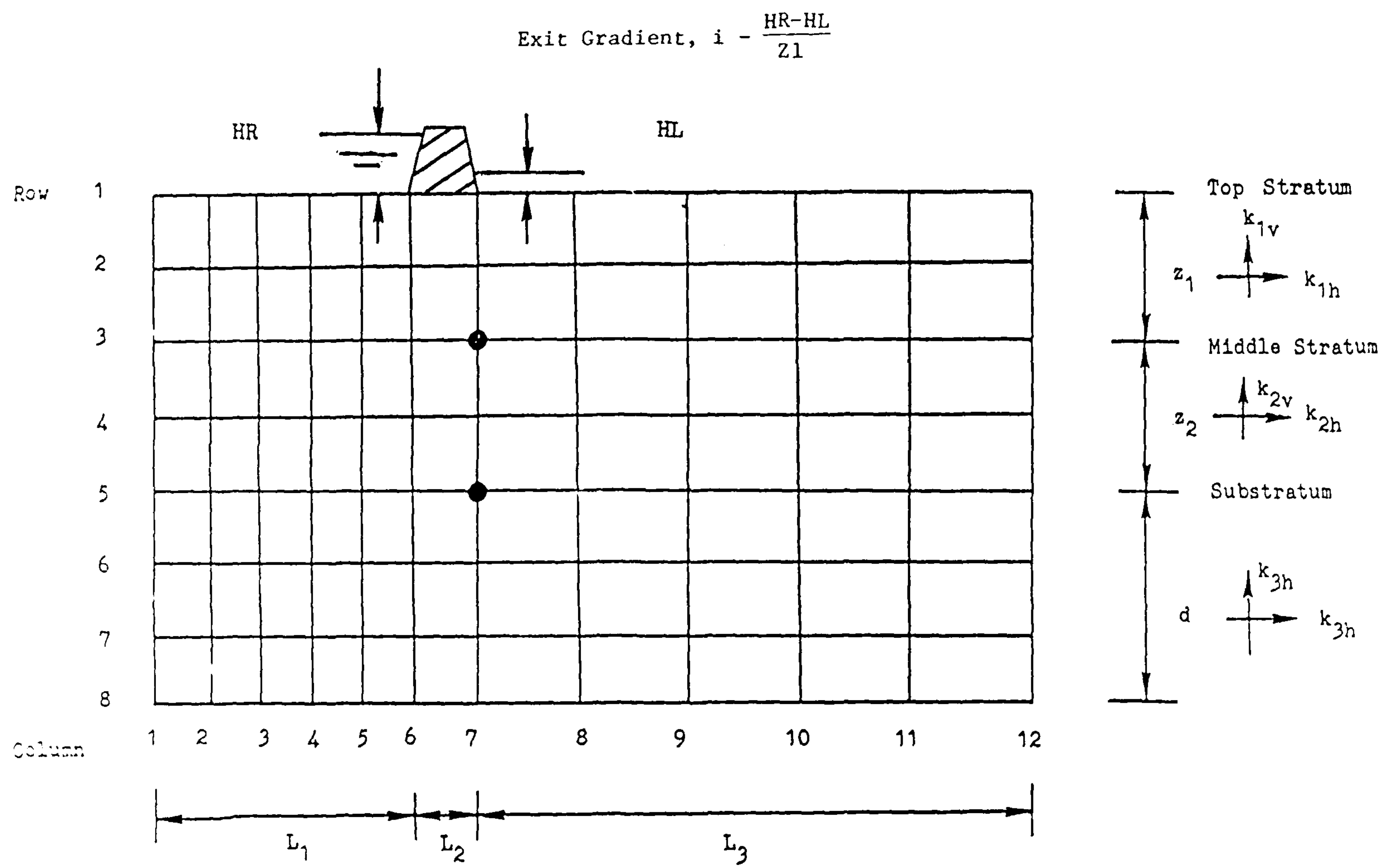
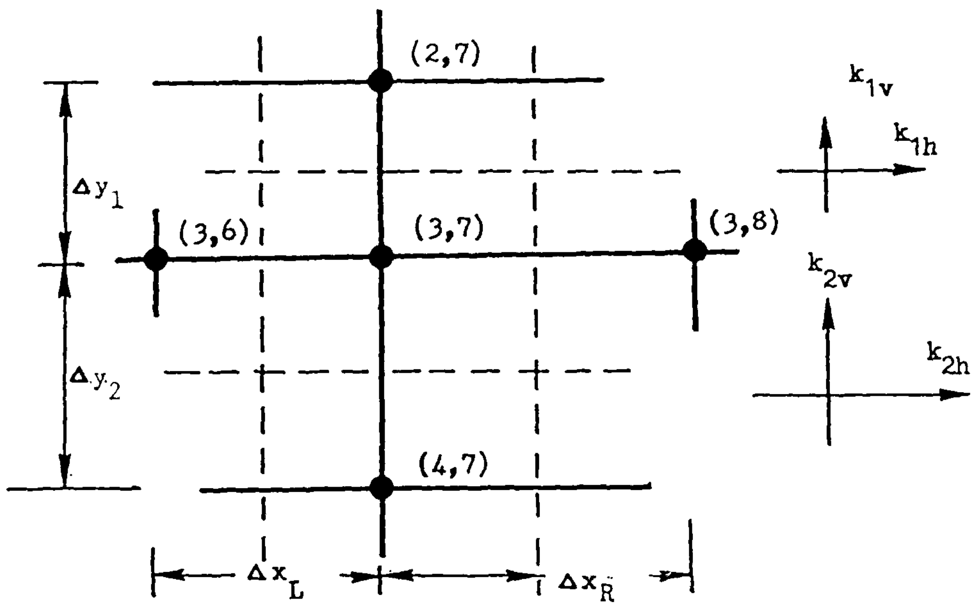


Figure 7. Variables and grid used by program LEVEE3L

$$q_{\text{to }(3,7)} = 0 = q_{(3,6)} + q_{(3,8)} + q_{(2,7)} + q_{(4,7)}$$



Flow from (3,6) to (3,7) :

q = kiA

$$q_{(3,6)} = \left[\frac{k_{1h}\,\Delta y_1 + k_{2h}\,\Delta y_2}{\Delta y_1 + \Delta y_2}\right]\left[\frac{h_{3,6} - h_{3,7}}{\Delta x_L}\right]\left[\frac{\Delta y_1 + \Delta y_2}{2}\right]$$

Other flows similar.

Figure 8. Program LEVEE3L, flow at interior node

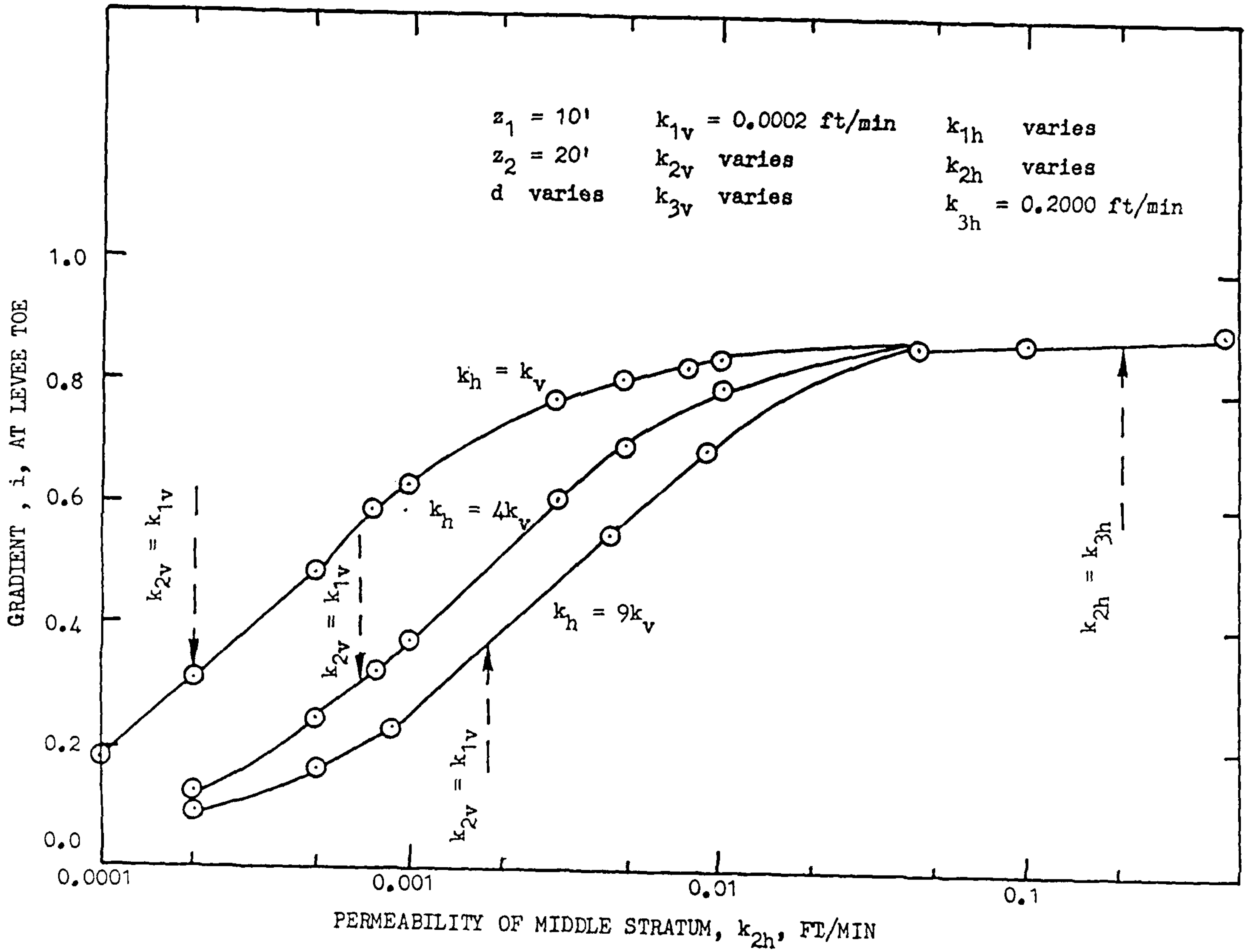


Figure 9. Exit gradient, i , through the top blanket at levee toe versus permeability of middle stratum

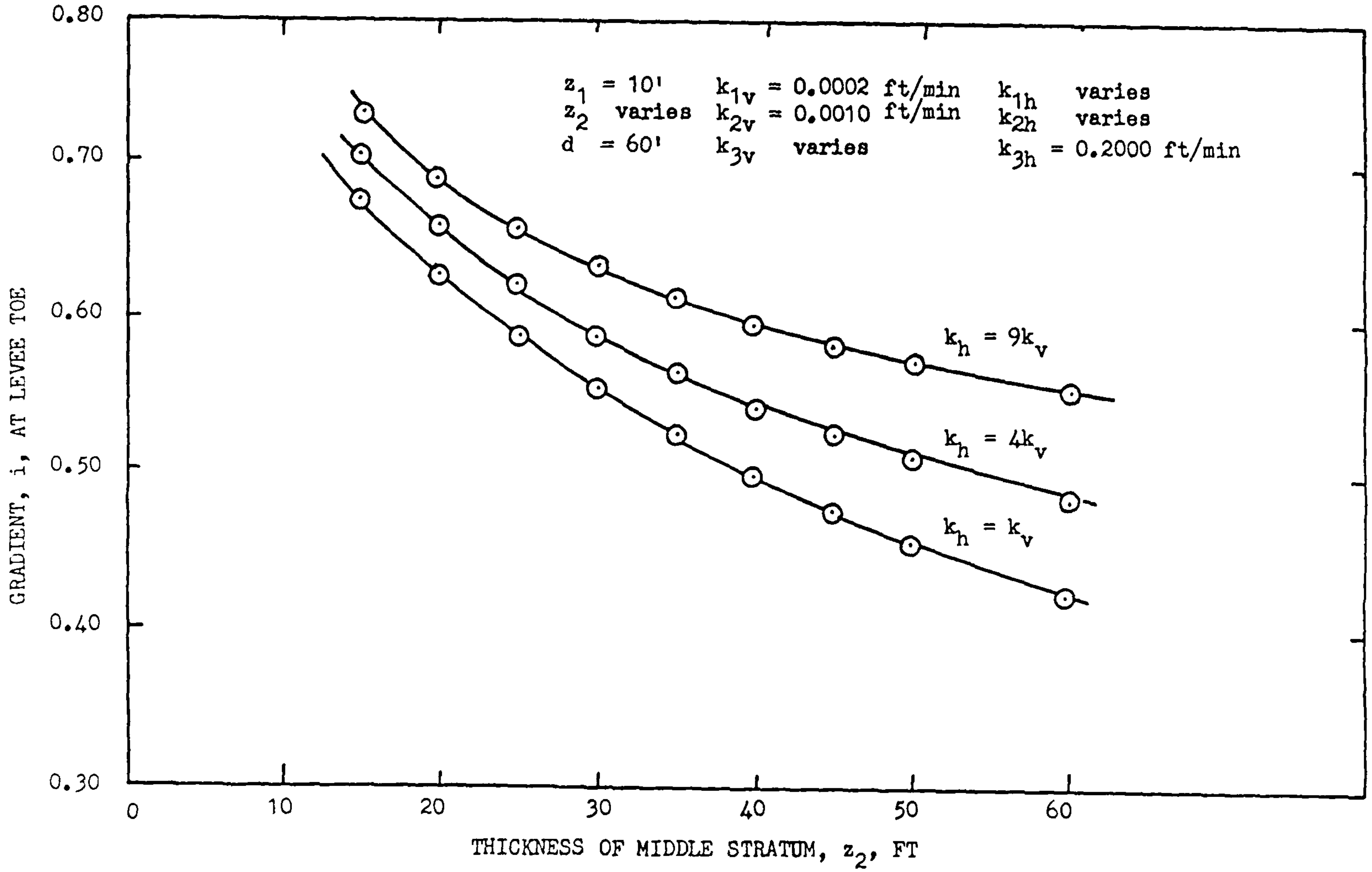


Figure 10. Gradient versus thickness of middle stratum

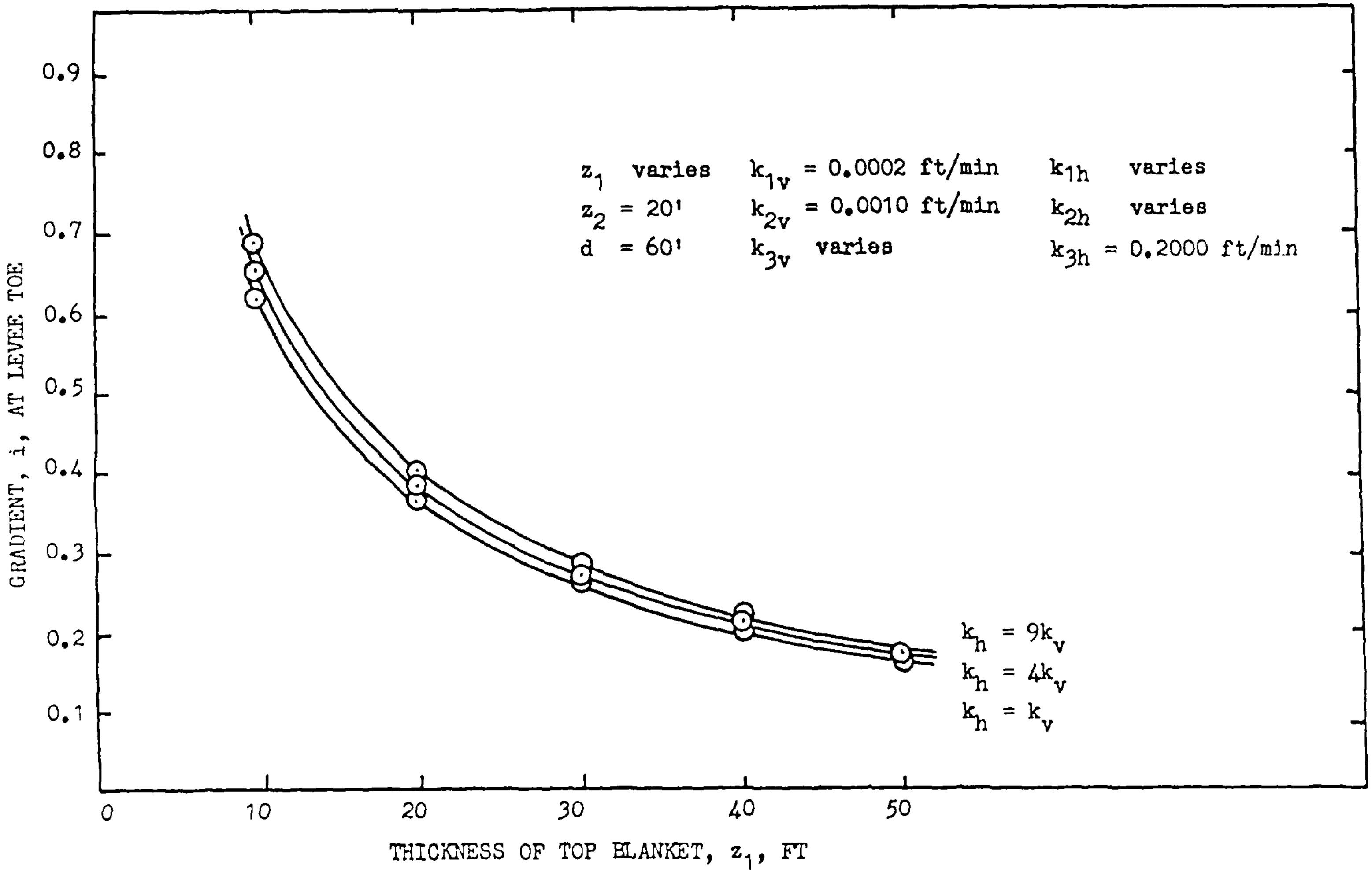


Figure 11. Gradient versus thickness of top blanket

as a function of the permeability of the middle stratum and the permeability ratio within each stratum. The results are presented in Figure 9. It is shown that the gradient increases as permeability of the middle stratum increases and the gradient decreases as the permeability ratio within the layers increases.

19. In the second study, the thickness of the top blanket, thickness of the substratum, and the vertical permeabilities were fixed and the gradient investigated as a function of middle stratum thickness and permeability ratio. The results are presented in Figure 10. It is shown that the gradient decreases as the middle stratum thickness increases and the gradient increases as the permeability ratio within the layers increases.

20. The third parametric study was similar to the second except that the thickness of the middle stratum was fixed and the thickness of the top blanket was varied. The results are shown in Figure 11. It is shown that the gradient decreases as the top blanket thickness increases (as is well known) and that the gradient decreases as permeability ratio increases.

Actual Versus Predicted Performance

21. The program LEVEE3L was used to analyze two locations where a moderately pervious middle stratum is present and where piezometric data are available. Although LEVEE3L is quite useful to predict performance where foundation conditions are reasonably well known, its generality leads to complications when used to back-calculate permeability values or rations. Values must be assumed for five unknowns in order to back-calculate the value of the sixth; a unique solution for permeability ratios cannot be obtained. Also, predictions can be very sensitive to the selected ground elevation, which often must be assumed. To illustrate the capabilities of the program, it was assumed that the ratio $k_{1v}:k_{1h}:k_{2v}:k_{2h}:k_{3v}:k_{3h}$ was of the form $1:4:k_{2v}:4k_{2v}:$-250:1,000. This corresponds to a ratio of 1,000 in a conventional analysis. The program was then used to back-calculate the values of k_{2v} and k_{2h}. A discussion of these analyses follows.

Rock Island District, Sny Island Range F

22. This piezometer range was established in 1954 on the east bank of the Mississippi River at river mile 300.1 above the confluence with the Ohio. It was previously analyzed by Cunny (1980). A soil profile for the site is

shown in Figure 12. The top stratum thickness ranges from 4.8 to 10.0 ft and generally consists of 2 to 4 ft of lean clay overlying silt and silty sand. Considerable seepage has been reported at this location: toe seepage, sand boils and pin boils in 1960, pin boils in 1965, and light toe seepage in 1973. These observations do not correlate well with river stage, as stages were the highest in 1973 and lowest in 1960. These discrepancies may in part be related to levee enlargement between 1965 and 1967 and provision of a berm that lengthened the effective base width.

23. Parameters used in the analyses are listed in Table 1. The column labeled "conventional analysis" summarizes values presented by Cunny (1980). Using LEVEE3L, the profile was modeled as a 3.0-ft-thick clay top blanket overlying a 5.0-ft-thick middle stratum. Two computer analyses are reported. In analysis "A," the landside distance to an open exit, L_3, was taken as 3,000 ft to represent a foundation with infinite landward extent. Analysis "B" was made assuming L_3 as 400 ft to match the observed sluggish response of piezometer F-4, which suggested that most of the seepage was exiting relatively close to the levee. Results of the computer analyses are plotted with the actual data in Figures 13 through 16. A reasonable match to the observed performance was obtained using a permeability ratio of 1:4:50:200:-250:1,000. Although the finite difference grid was developed primarily with the purpose of assessing heads and gradients at the levee toe, heads and gradients for other piezometer locations were determined by interpolation of the final heads reported in the program output file. The results of analyses "A" and "B" are virtually identical in the vicinity of the levee, but analysis "B" provides a better match remote from the levee.

24. A shortcoming shared by both the conventional analysis and the three-layer analysis is the need to assign a single value for the ground elevation when the ground is in fact uneven. The appropriate ground elevation for analysis can be inferred from piezometric response using Equation 3 in this report, as the residual head should be zero for a river stage equal to the landside ground elevation. A value of 457.5 was determined by extrapolating a line through the piezometric data down to a point where the piezometric elevation matched the river elevation. This ground elevation is 2.0 ft lower than the ground elevation at piezometer F-3 assumed by Cunny (1980) with the result that higher residual heads are predicted herein. For a river stage of 472.8 (levee crest), the predicted piezometric elevation at F-3 is 460.8. This

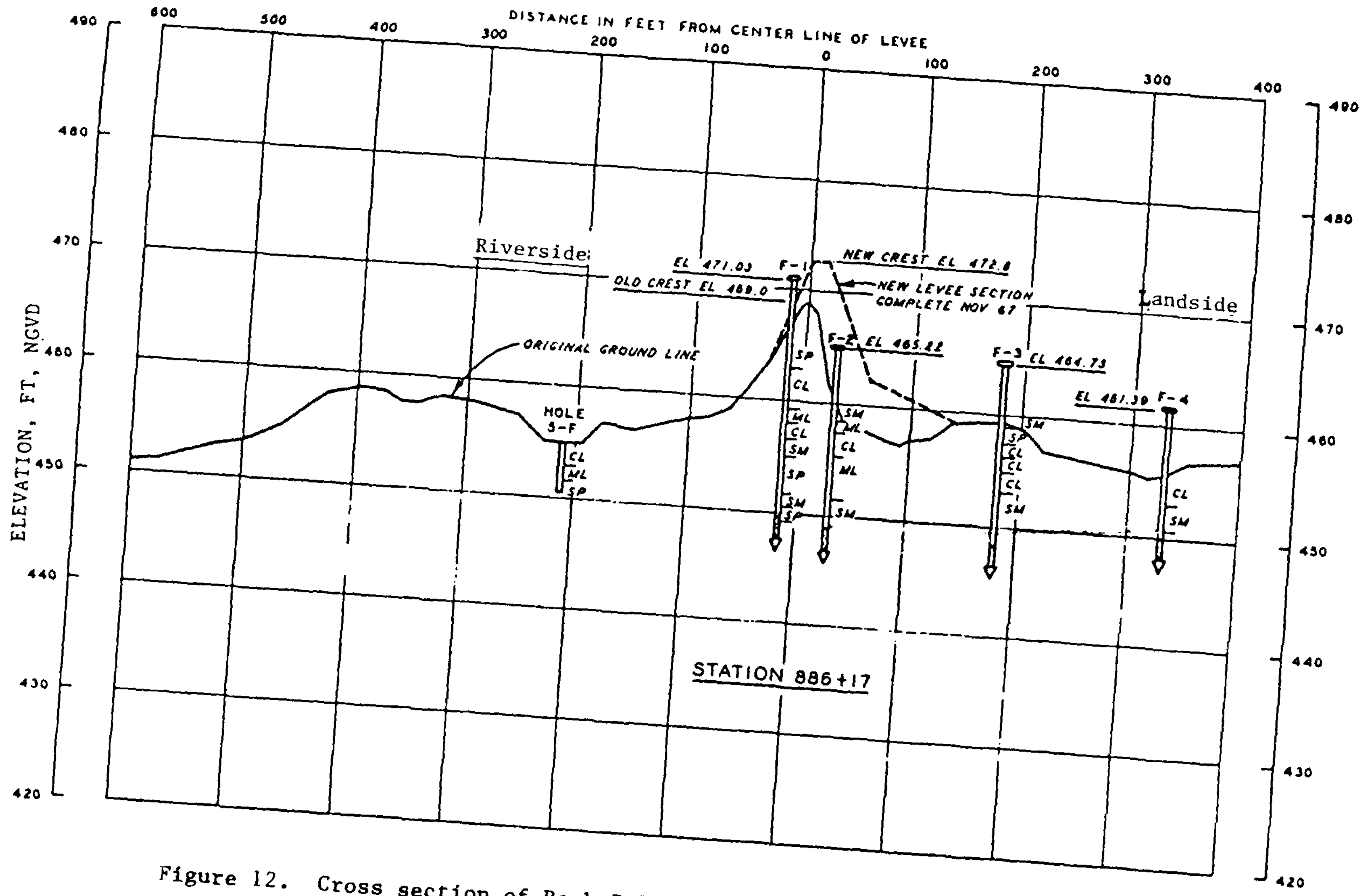


Figure 12. Cross section of Rock Island District, Sny Island, Range F

Table 1

Parameters Used for Analyses, Rock Island District, Syn Island, Range F

Analysis Parameter*	Conventional Analysis (Cunny 1980)	LEVEE3L Computer Analysis "A"	LEVEE3L Computer Analysis "B"
L_1 (ft)	--	510	510
L_2 (ft)	--	100	100
L_3 (ft)	Infinite	3,000	400
z_1 (ft)	6.9 ft at F-3	3.0	3.0
z_2 (ft)	--	5.0	5.0
d (ft)	34	34.0	34.0
k_{1v} (ft/min)	--	0.0002	0.0002
k_{1h}	--	0.0008	0.0008
k_{2v}	--	0.0100	0.0100
k_{2h}	--	0.0400	0.0400
k_{3v}	--	0.0500	0.0500
k_{3h}	--	0.2000	0.2000
k_f/k_{bl}	31	1,000	1,000
Levee crest	472.8	472.8	472.8
Ground el	459.5	457.5	457.5
s (ft)	219	--	--
x_3 (ft)	108	--	--
h_o at H_{max}	1.3 at F-3	5.0 at F-3	3.3 at F-3

* Defined in Figures 2 and 7.

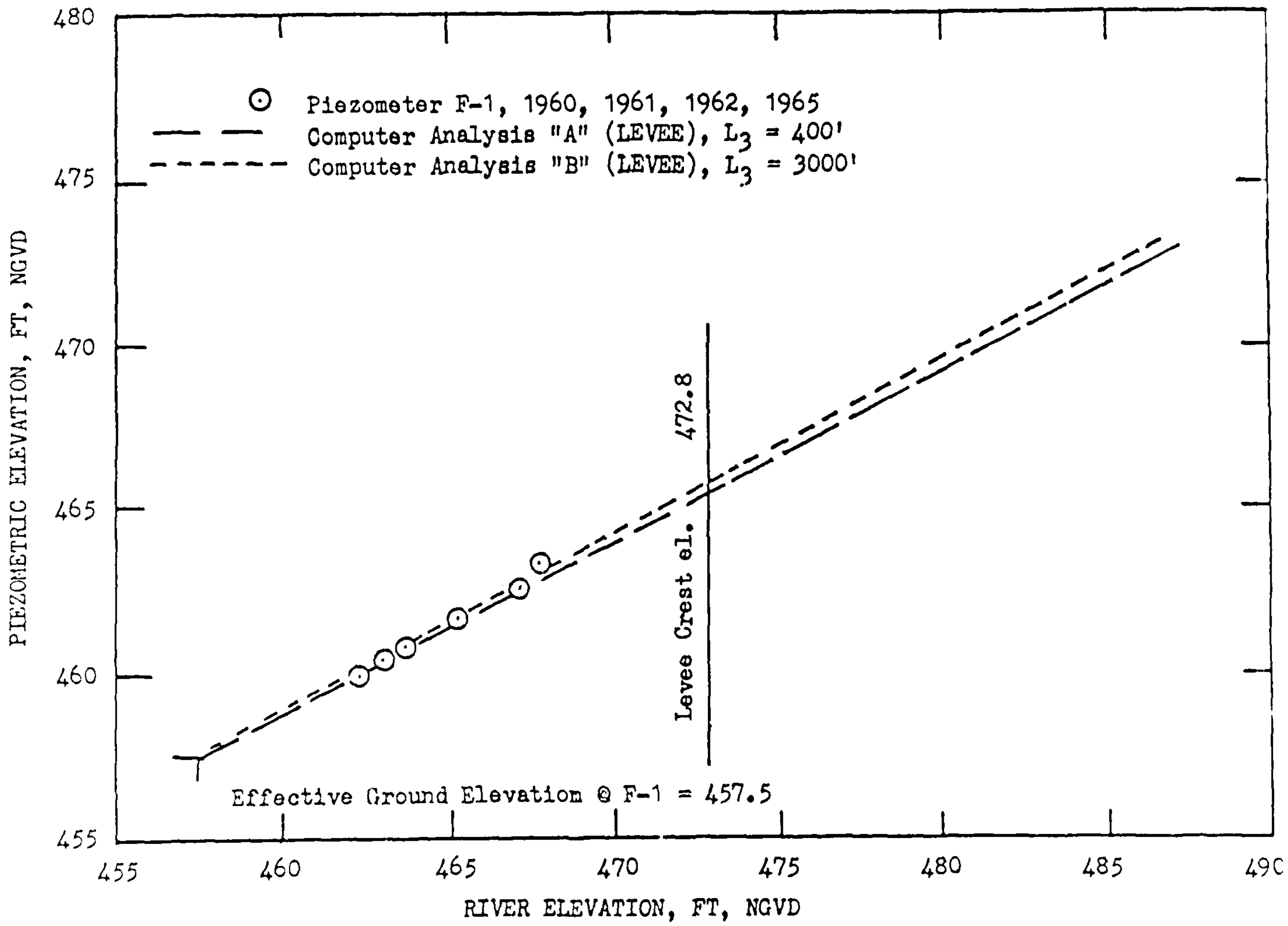


Figure 13. Results of analyses, Rock Island District, Sny Island, Range F, piezometer F-1

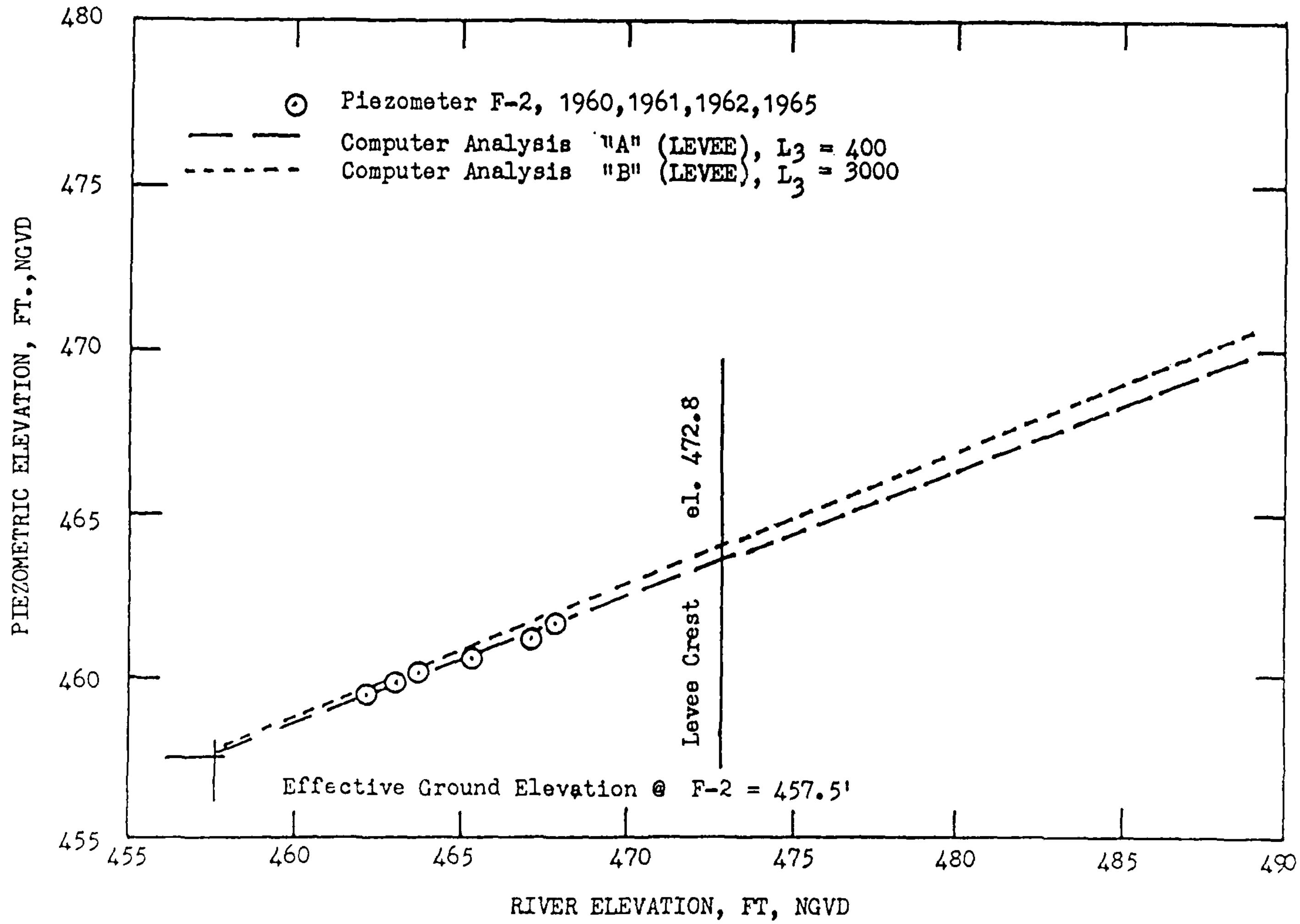


Figure 14. Results of analyses, Rock Island District, Range F, piezometer F-2

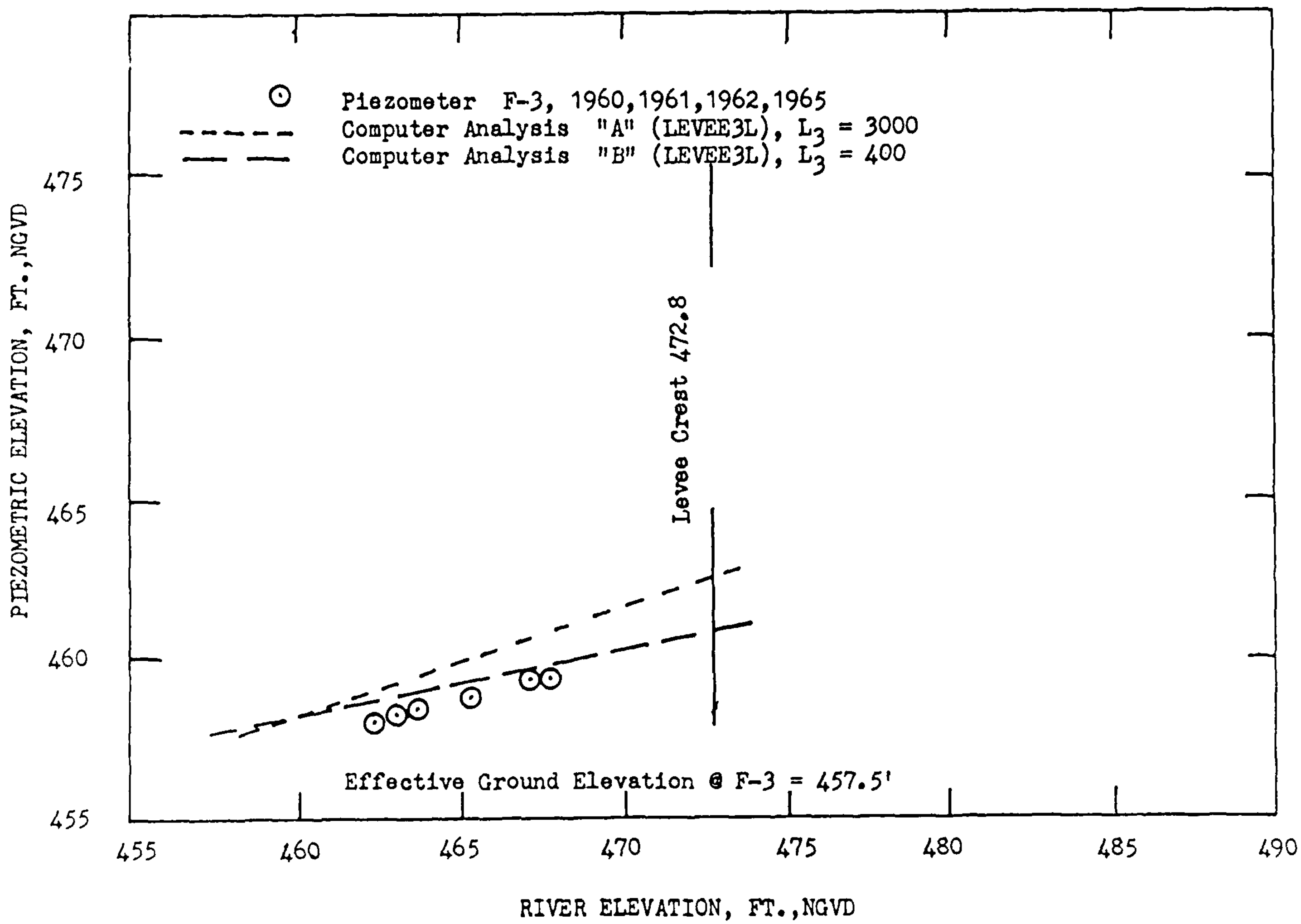


Figure 15. Results of analyses, Sny Island, Range F, piezometer F-3

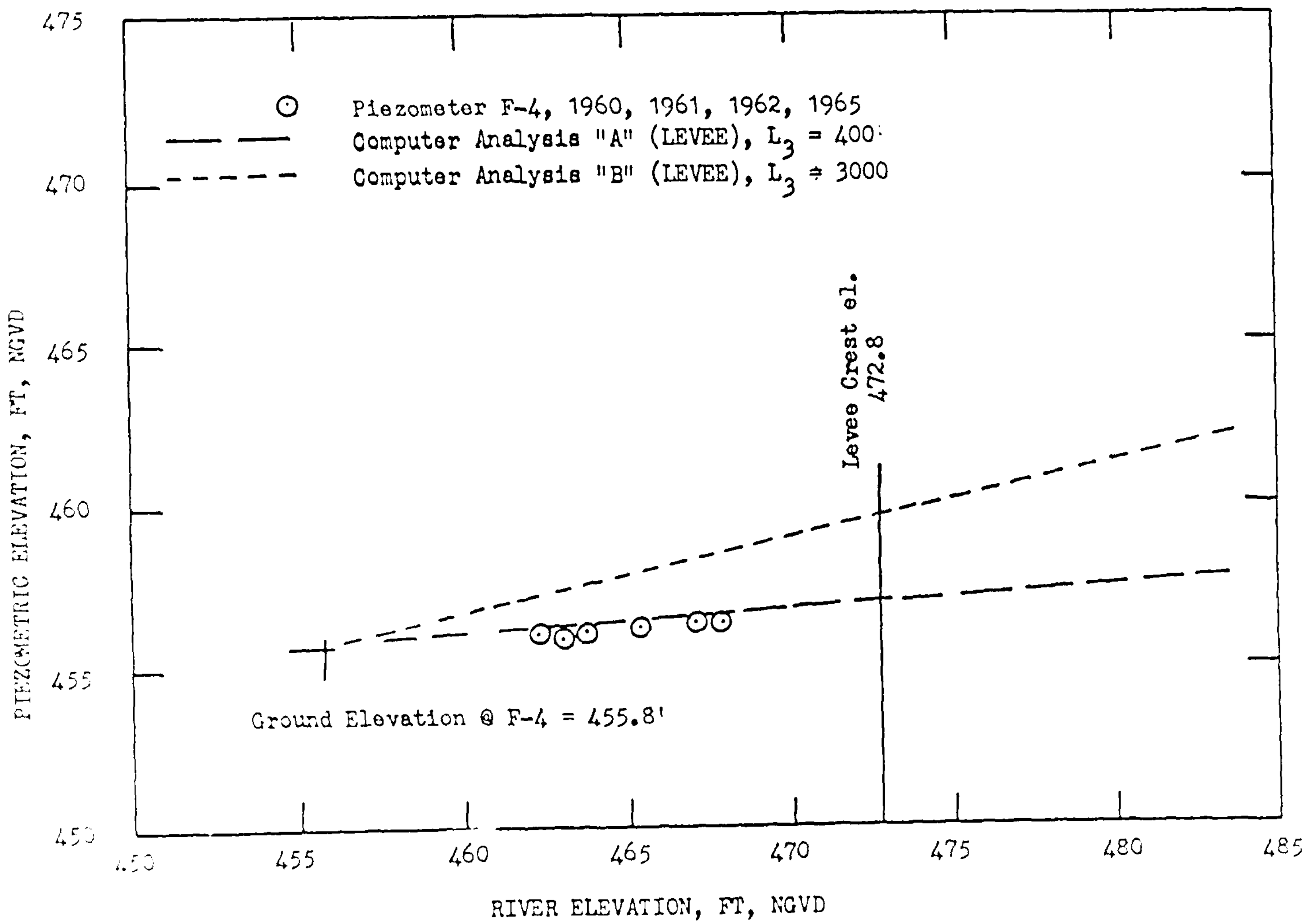


Figure 16. Results of analyses, Rock Island District, Sny Island, Range F, piezometer F-4

corresponds to a head of 3.3 ft. As the tip of F-3 is located below the base of the middle stratum, the exit gradient at F-3 depends on the assumption made for the effective top blanket thickness.

25. As F-3 is some distance landward of the levee toe and below the middle stratum, it does not directly provide information regarding seepage conditions in the top blanket at the levee toe. The computer solution gives a residual head of 5.60 ft at this point with the river stage at the levee crest. Dividing this value by a top blanket thickness of 3.0 ft, a gradient of 1.87 is obtained, well above critical. This is consistent with past observations of heavy seepage and boiling at Sny Island and indicated that the boils are likely related to the presence of relatively thin clay top blanket deposits underlain by silty middle strata that provide little seepage resistance.

Vicksburg District, Eutaw, Miss., Line D

26. This piezometer range is located on the east bank of the Mississippi River one-half mile from the town of Eutaw, Miss. The soil profile at the site is shown in Figure 17. A moderately pervious middle stratum of 5 to 40 ft of very fine sand, silty sand, and sandy silt lies between the top blanket and pervious substratum. These deposits lie in an ancient channel of the Mississippi River (WES 1956a). Piezometer readings are available from 1961 (WES 1964) and 1973 (McClellan 1985).

27. Parameters used in the analysis are listed in Table 2. The column labeled "conventional analysis" summarizes values obtained from TM 3-424 (WES 1956a). Using LEVEE3L, the profile was modeled as a 9.0-ft-thick clay top blanket overlying a 9.0-ft-thick middle stratum. These values were judgmentally selected based on inspection of the profile and the fact that piezometer tops are located in a number of different materials. Results of computer analyses are compared to observed performance in Figures 18 through 22. Although LEVEE3L was developed primarily for analyzing the levee toe, other piezometer locations were analyzed by interpolating final heads in the program output file. A reasonable fit through the scattered observed performance in the vicinity of the levee toe (piezometers D-6 and D-7) was obtained using a permeability ratio of 1:4:25:100:250:1,000. This also fit the limited data at riverside piezometers D-1 and D-2. At piezometers D-3 and D-4, under the levee, the slope of the curve is approximately correct. Landside of the levee

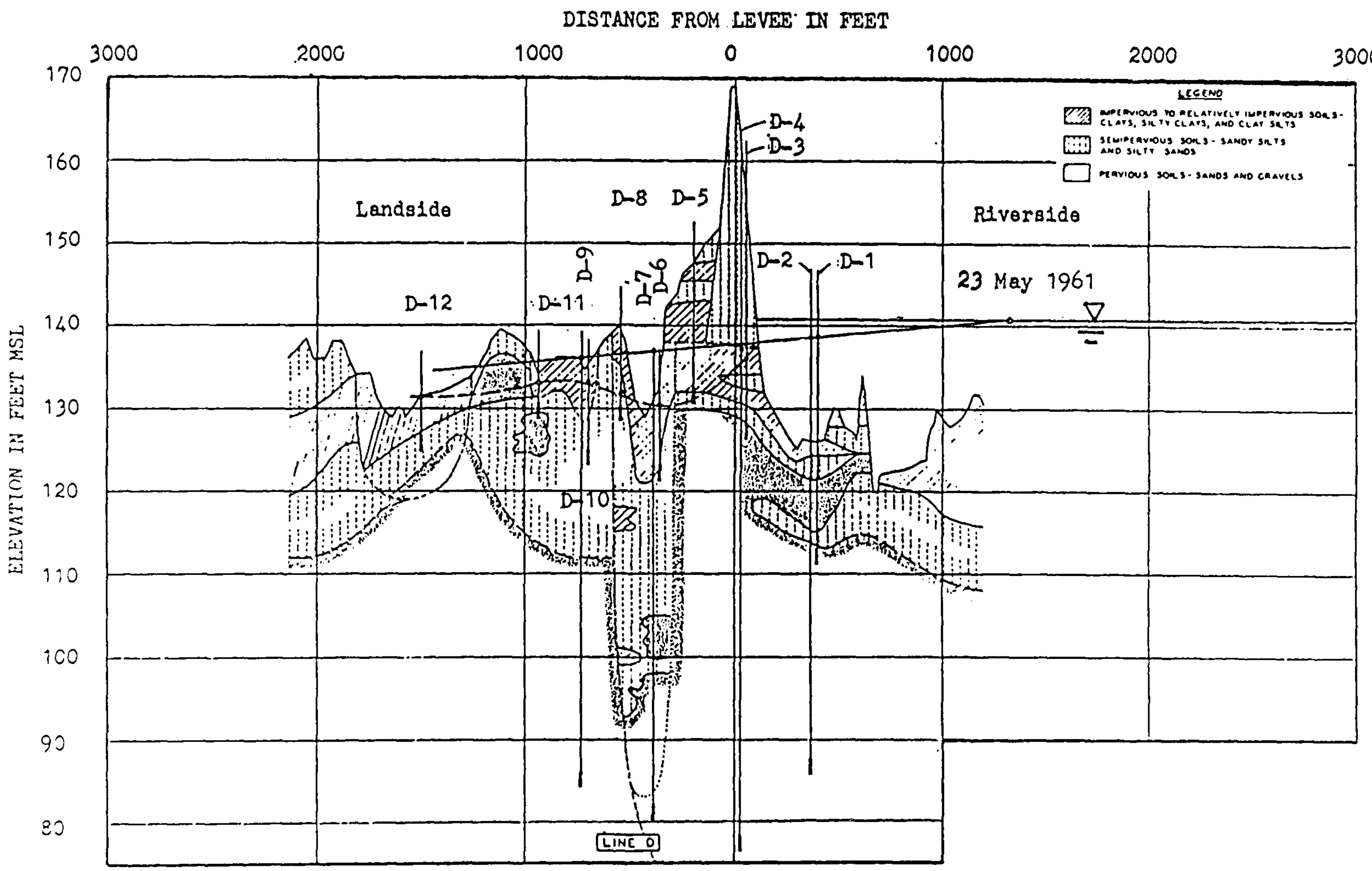


Figure 17. Cross section of Vicksburg District, Eutaw, Miss., Line D (after WES 1964)

Table 2

Parameters Used for Analyses, Vicksburg District, Eutaw, Miss, Line D

Analysis Parameter*	Conventional Analysis	LEVEE3L Computer Analysis
L_1 (ft)	2,500	2,500
L_2 (ft)	--	450
L_3 (ft)	Infinite	750
z_1 (ft)	18.0	9.0
z_2 (ft)	--	9.0
d (ft)	70.0	70.0
k_{1v} (ft/min)	--	0.00022
k_{1h}	--	0.00088
k_{2v}	--	0.0055
k_{2h}	--	0.0220
k_{3v}	--	0.0550
k_{3h}	0.2200	0.2200
k_f/k_{bl}	800	--
Levee crest	161.0	161.0
Ground el	135.0	135.0
s (ft)	1,500	--
x_3 (ft)	1,000	--
h_o at H_{max}	10.4	8.0

* Defined in Figures 2 and 7.

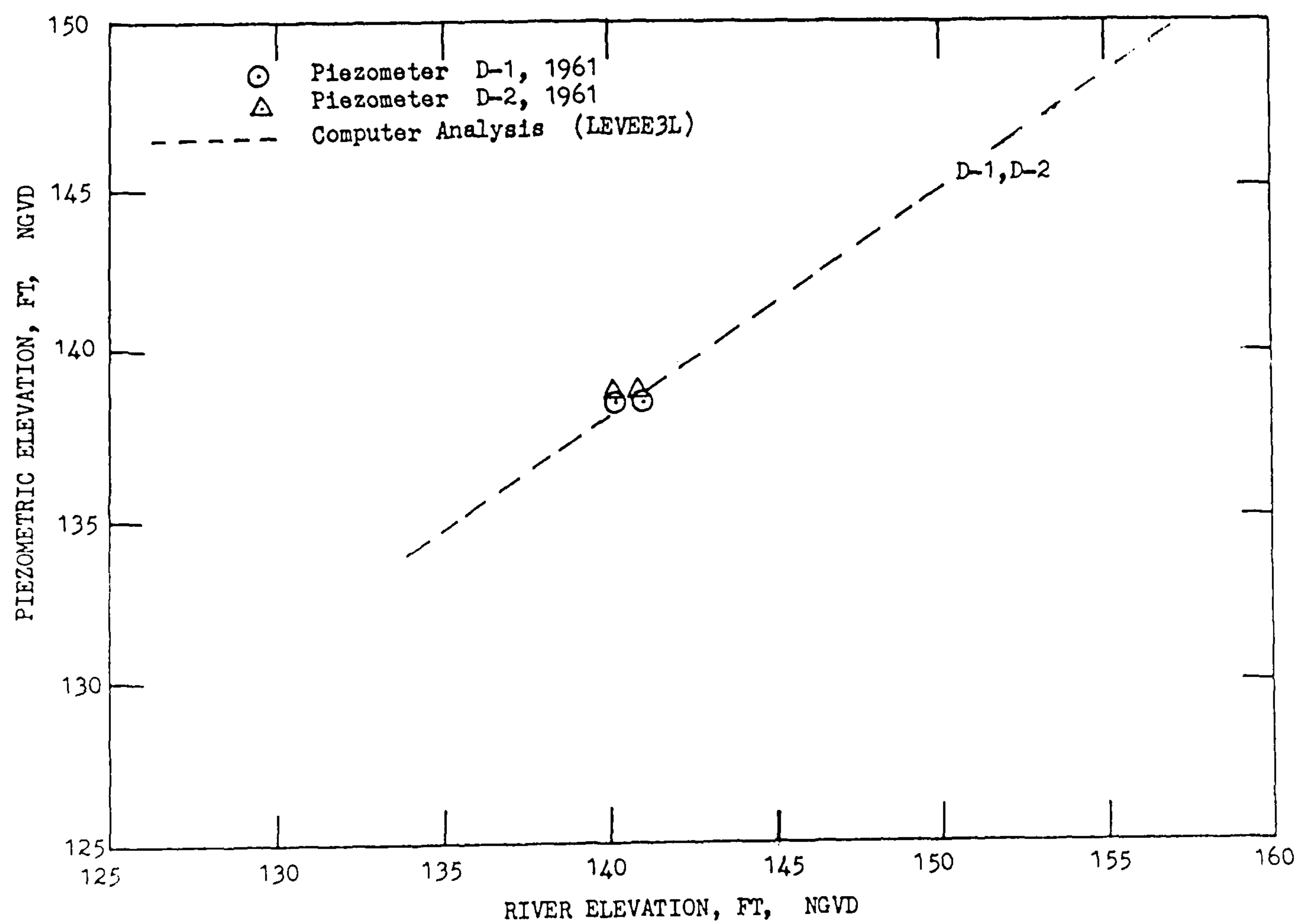


Figure 18. Results of analyses, Vicksburg District, Eutaw, Miss, Line D, piezometers D-1 and D-2

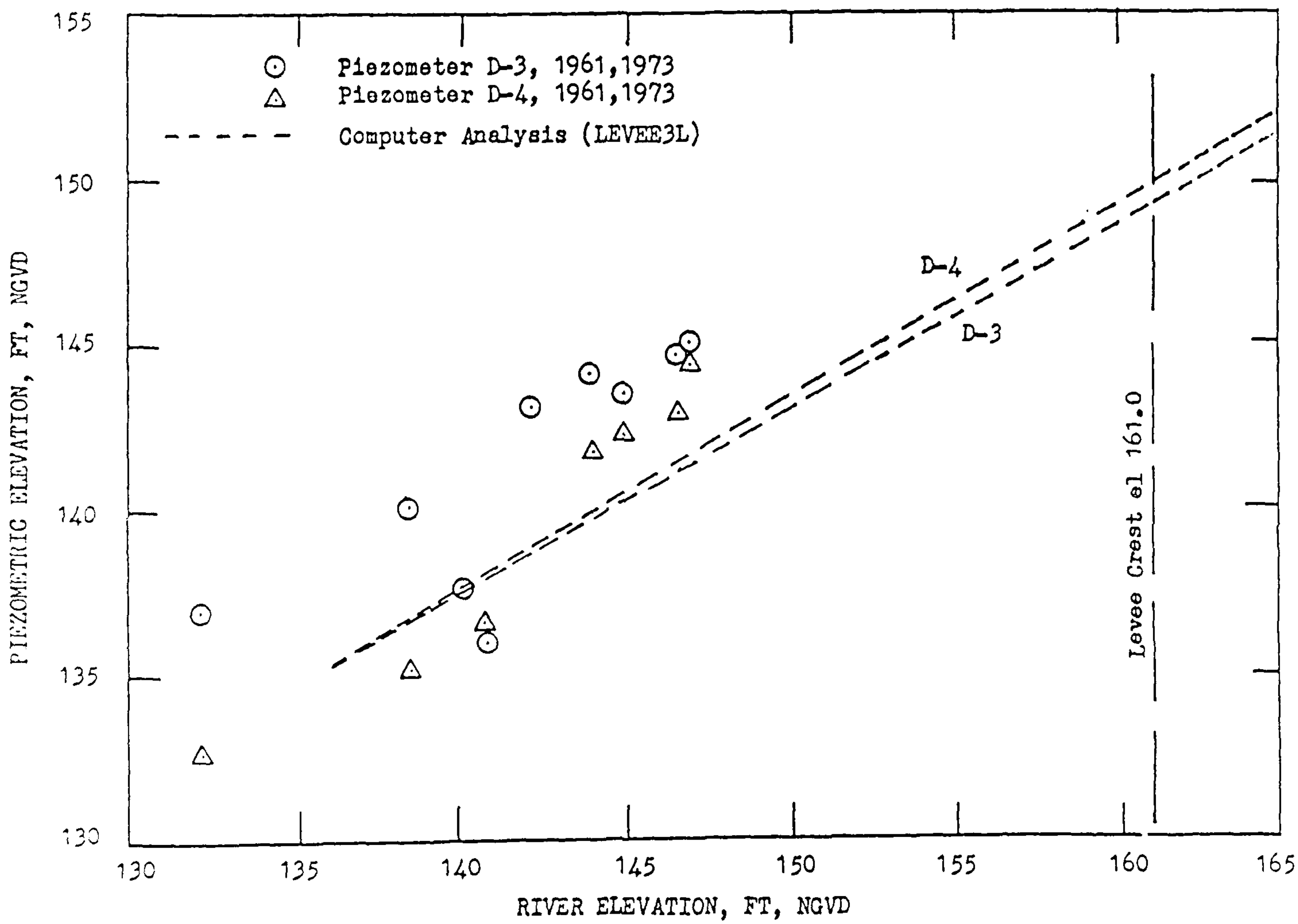


Figure 19. Results of analyses, Vicksburg District, Eutaw, Miss, Line D, piezometers D-3 and D-4

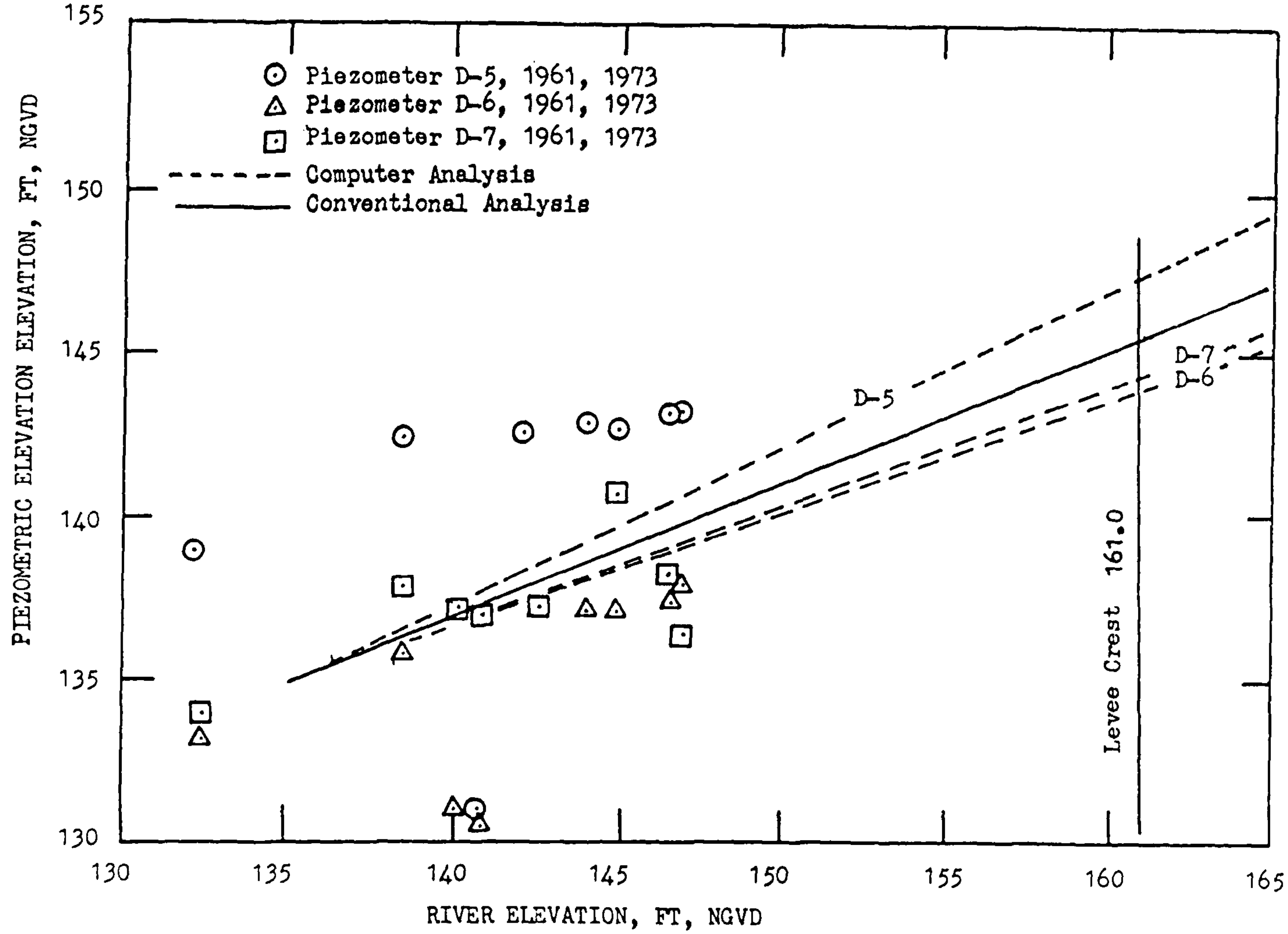


Figure 20. Results of analyses, Vicksburg District, Eutaw, Miss., Line D, piezometers D-5 through D-7

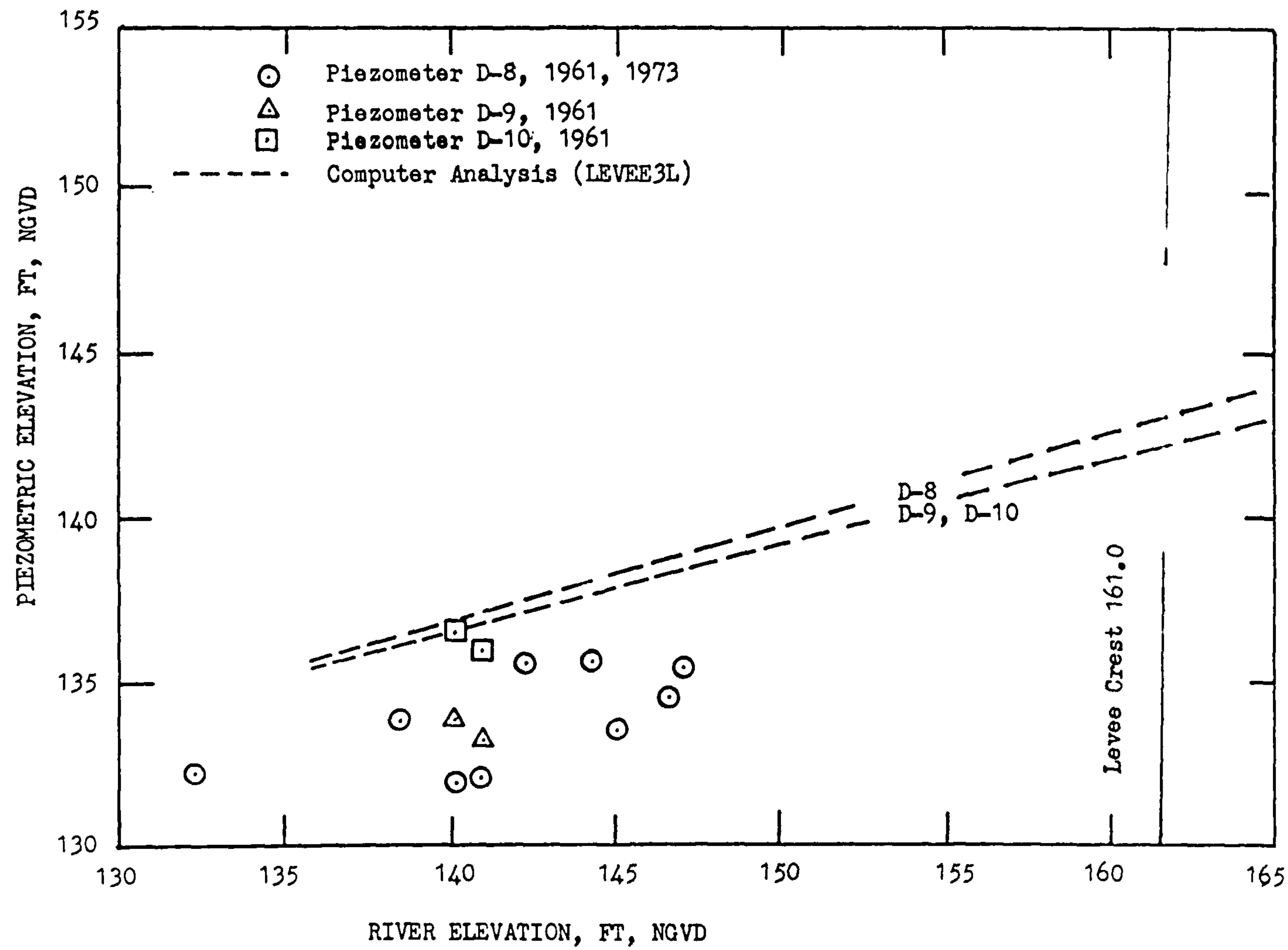


Figure 21. Results of analyses, Vicksburg District, Eutaw, Miss., Line D, piezometers D-8 through D-10

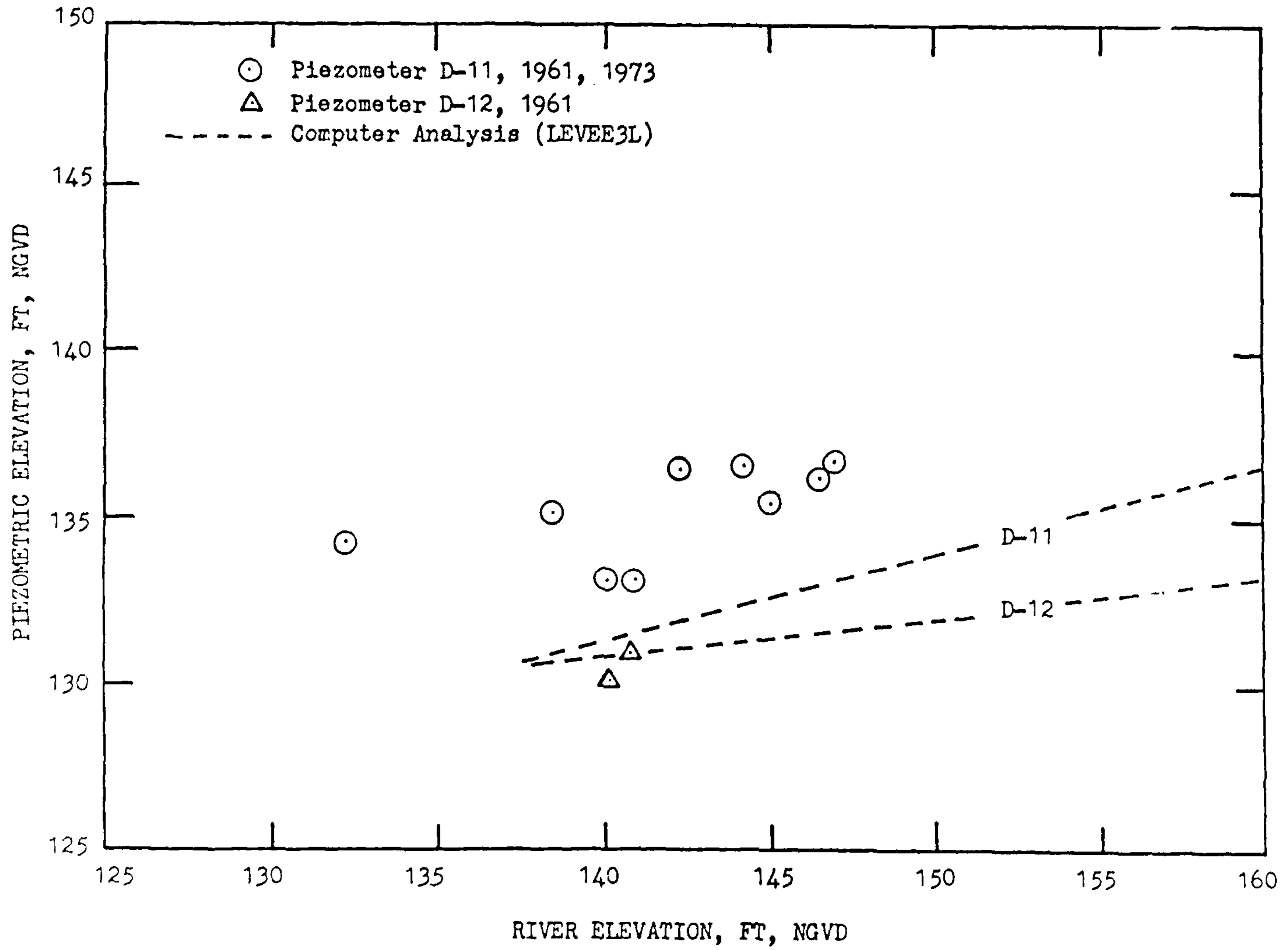


Figure 22. Results of analyses, Vicksburg District, Eutaw, Miss., Line D, piezometers D-11 and D-12

toe, the predictions fall on both sides of observed data, depending on the piezometer location analyzed.

28. The great variability in piezometric response at this site points up the problems inherent in analyzing irregular soil profiles. Despite the ability of LEVEE3L to account for the thick silt layer below the clay top blanket, the analysis remains uncertain and subjective because the irregular ground surface elevation and top blanket thickness must be treated as single "effective" values. It appears that the program LEVEEIRR described in Part V of this report offers some advantage over LEVEE3L for such conditions, and it may be desirable to develop a program that combines some of the features of both.

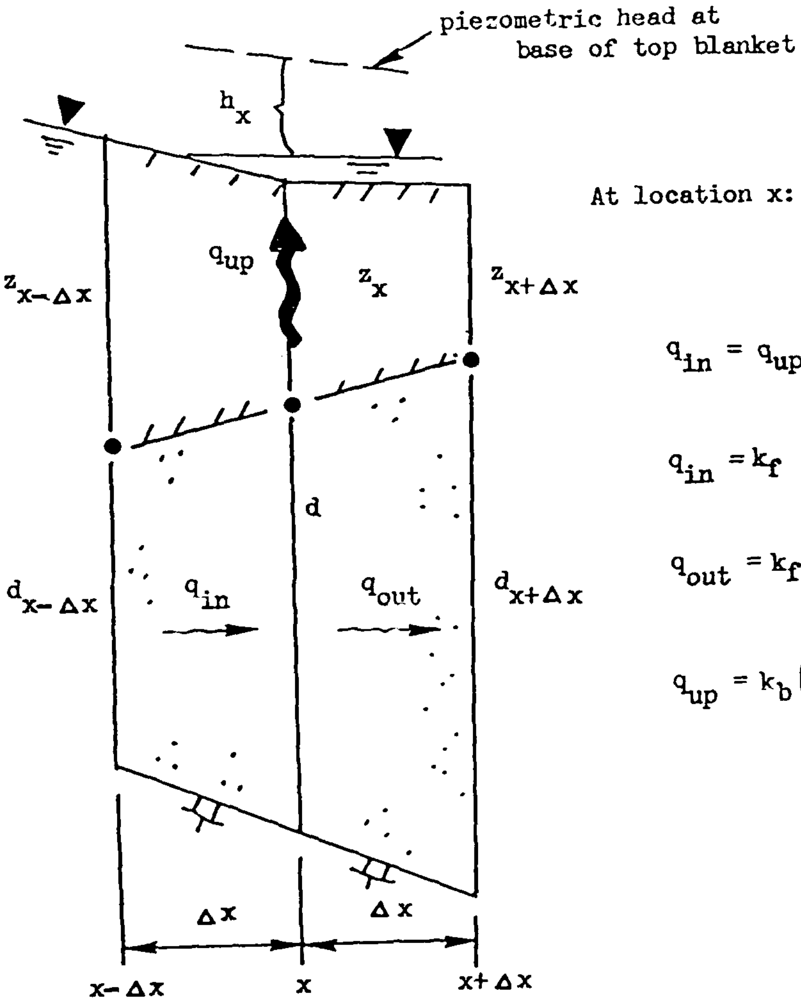
PART V: FOUNDATIONS CHARACTERIZED BY TWO LAYERS OF IRREGULAR SHAPE

Numerical Modeling Technique

29. To analyze underseepage conditions for foundations consisting of two layers of nonuniform thickness with non-horizontal boundaries, a computer program named LEVEEIRR was written. LEVEEIRR solves the same differential equation for the same assumptions as Bennett's (1946) solution; however, the soil boundary elevations and the layer thicknesses a and d need not be constant but may vary as a piecewise linear function of horizontal distance x . Input to the program consists of the same parameters used for conventional analysis, with the addition that the elevations of the top of the blanket, top of the substratum, and bottom of the substratum are specified for a selected set of x-coordinates. Between each specified x-coordinate, the program generates nine additional nodes along the interface between the top blanket and substratum. The head at each node is calculated by iteratively solving a finite difference equation for the flow at each node. The technique used in LEVEEIRR is illustrated in Figure 23. The program output provides the residual head and gradient at every node point, and thus allows calculation of the expected gradient at local discontinuities such as landside ditches, thin spots in the top blanket, and edges of clay plugs. The use of LEVEEIRR is described with examples in Appendix B.

Effect of Nonuniform Layer Thickness

30. To illustrate the capabilities of LEVEEIRR, the common problem of excavating a ditch adjacent to a levee was investigated. It was assumed that the top blanket had a uniform thickness of 20 ft before excavating the ditch. If was further assumed that the thickness of the substratum was 100 ft, the net head on the levee was 20 ft, and the permeability ratio was 500. The depth of the ditch, D , and the distance from the ditch crown to the levee toe, L , were then varied and the gradient at the bottom of the ditch plotted as a function of the two variables. Results of the analysis are shown in Figure 24. As would be expected, it is shown that the gradient increases with increasing ditch depth and decreases with increasing distance from the levee.



At location x:

$$q_{in} = q_{up} + q_{out}$$

$$q_{in} = k_f \left(\frac{h_{x-\Delta x} - h_x}{x} \right) d$$

$$q_{out} = k_f \left(\frac{h_x - h_{x+\Delta x}}{x} \right) d$$

$$q_{up} = k_b \left(\frac{h_x}{z_x} \right) \Delta x$$

Figure 23. Analysis technique used in LEVEEIRR

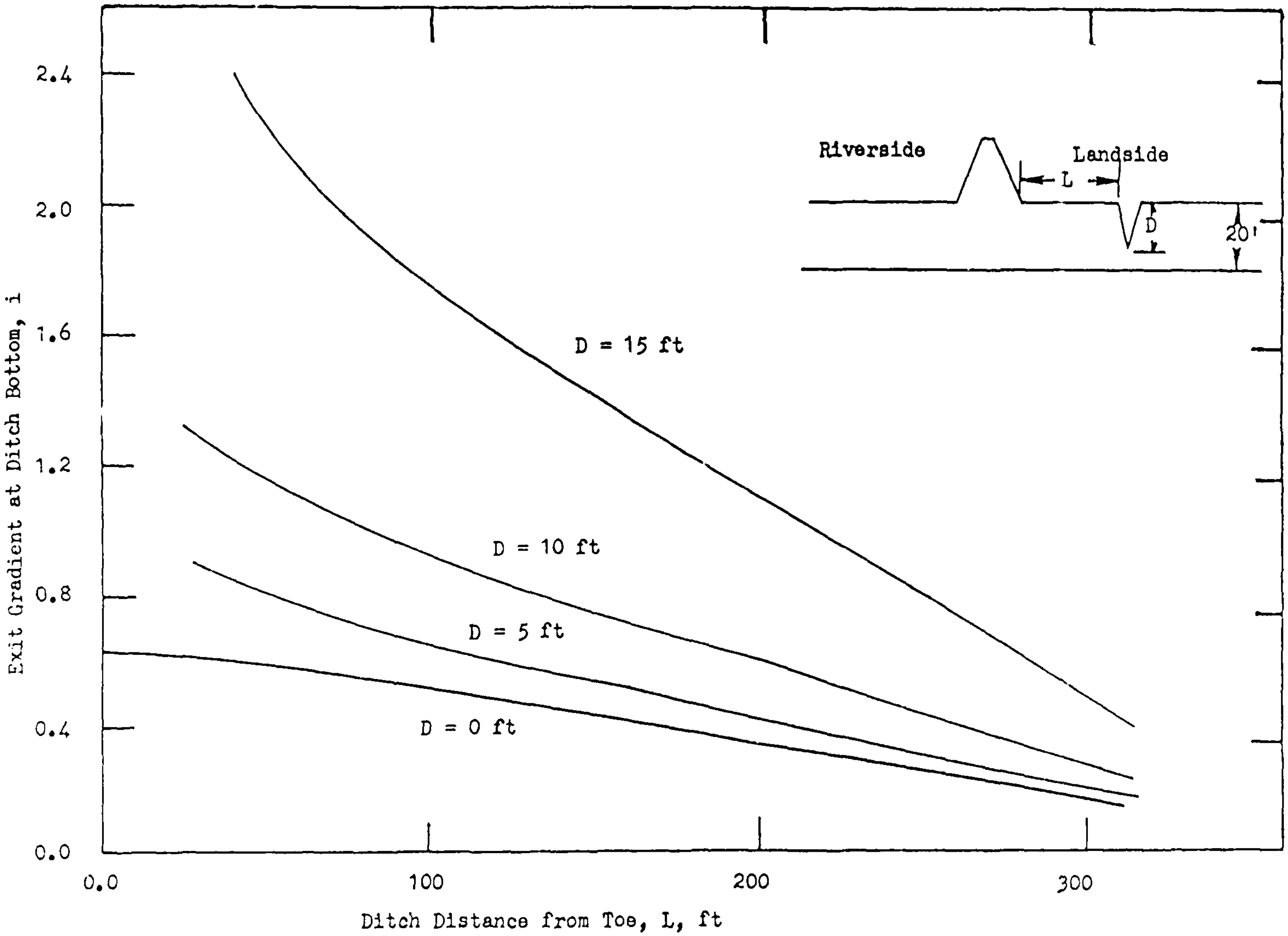


Figure 24. Effect of landside ditch

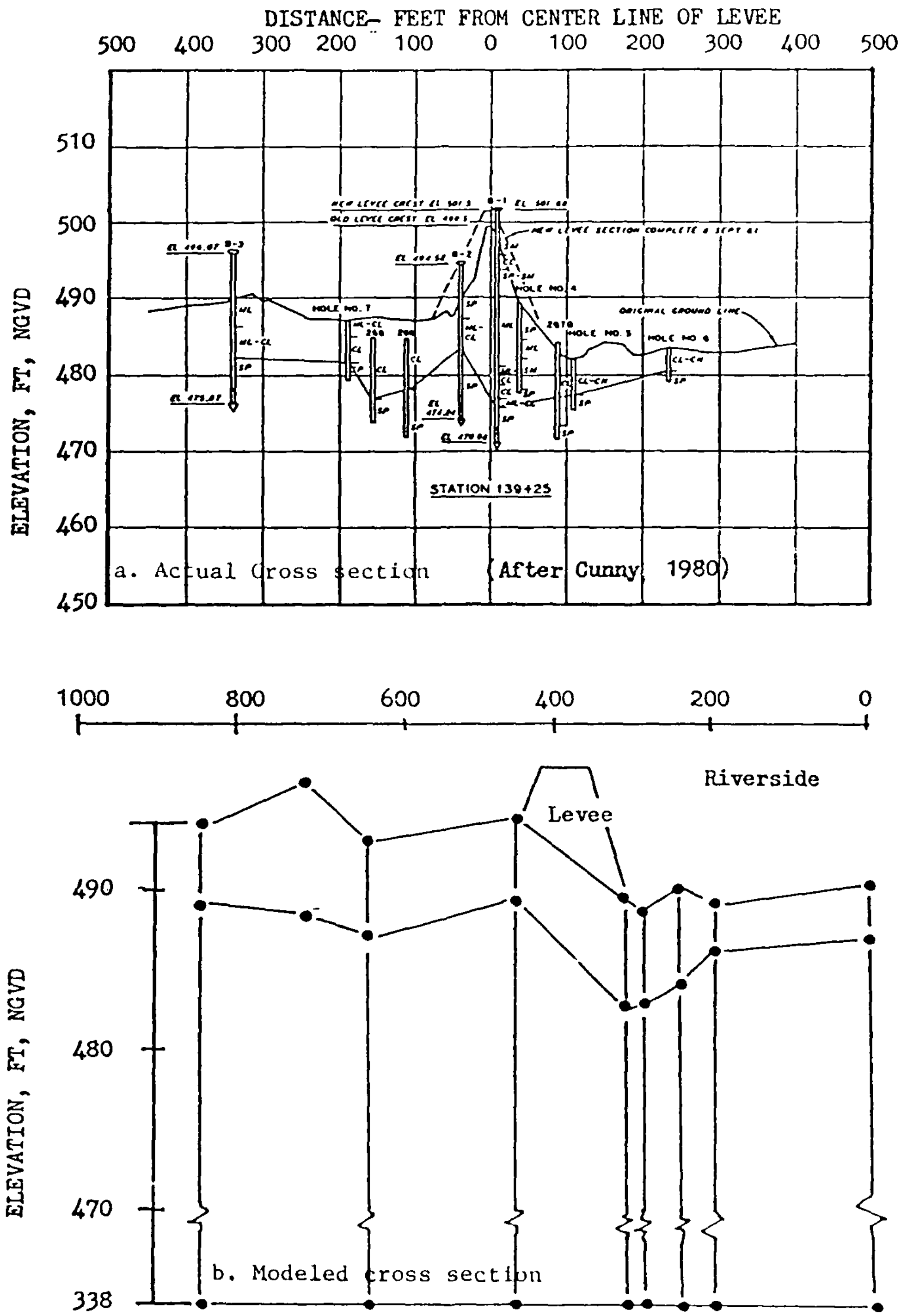


Figure 25. Actual and modeled cross section of Rock Island District, Hunt, Range "B"

Actual Versus Predicted Performance

31. The program LEVEEIRR was used to analyze four levee reaches having markedly irregular subsurface conditions. For each reach, the assumed permeability ratio was varied to find the ratio that best corresponded to observed performance. A discussion of these analyses and results follows.

Rock Island District, Hunt, Range B

32. This piezometer range was established in 1957 on the east bank of the Mississippi River about 25 miles upstream from Quincy, Ill., in the pool area of Lock and Dam 20. It was previously analyzed by Cunny (1980). A foundation profile and the idealized section used for computer modeling are shown in Figure 25. Irregularities in the profile include a landside ground elevation about 5 ft higher than the riverside and an impervious top stratum varying from 5.3 to 8.2 ft thick. There are three piezometers at the site: B-1 near the levee crest, B-2 near the levee toe, and B-3 on a small ridge about 350 ft landward of the levee centerline.

33. Parameters used in the analyses are shown in Table 3. Piezometric elevations calculated using LEVEEIRR are compared to observed piezometric elevations in Figure 26. Two computer analyses were performed. Analysis "A" assumed a permeability ratio of 64, the same as the value used by Cunny. Although this value provided a reasonable match to the observed data at the three piezometer locations, a somewhat better fit was obtained by reducing the top blanket permeability until the permeability ratio was 20. The latter results are labeled analysis "B." It should be noted that LEVEEIRR is capable of predicting piezometric elevations even where they are below ground level, as is the case for B-1 and B-3, so long as there are artesian (confined seepage) conditions in the pervious substratum. Assuming a flood level at the top of the levee (501.5) and an interior water elevation of 487.0, a maximum gradient of 0.73 is predicted to occur at the landside levee toe near piezometer B-2.

Memphis District, Commerce, Miss., Line H

34. This piezometer range was established in 1942 about 10 miles north of Tunica, Miss. Heavy seepage damage was reported at the site during the 1937 high water. The levee is located about 2,200 ft from the Mississippi River on terrain characterized by numerous ridges, ditches, and swales. A foundation profile and the idealized cross section used for analysis are shown

Table 3

Parameters Used for Analyses, Rock Island District, Hunt, Range B

Analysis Parameter (after Cunny 1980)	Conventional Analysis	LEVEEIRR Computer Analysis "A"	LEVEEIRR Computer Analysis "B"
L_1 (ft)	--	310	310
L_2 (ft)	137	140	140
L_3 (ft)	Infinite	2,000	2,000
d (ft)	112	Varies	Varies
z (ft)	5.3 to 8.2	-(Varies; 5.0 at B-2)-	
k_f (ft/min)	--	0.1280	0.1280
k_{bl} (ft/min)	--	0.0020	0.0064
k_f/k_{bl}	64	64.0	20.0
s (ft)	459	--	--
x_3 (ft)	227	--	--
Levee crest	501.5	501.5	501.5
Ground el	489.5 at B-2	Varies	Varies
H_{max}	12.0	-(Varies; 501.5 - ground el)-	
h_o at H_{max} at B-2	2.7	4.9	3.7
i_{max} at B-2	0.43	0.99	0.73

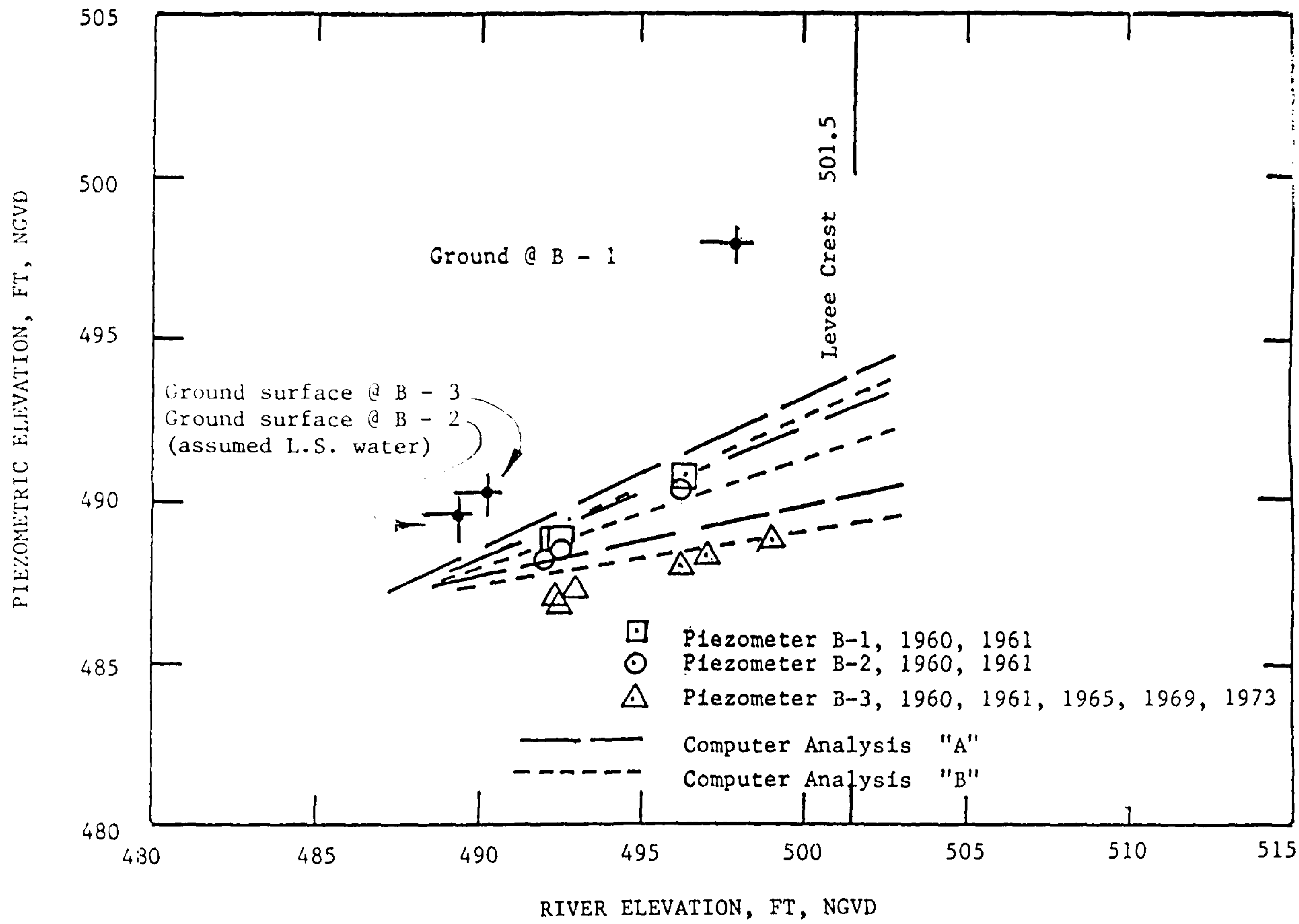


Figure 26. Results of analyses, Rock Island District, Hunt, Range "B"

in Figure 27. Seventeen piezometers were used for analysis at this section. Piezometric data were obtained in 1961 (WES 1964). As some of the piezometers are located on different but adjacent levee cross sections, some variation is observed for piezometers that are about the same distance from the levee.

35. Parameters used for analysis are shown in Table 4. The column titled "Conventional Analysis" provides values reported in TM 3-424 (WES 1956a) for comparison. Piezometric elevations calculated using LEVEEIRR are compared to observed data in Figures 28 through 32. The predictions are based on a permeability ratio of 514, a value that was calculated using the two permeability values reported in TM 3-424. (Permeability ratios and permeability values reported in TM 3-424 are not exactly consistent). It should be noted that reasonable predictions can be obtained using LEVEEIRR for widely different distances from the levee toe.

Memphis District,
Stovall, Miss., Line B

36. This piezometer range was established in 1948 about 3.5 miles west of Stovall, Miss. Seepage damage occurred at the site during the 1937 high water. A foundation profile and the idealized cross section used for analysis are shown in Figure 33. Irregularities in the profile include a very thin riverside top stratum due to removal of borrow materials, a thick landside top stratum, and a silt plug below the levee centerline. Piezometric data were obtained in 1961 (WES 1964).

37. Parameters used for analysis are shown in Table 5. The column titled "Conventional Analysis" provides values obtained from TM 3-424 for comparison. Two analyses using LEVEEIRR are reported. In analysis "A" the permeability ratio was taken as 432, the ratio of the two individual values reported in TM 3-424. For analysis "B" the permeability ratio was taken as 1,000. Piezometric elevations calculated using LEVEEIRR are compared to observed data in Figures 34 through 36. It is noted that the computer solutions plot below the observed data for piezometers in the substratum (E-15 and E-17) by several feet. Relatively high piezometric response has been observed at these piezometers. The profile at Stovall is an extreme case of different blanket materials and thicknesses on opposite sides of the levee. It is likely that the top blanket permeabilities are also much different on the two sides. Attempts to match the response of E-15 and E-17 by decreasing the riverside blanket thickness, increasing the permeability ratio, and shortening

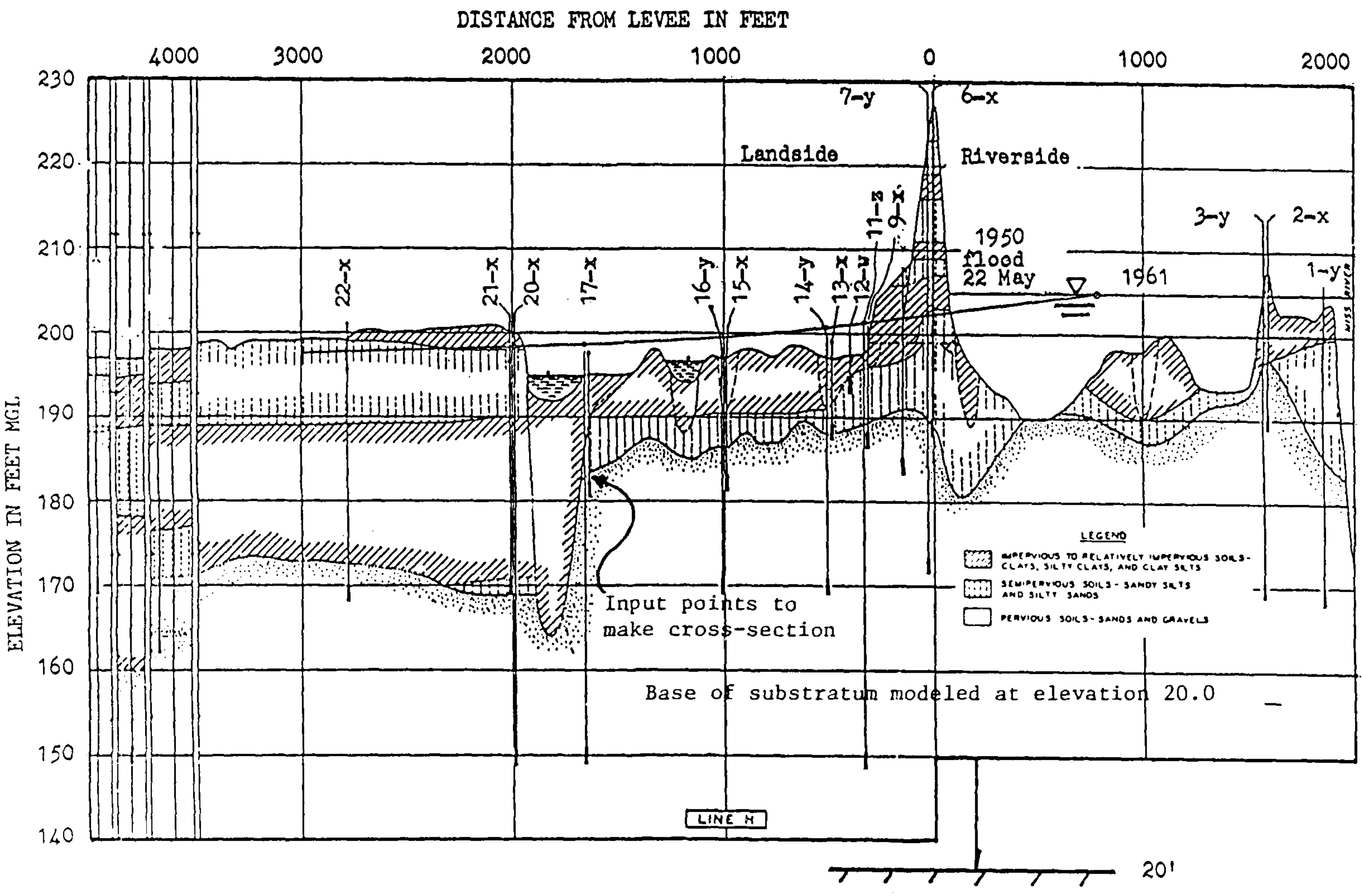


Figure 27. Actual and modeled cross sections of Memphis District, Commerce, Miss., Line H

Table 4

Parameters Used for Analyses, Memphis District

Commerce, Miss, Line H

Analysis Parameter	Conventional Analysis (WES 1956a)	LEVEEIRR Computer Analysis
L_1 (ft)	--	1,850
L_2 (ft)	--	214
L_3 (ft)	--	3,365
d (ft)	165	Varies
z (ft)	7.0	Varies
k_f (ft/min)	--	0.18000
k_{bl} (ft/min)	--	0.00035
k_f/k_{bl}	580	514
s (ft)	1,350	--
x_3(ft)	880	--
Levee crest	220.2	220.2
Ground el	197.5	197.5
H_{max} (ft)	22.7	22.7
h_o at H_{max} (ft)	9.0	8.7

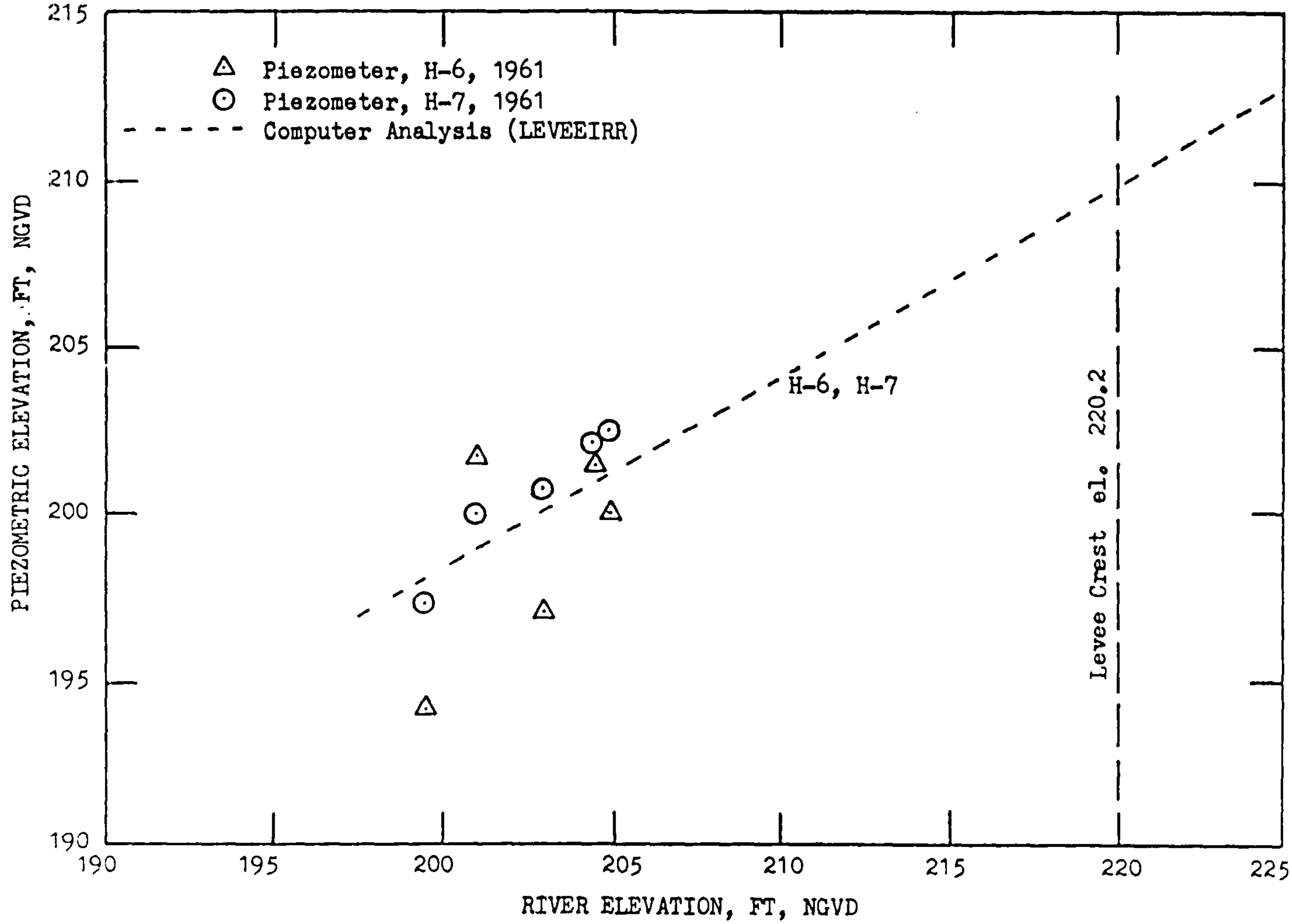


Figure 28. Results of analyses, Memphis District, Commerce, Miss., Line H, piezometers H-6 and H-7

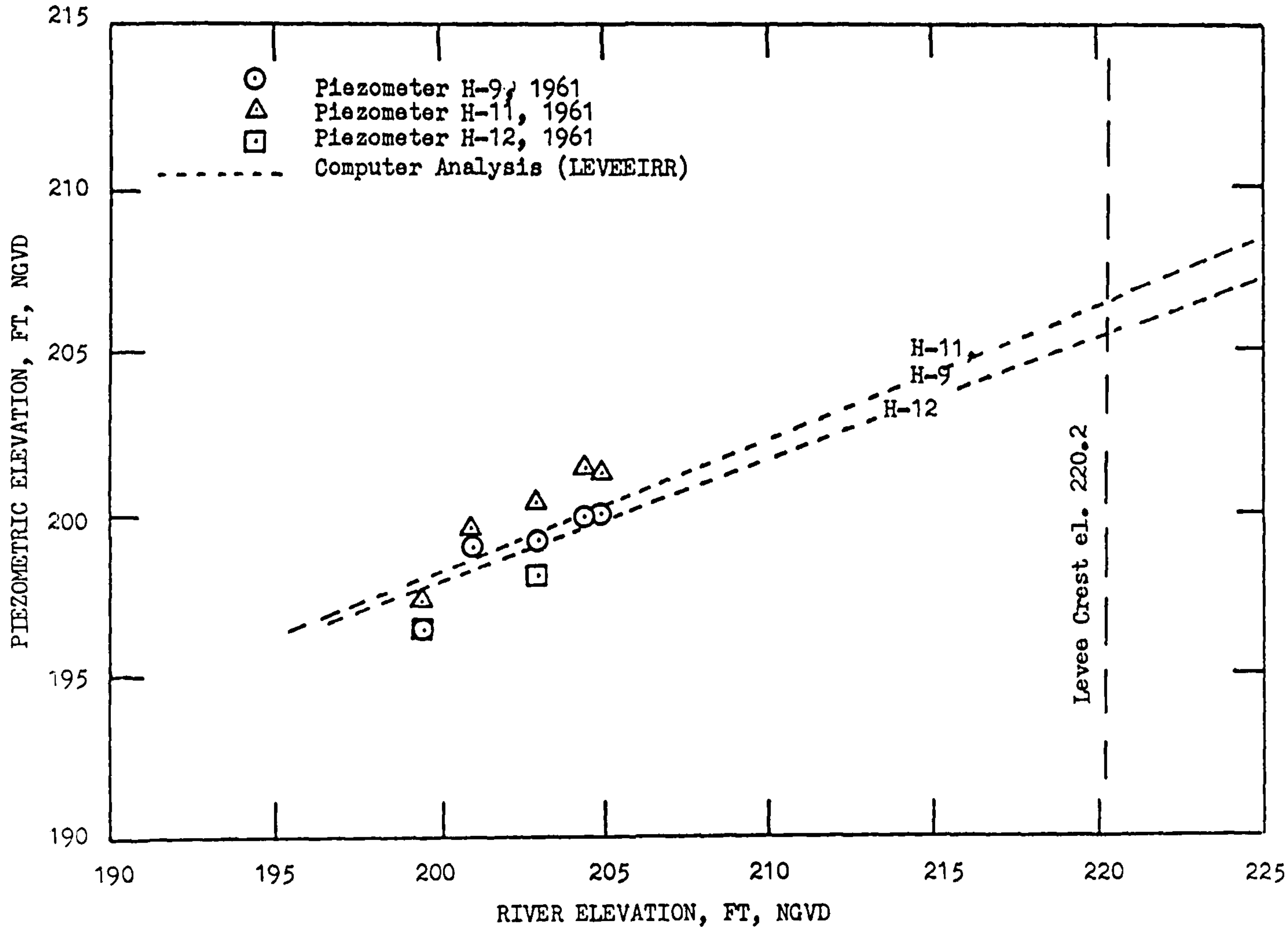


Figure 29. Results of analysis, Memphis Districts, Commerce, Miss., Line H, piezometers H-9, H-11, H-12

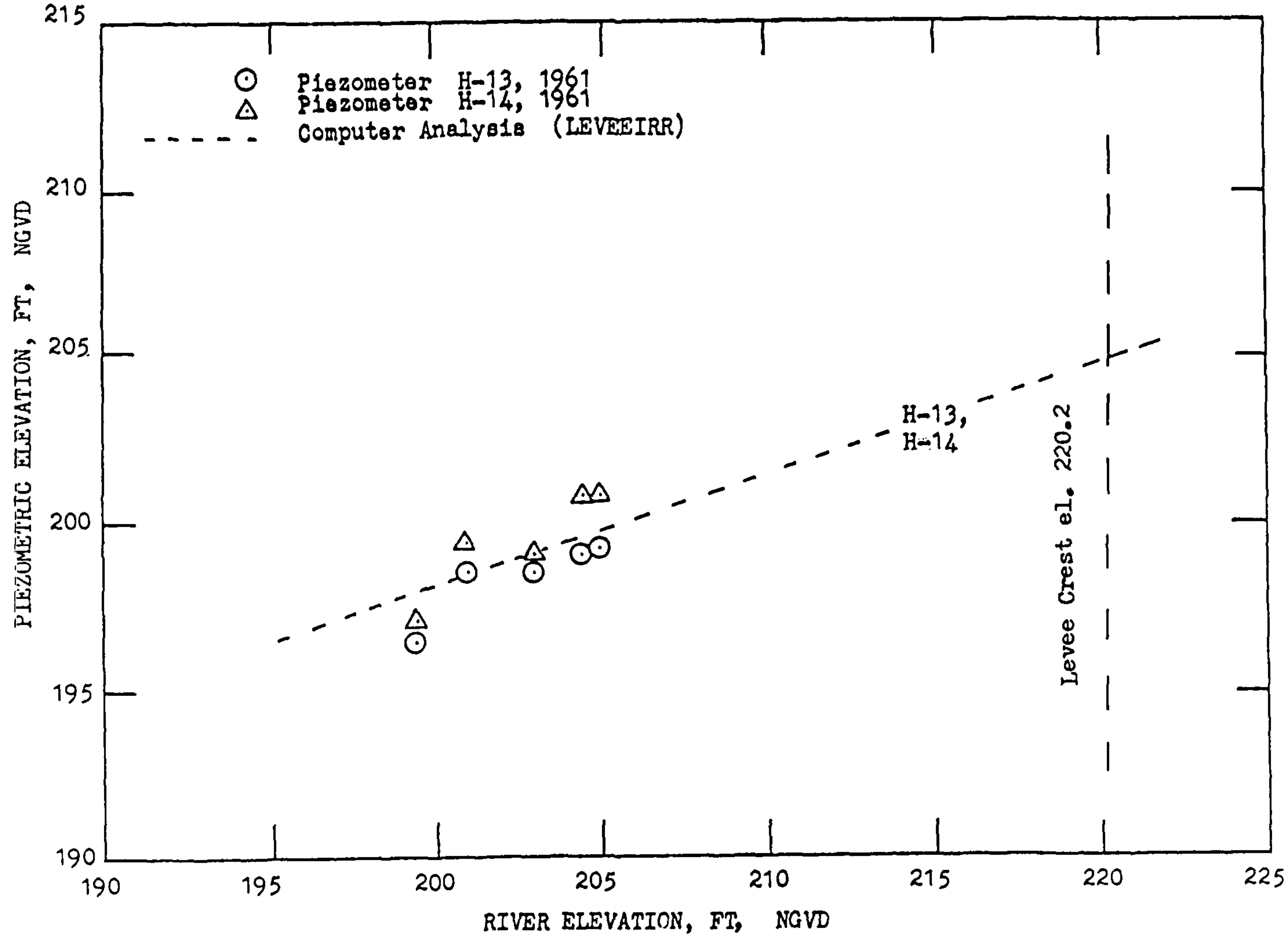


Figure 30. Results of analyses, Memphis District, Commerce, Miss., Line H, piezometers H-13 and H-14

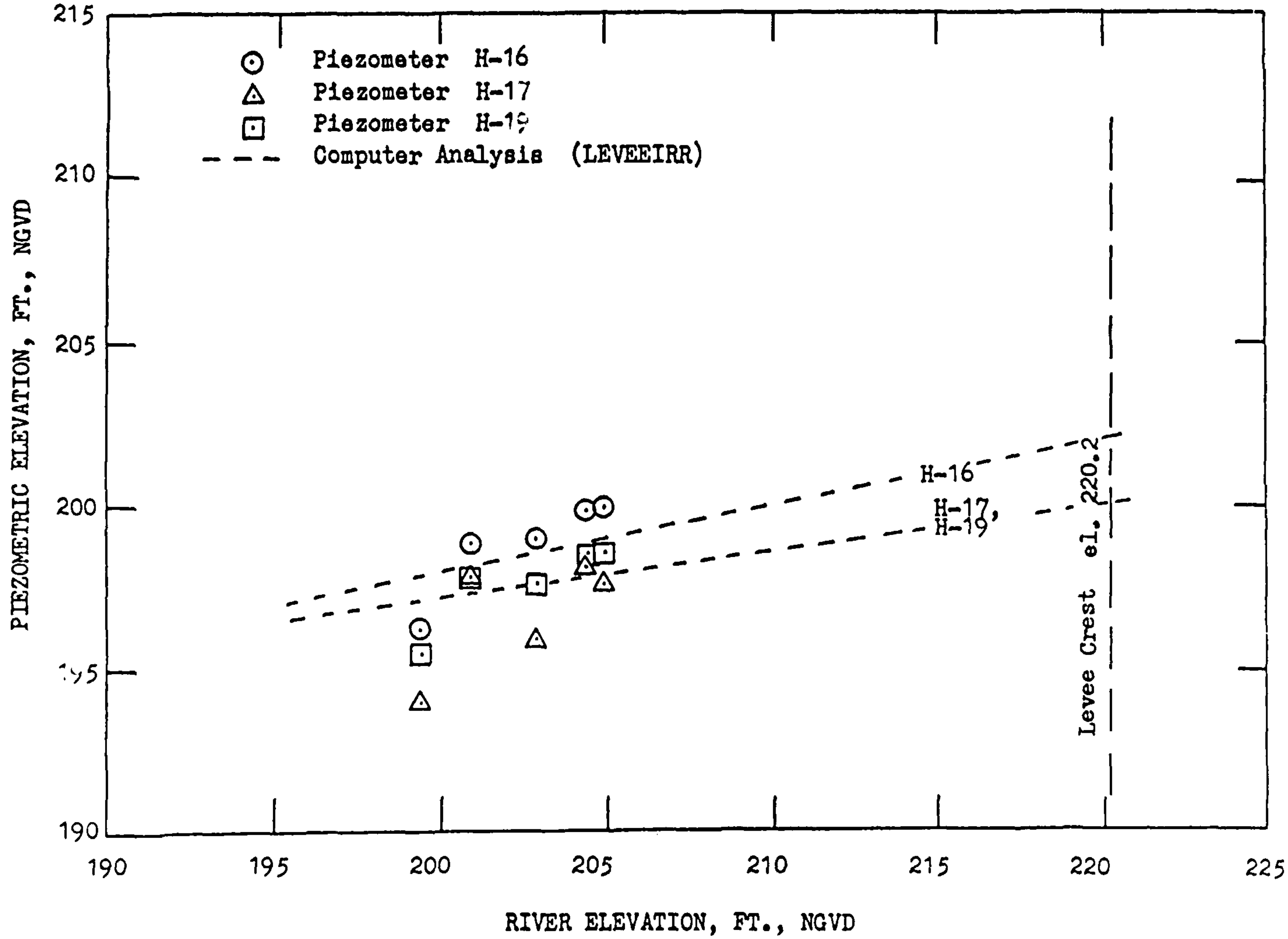


Figure 31. Results of analyses, Memphis District, Commerce, Miss., Line H, piezometers H-16, H-17, and H-19

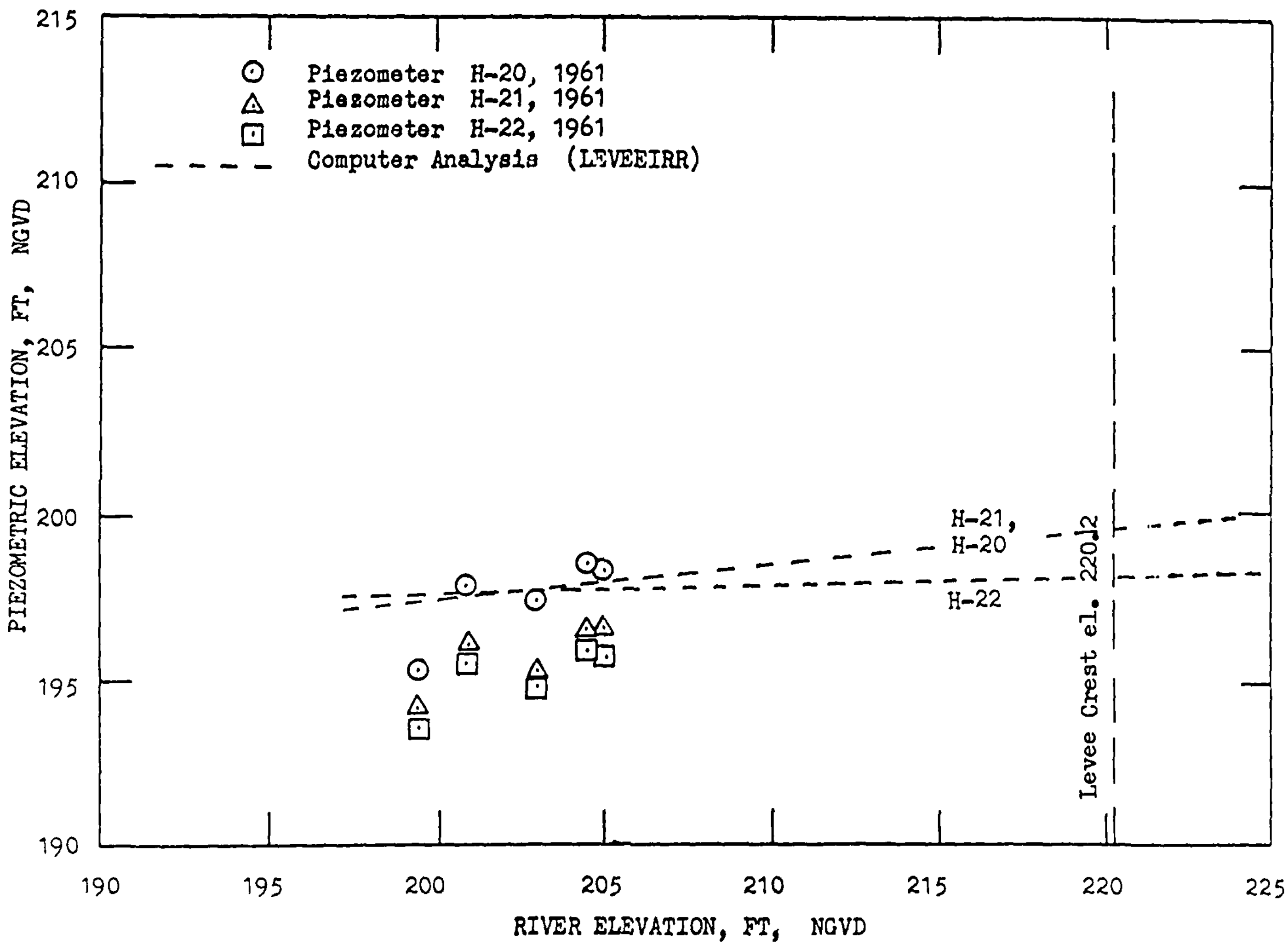


Figure 32. Results of analyses, Memphis District, Commerce, Miss., Line H, piezometers H-20 through H-22

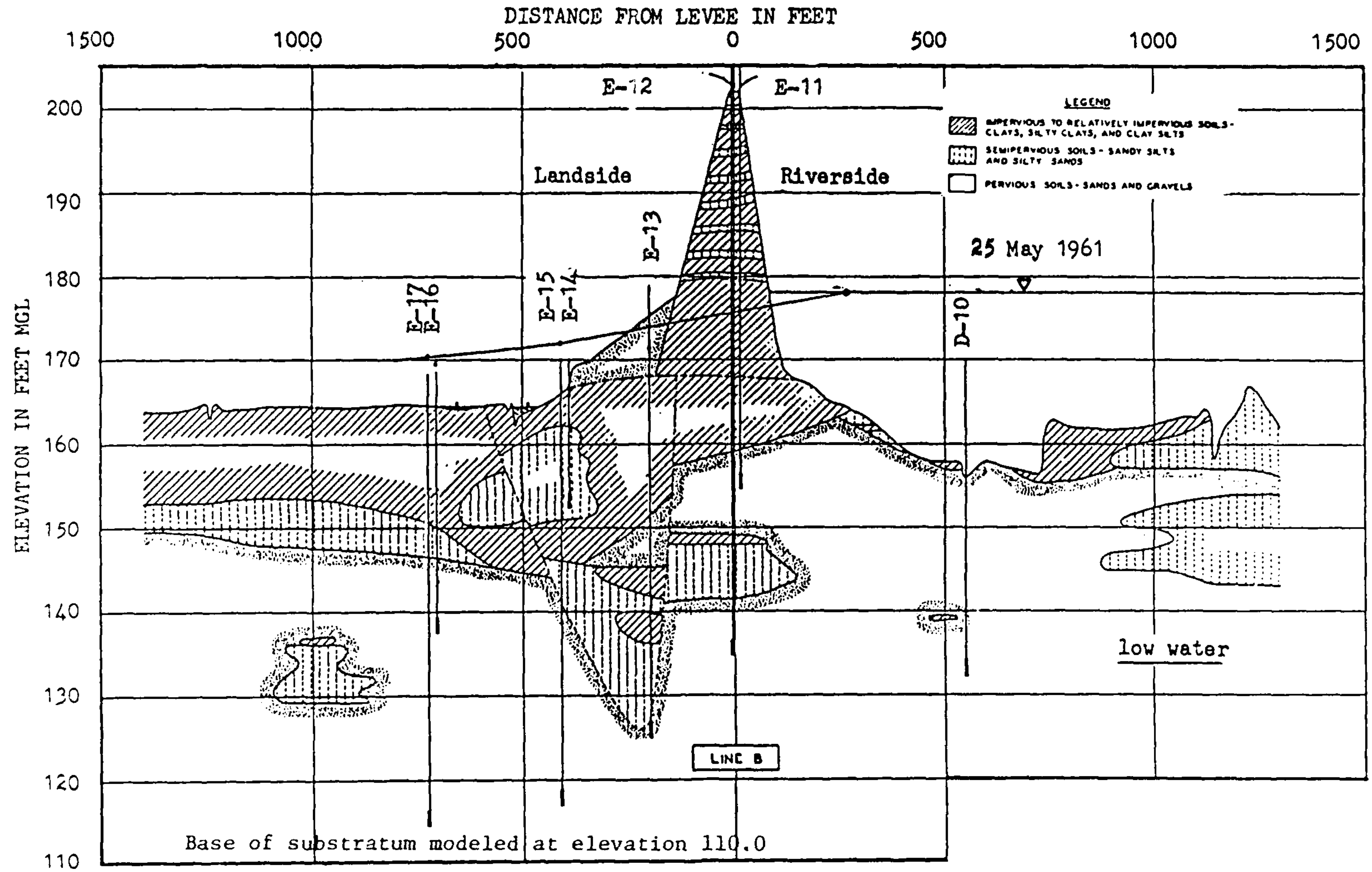


Figure 33. Actual and modeled cross sections of Memphis District, Stovall, Miss., Line B

Table 5

Parameters Used for Analyses, Memphis District

Stovall, Miss. Line B

Analysis Parameter	Conventional Analysis (WES 1956a)	LEVEEIRR Computer Analysis "A"	LEVEEIRR Computer Analysis "B"
L_1 (ft)	--	7,110	7,110
L_2 (ft)	--	243	243
L_3 (ft)	--	2,657	2,657
d (ft)	40	Varies	Varies
z (ft)	15	Varies	Varies
k_f (ft/min)	--	0.1900	0.3000
k_{b1} (ft/min)	--	0.00044	0.0003
k_f/k_{b1}	600	432	1,000
s (ft)	800	--	--
x_3 (ft)	750	--	--
Levee crest	194.3	194.3	194.3
Ground el	164.5	164.5	164.5
H_{max}	29.8	29.8	29.8
h_o at H_{max}	14.4	8.3	8.3

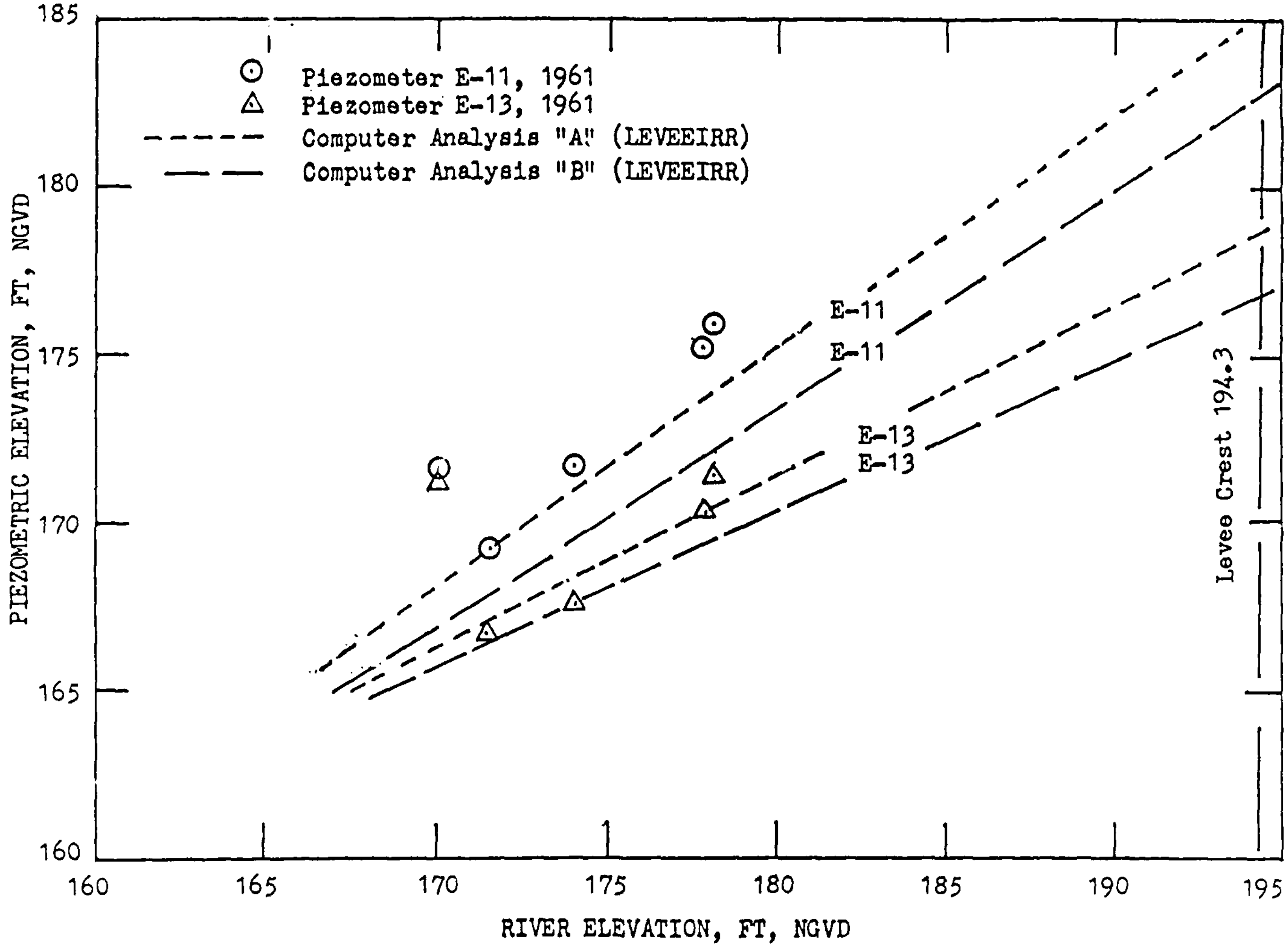


Figure 34. Results of analyses, Memphis District, Stoval, Miss., Line B piezometers E-11 and E-13

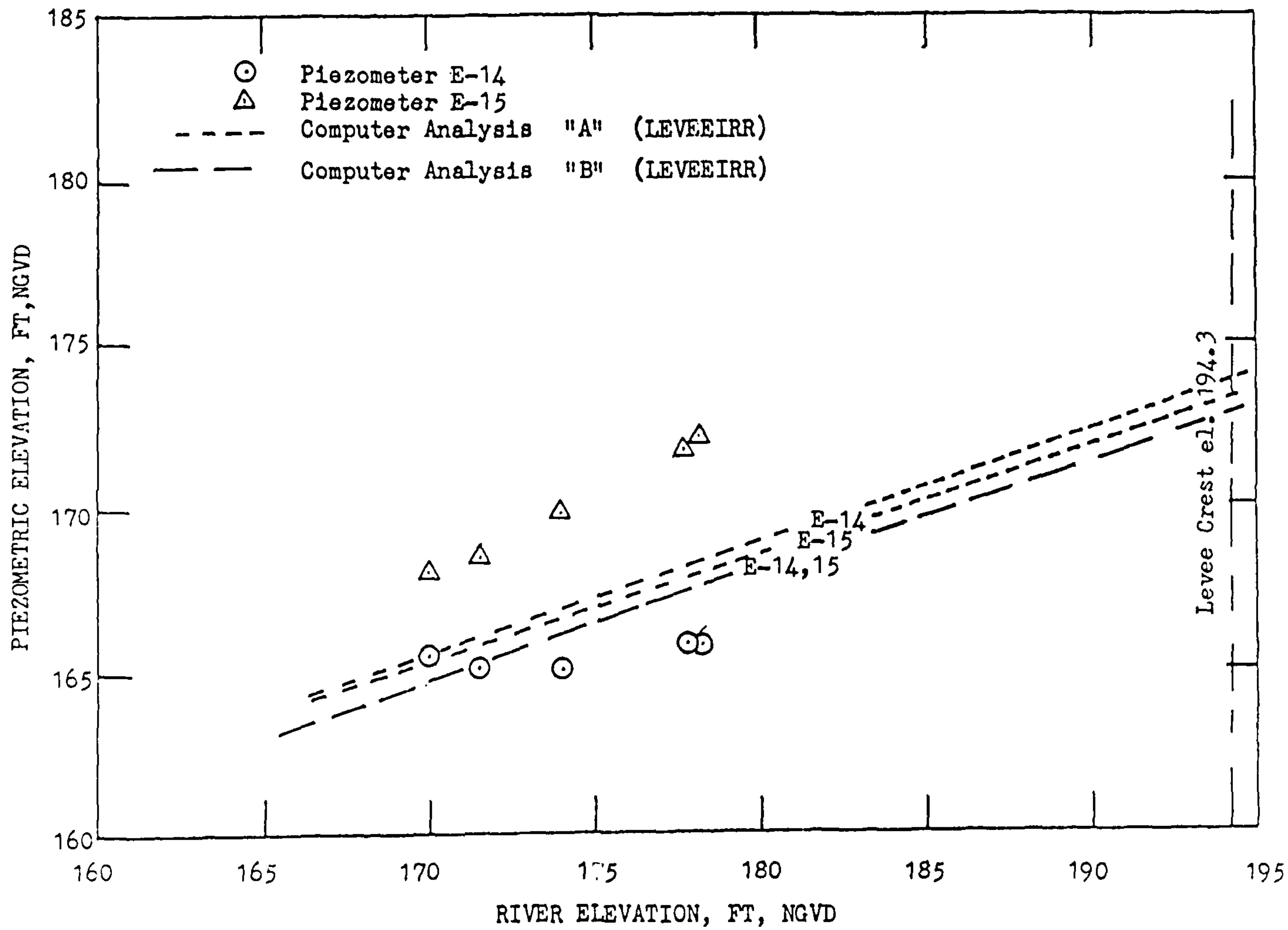


Figure 35. Results of analyses, Memphis District, Stovall, Miss., Line B, piezometers E-14 and E-15

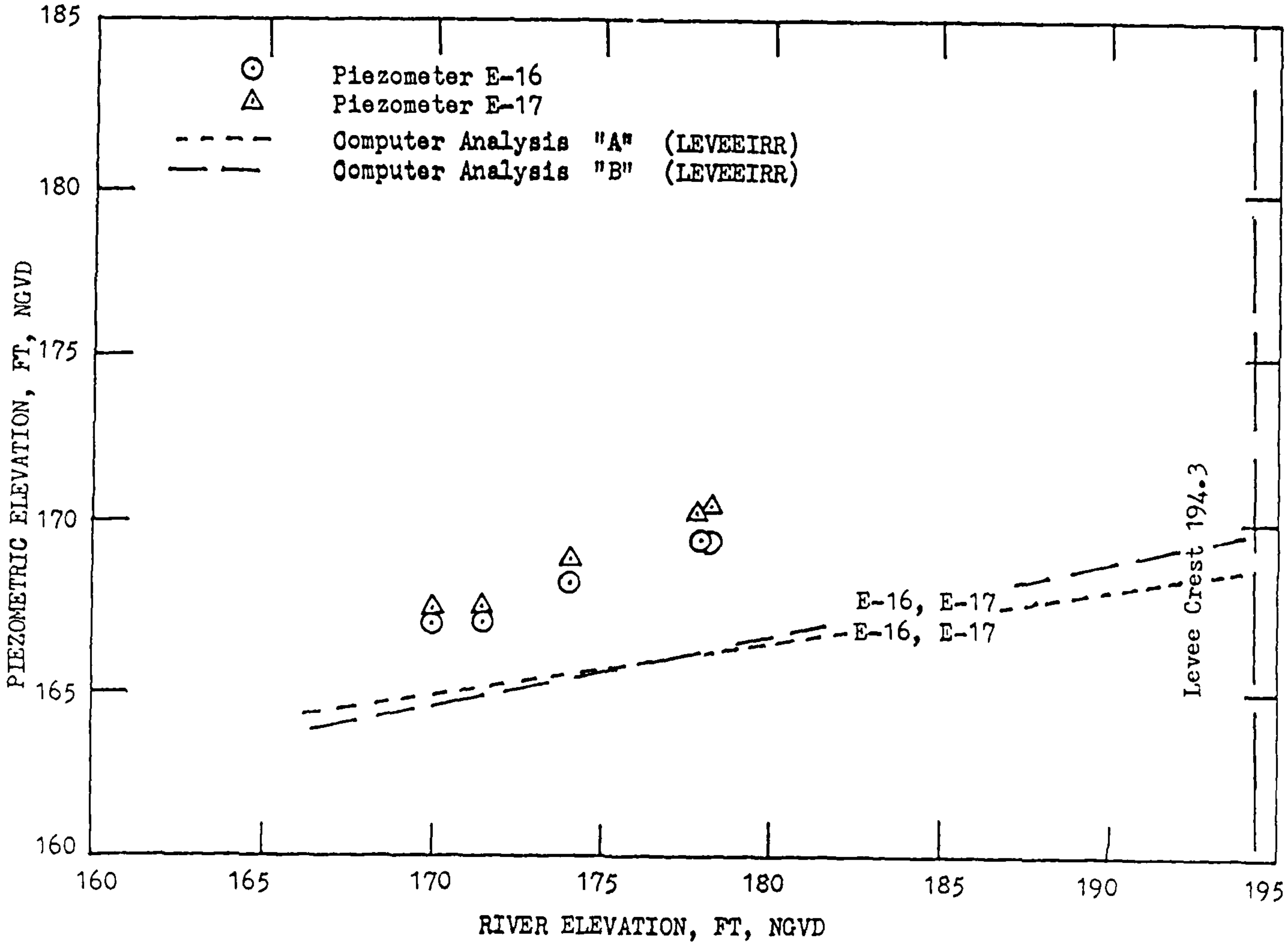


Figure 36. Results of analyses, Memphis District, Stovall, Miss., Line B, piezometers E-16 and E-17

the entrance distance all had relatively little effect. A modification of LEVEEIRR to allow different permeabilities on opposite sides of the levee may afford a better analysis of such sections.

Vicksburg District,
Bolivar, Miss., Line D

38. This piezometer range is located along the east bank levee of the Mississippi River 2 miles northwest of Benoit, Miss. The river at this site is about 8 miles from the levee; however, Bolivar Chute lies about 1,200 to 1,500 ft riverward of the levee. A line of nine piezometers, D-1 through D-9, run perpendicular to the levee at this site. A soil profile at the piezometer line is shown in Figure 37. Irregularities in the profile include riverside borrow pits, landside sublevees, a landside ditch, and a massive clay-filled abandoned channel about 1,000 to 2,000 ft landside of the levee. The effect of this channel is to concentrate seepage between the landside levee tow and the channel.

39. The analyses gave more weight to 1973 flood data, where available, than 1961 data. Data for 1961 were obtained during a falling river, and an inverse relationship between river stage and piezometric elevation was apparent. Data points at higher river stages are generally 1973 data, and those at lower stages are generally 1961 data. Data from piezometers D-1 and D-7 appears unreliable as it plots considerably lower than other piezometric data. This may be due to the piezometer tops being founded in fine-grained blanket materials rather than in the pervious substratum. Parameters used in the analyses are shown in Table 6. Results of the analyses for all nine piezometer locations are shown in Figures 38 through 41. A permeability ratio (k_f/k_b) of 1,000 was found to provide the best fit to the observed data. These results are labeled "Analysis A." Performance predictions for an assumed permeability ratio of 100 are also shown (Analysis B), and it is seen that the difference is relatively small, particularly at relatively large distances landside of the levee.

40. Assuming a flood to the project flow line of el 166.4, a landside tailwater of 140.5, and a permeability ratio of 1,000, a gradient at the levee toe of 0.82 is calculated. Assuming a permeability ratio of 100 reduces the gradient to 0.63.

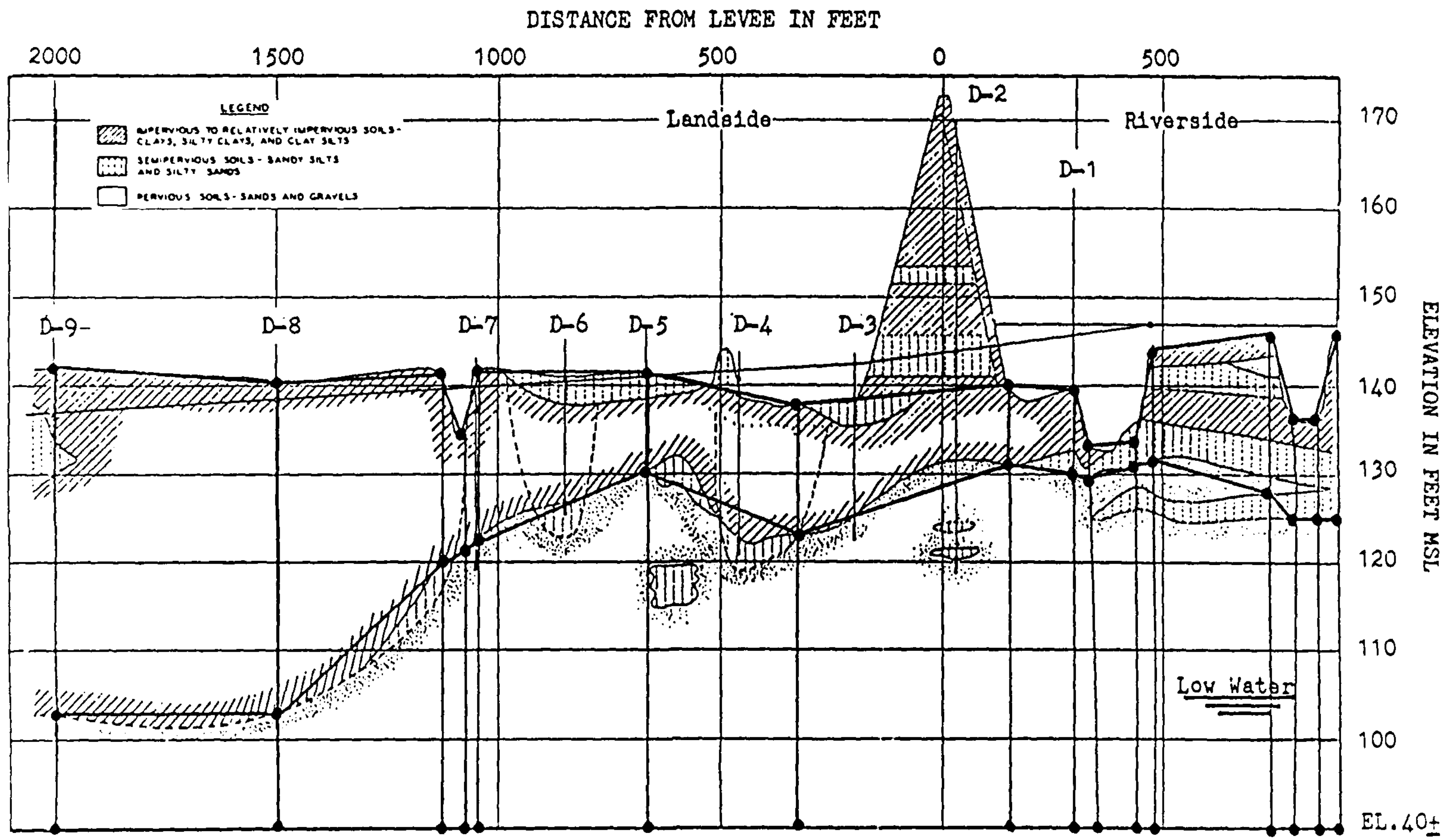


Figure 37. Actual and modeled cross sections of Vicksburg District, Bolivar, Miss., Line D

Table 6

Parameters Used for Analyses, Vicksburg District, Bolivar, Miss., Line D

Analysis Parameter	Conventional Analysis (WES 1956a)	LEVEEIRR Computer Analysis "A"	LEVEEIRR Computer Analysis "B"
L_1 (ft)	--	2,500	2,500
L_2 (ft)	--	340	340
L_3 (ft)	--	2,150	2,150
d (ft)	90	Varies	Varies
z (ft)	7.0	Varies	Varies
k_f (ft/min)	0.2400	0.2400	0.0024
k_{b1} (ft/min)	--	0.00024	0.0024
k_f/k_{b1}	100 to 200	1,000	100
s (ft)	500	--	--
x_3 (ft)	350	--	--
Flow line	167.2	166.4	166.4
Tailwater	141.0	140.5	140.5
H_{max}	26.2	25.9	25.9
h_o at H_{max} at B-2	10.8	10.6	8.2
i_{max}	>1	0.82	0.63

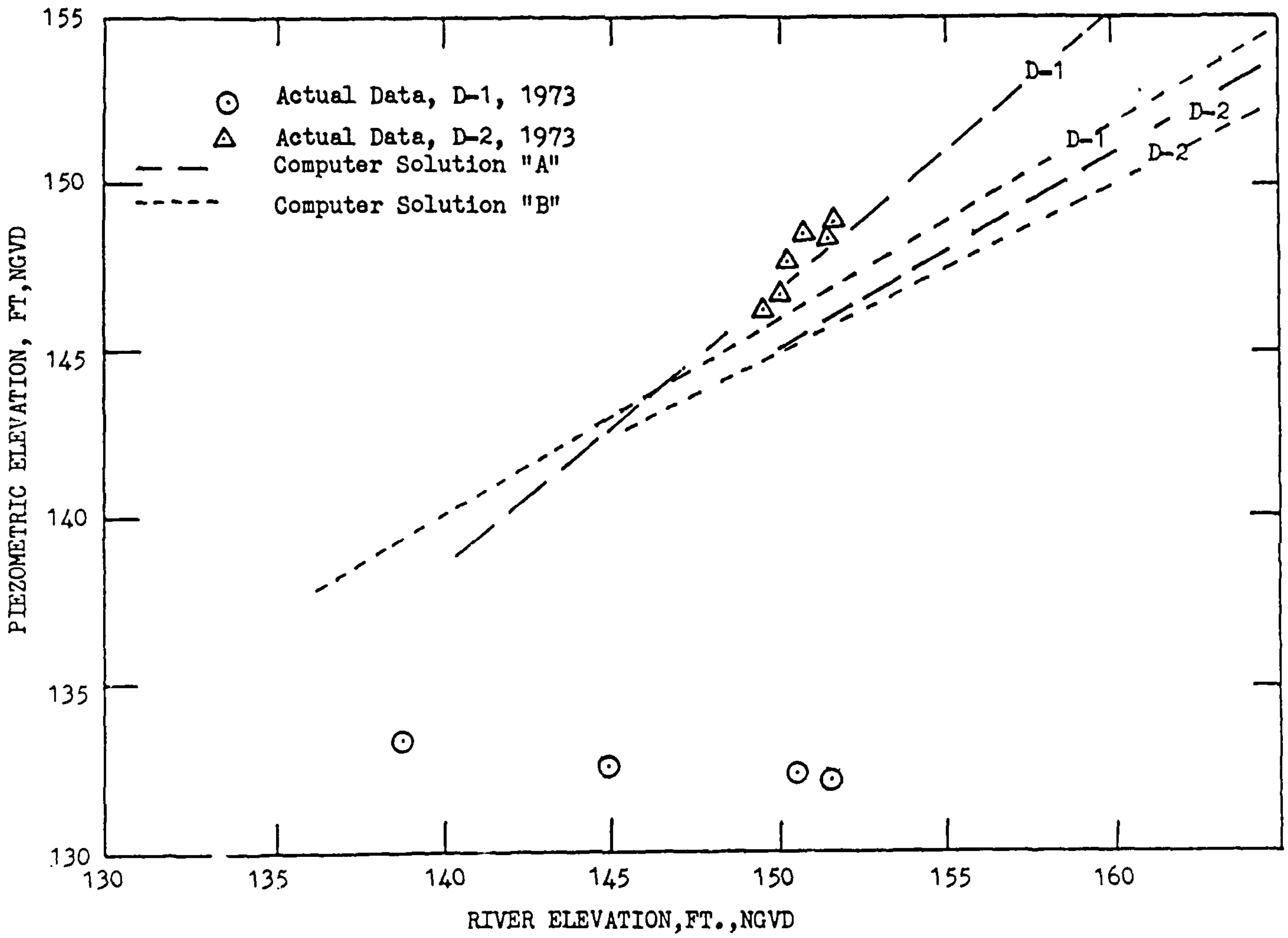


Figure 38. Results of analyses, Vicksburg District, Bolivar, Miss., Line D, piezometer D-1 and L-2

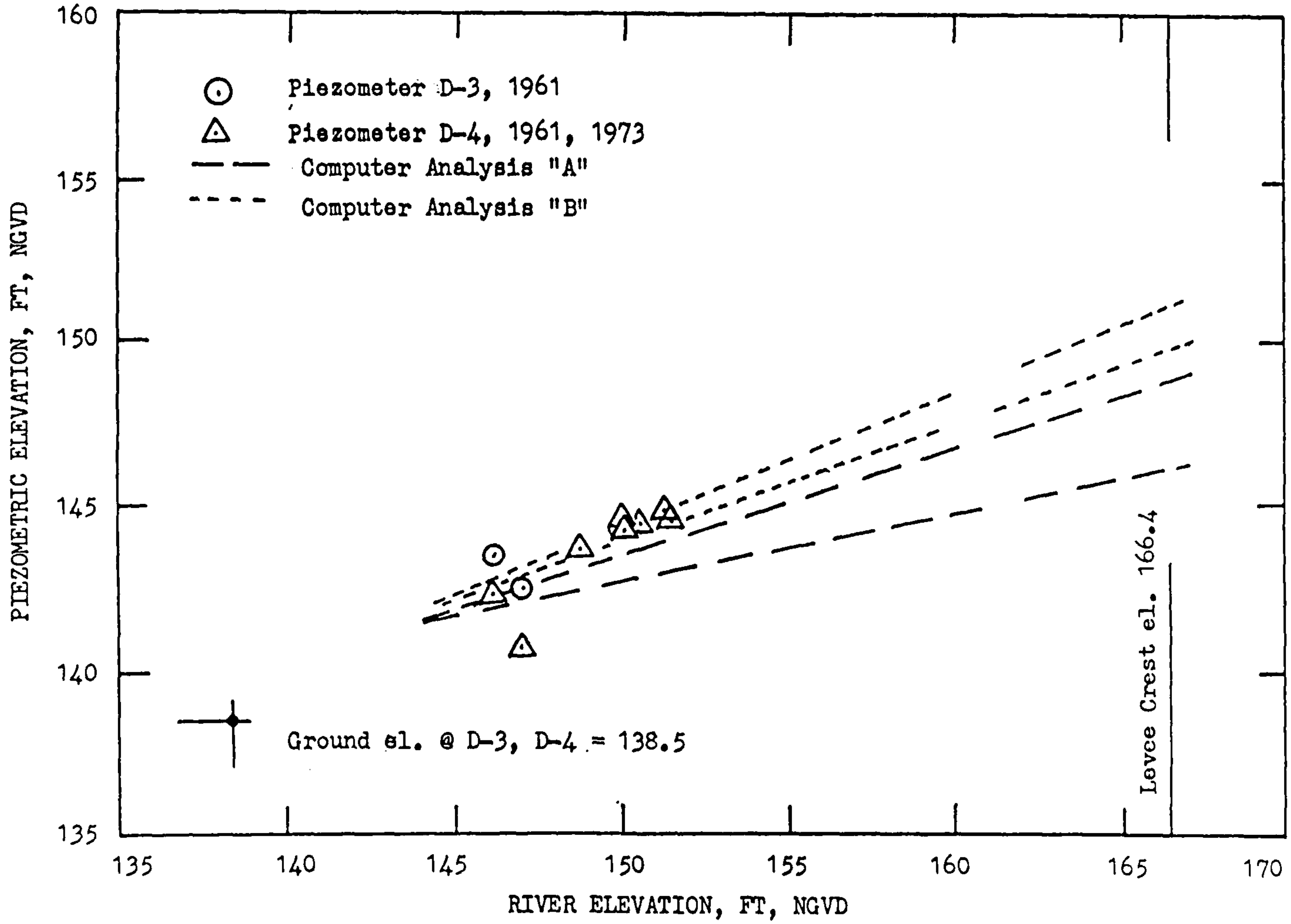


Figure 39. Results of analyses, Vicksburg District, Bolivar, Miss., Line D, piezometers D-3 and D-4

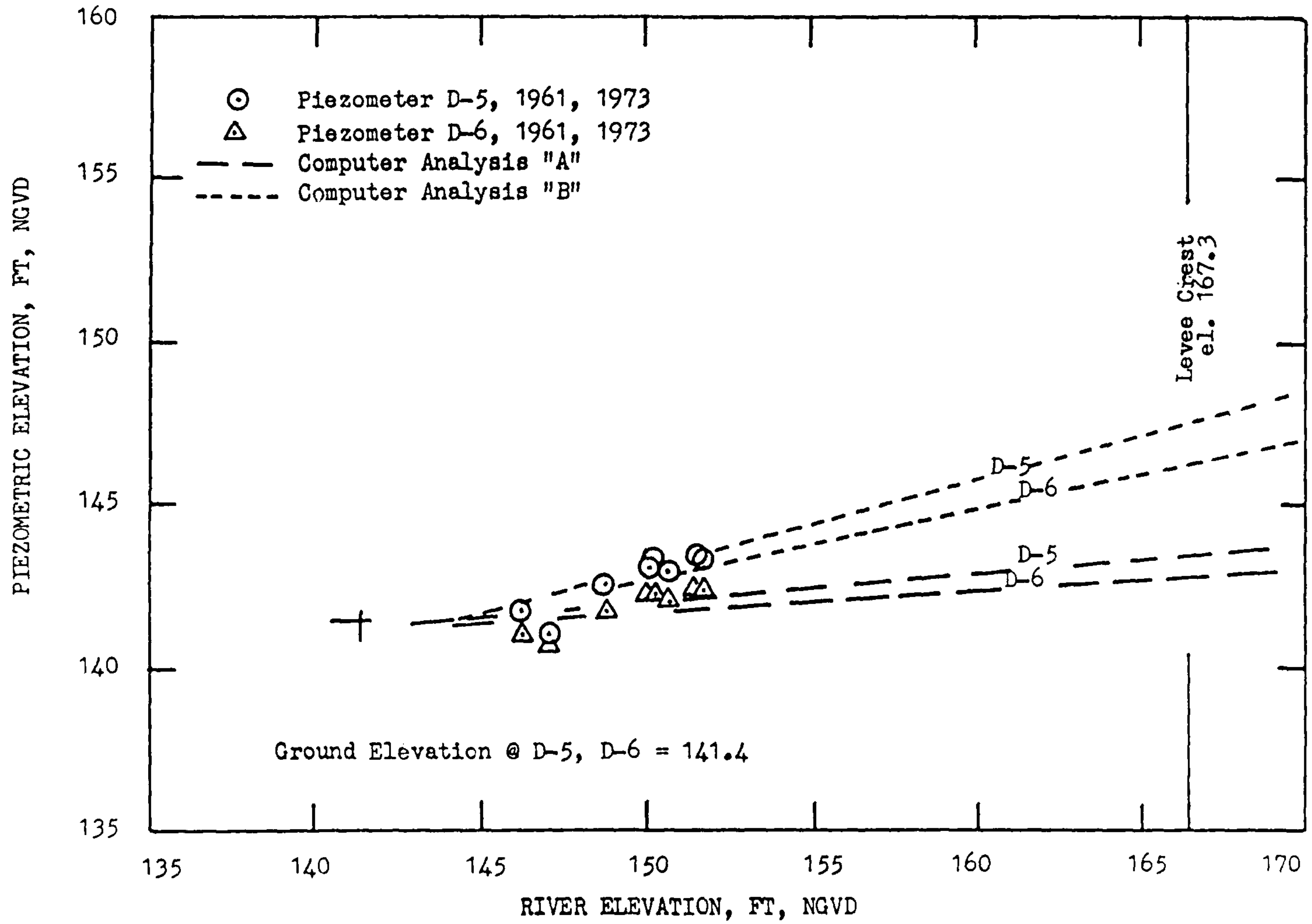


Figure 40. Results of analyses, Vicksburg District, Bolivar, Miss., Line D, piezometers D-5 and D-6

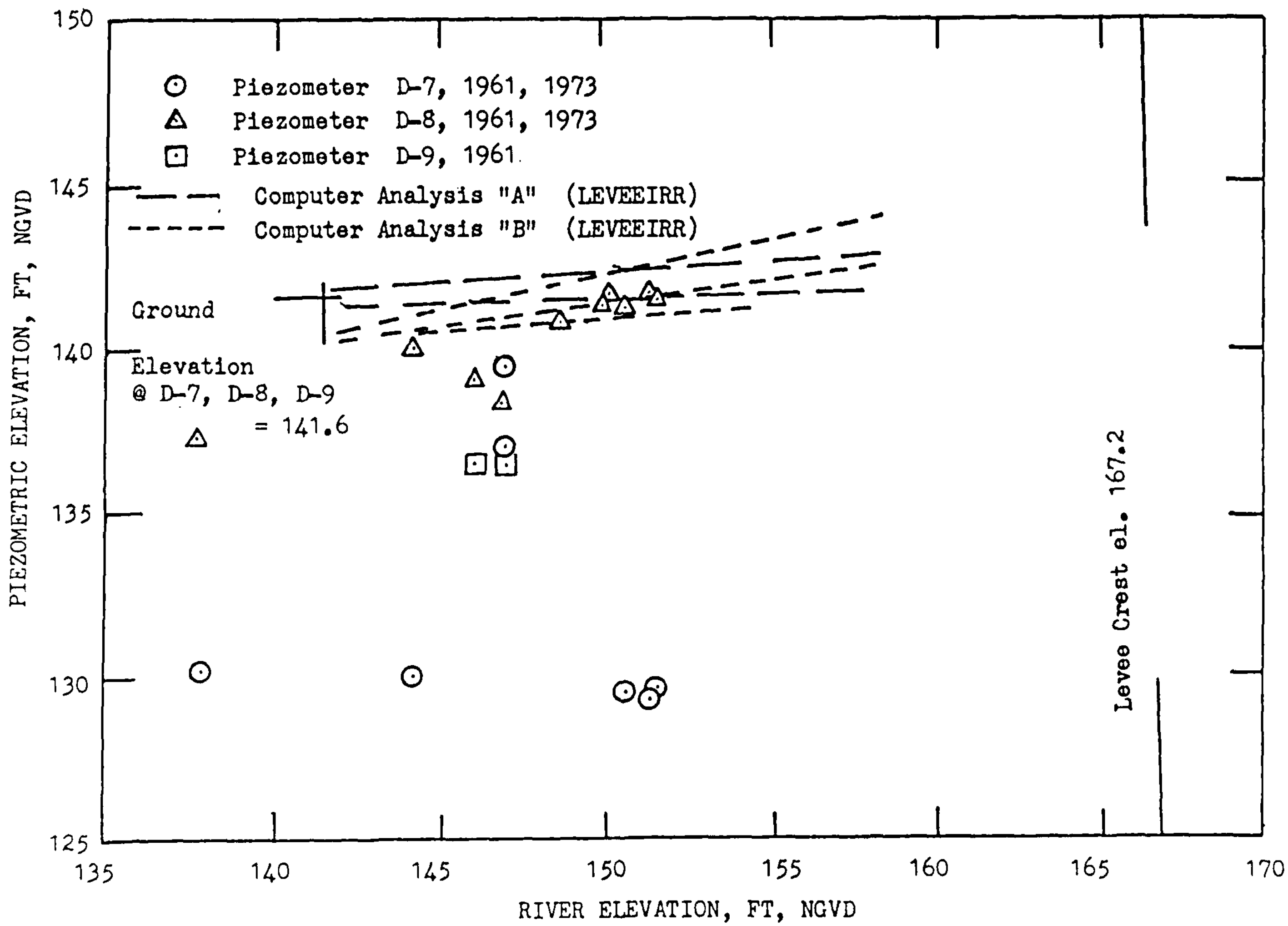


Figure 41. Results of analyses, Vicksburg District, Bolivar, Miss., Line D, piezometers D-7 through D-9

PART VI: ANGLES OR "CORNERS" IN LEVEE ALIGNMENT

Numerical Modeling Technique

41. To analyze underseepage at angles or corners in levee alignment where flow conditions are not 2-D, a computer program named LEVEECOR was written. Input to the program consists of the same parameters used for conventional analysis plus the angle and radius of the same parameters used for conventional analysis plus the angle and radius of the levee bend and the distance to the river on either side of the bend. these variables are illustrated in Figure 42. Using the specified dimensions, LEVEECOR generates an irregularly shaped grid of node points in a horizontal plane as shown in Figure 43. The grid represents the entire thickness of the pervious substratum. the differential equation for steady-state flow is expressed in finite difference form at each node, and a solution is obtained by iteration. Flow is assumed horizontal in the substratum and vertical in the top blanket. At each node, the horizontal flow in the substratum from four adjacent nodes plus the vertical flow through the top blanket (downward on the riverside and upward on the land side) must sum to zero. The technique used is approximate; the horizontal flow components are not exactly perpendicular in the vicinity of the corner. Gradients between nodes are approximated as the difference in head divided by the distance between nodes; flow areas between nodes are approximated using the average distances between nodes. The analysis technique is illustrated in Figure 44. To ensure that results are generally consistent with the conventional solution at points remote from the corner, the head at the landside boundary (Row 1) is automatically matched to the conventional solution for a foundation of infinite landward extent. the use of LEVEECOR is described with examples in Appendix C.

Effect of Levee Curvature

42. To assess the effect of levee curvature, a parametric study was performed using LEVEECOR. Typical dimensions and permeability values were assumed, and the residual head at the levee toe in the corner (node 3,8) was plotted as a function of the bend angle, θ , and the radius of curvature. Assumptions and results are shown in Figure 45. It is shown that there is a

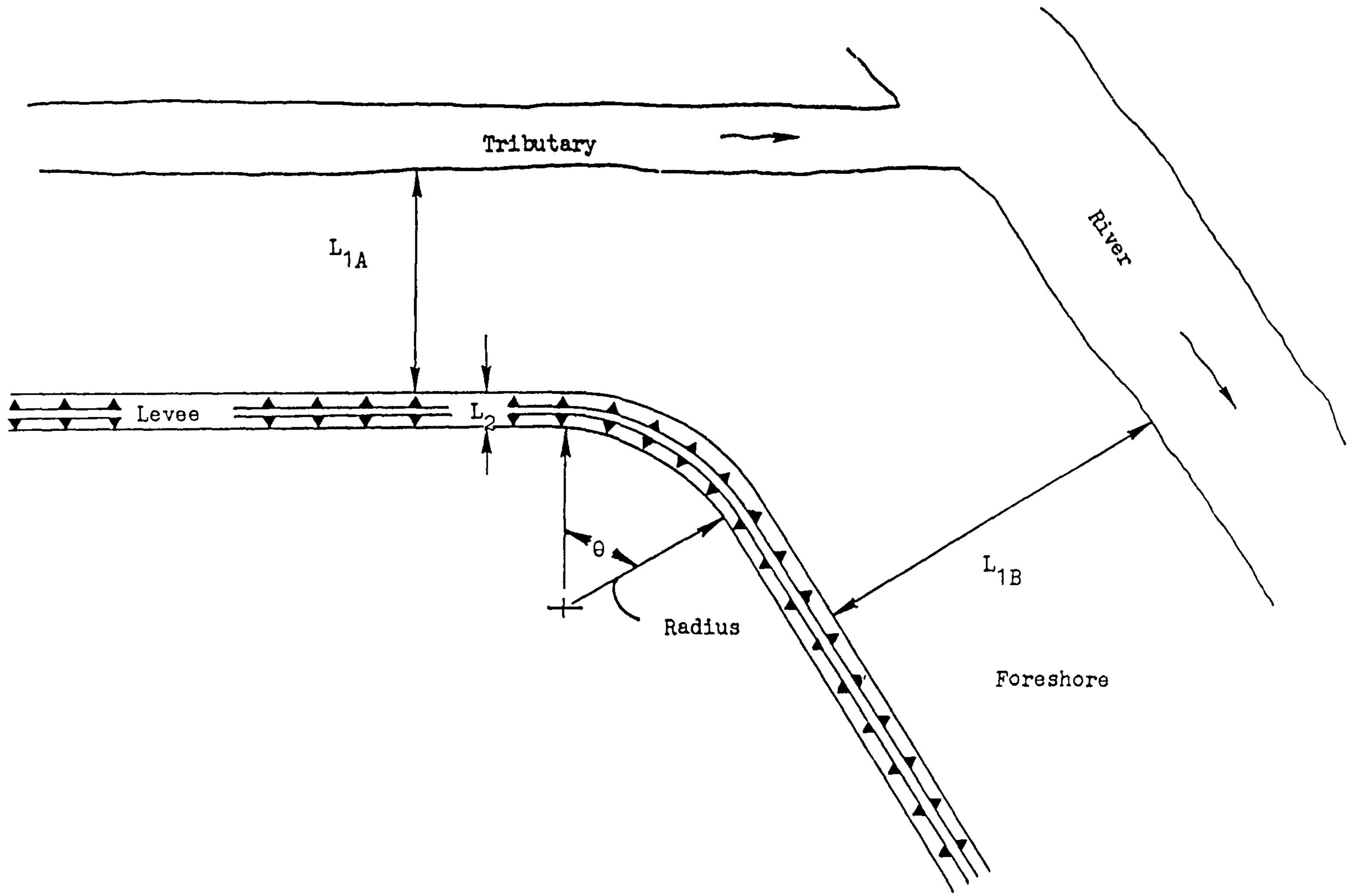


Figure 42. Levee geometry used by program LEVEECOR

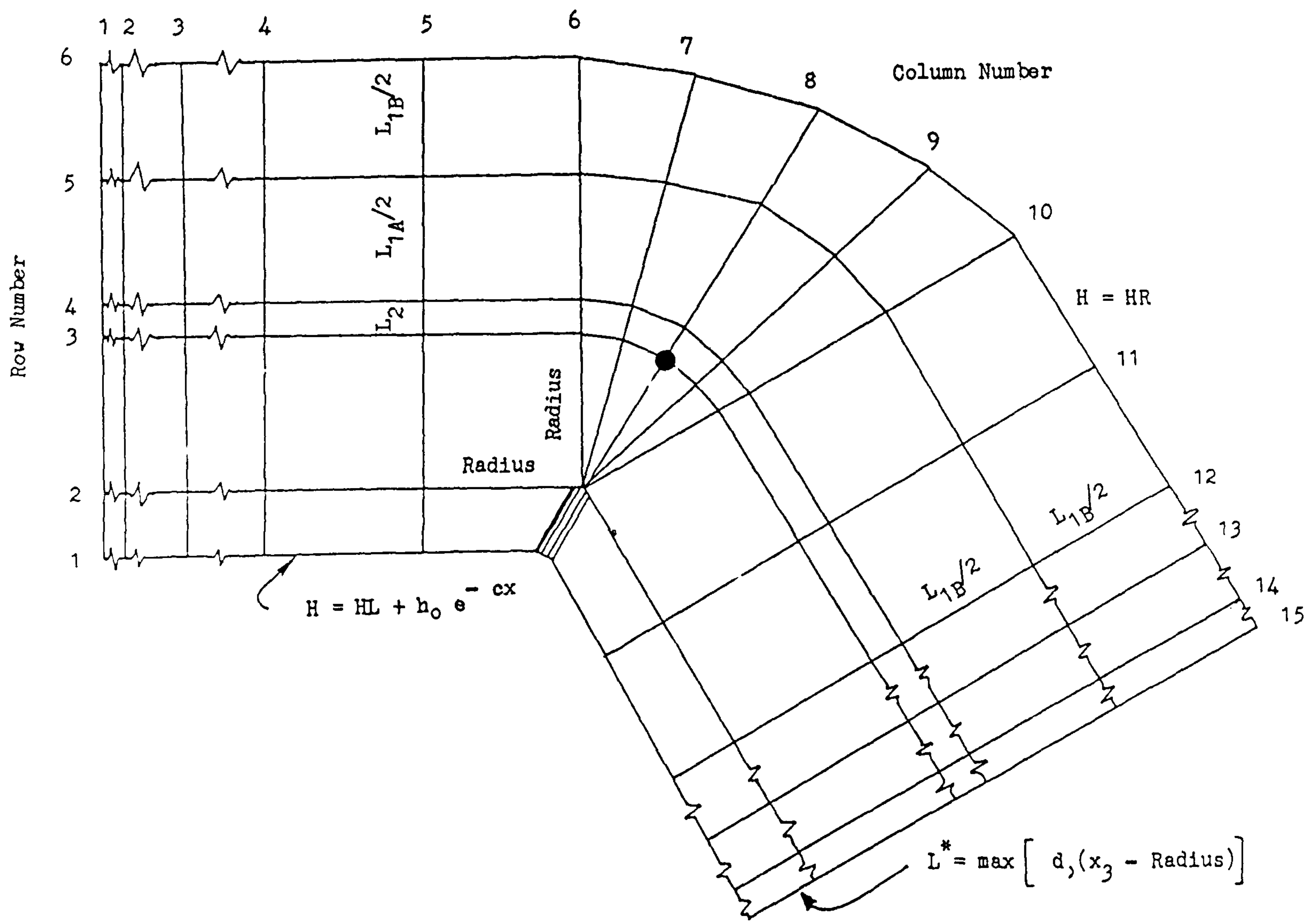
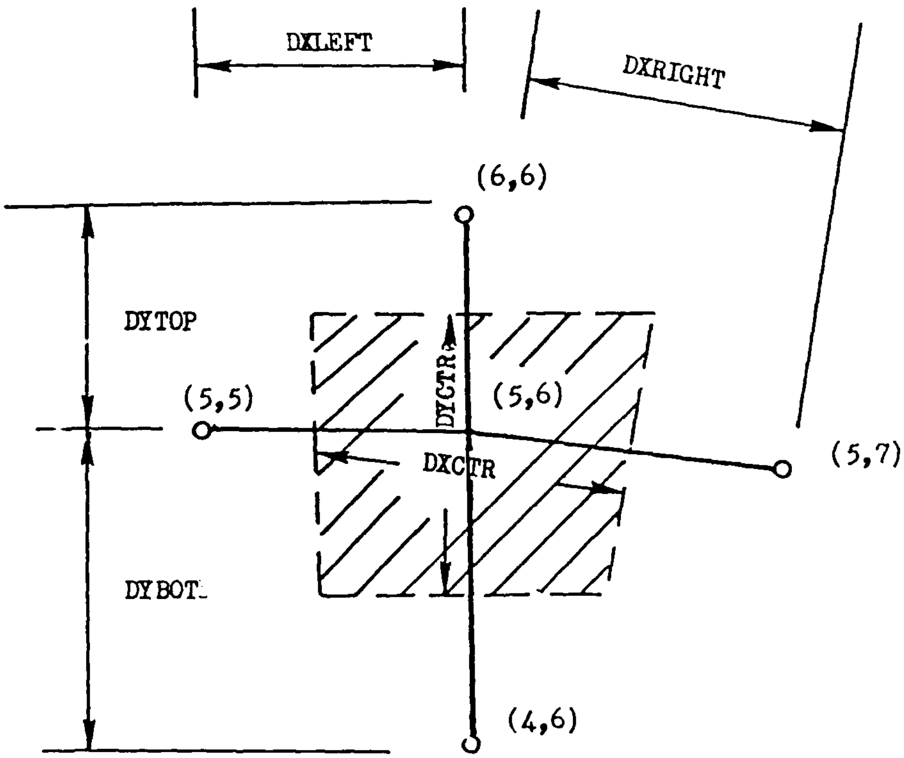


Figure 43. Grid generated by program LEVEECOR

Flow at an Interior Node

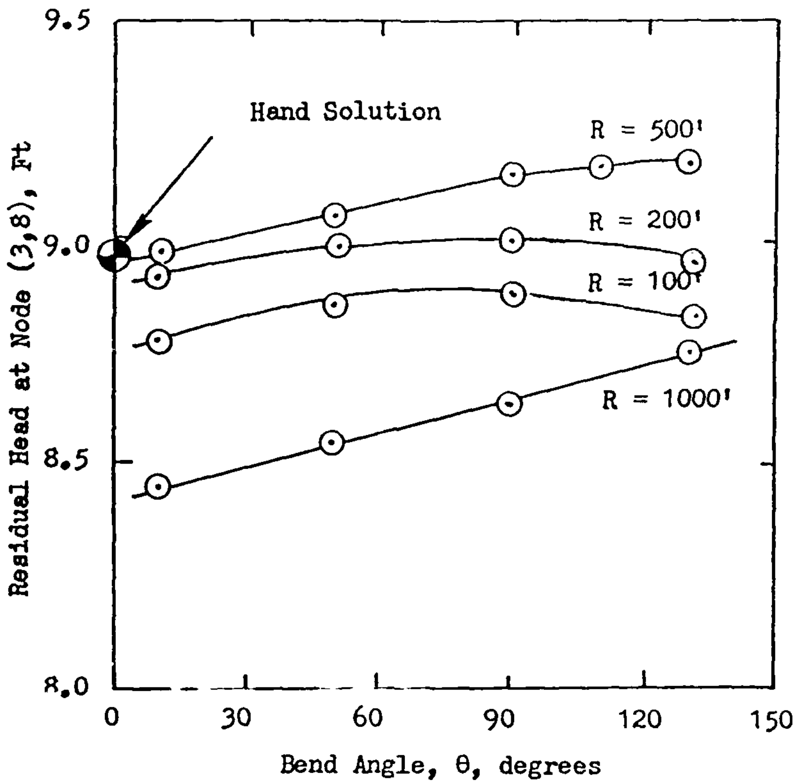
$$\sum q_{\text{to }(5,6)} = 0 = q_{(5,5)} + q_{(6,6)} + q_{(5,7)} + q_{(4,6)} + q_{Down}$$



$$q_{(5,5)} = \left[k_f \right] \left[\frac{h_{5,5} - h_{5,6}}{DXLEFT} \right] \left[DYCTR \right] \left[d \right]$$

$$q_{Down} = \left[k_{br} \right] \left[\frac{HR - h_{5,6}}{Z} \right] \left[DXCTR \right] \left[DYCTR \right]$$, where HR is the riverside head at 5,6

Figure 44. Flow at an interior node, program LEVEECOR



Head on Levee	20 ft
Distance to River	1,500 ft
Distance to Tributary	1,500 ft
Levee Base Width	300 ft
k_f	0.2000 ft/min
$k_{br} = k_{bl}$	0.0002 ft/min
d	80 ft
z	10 ft

Figure 45. Results of parametric study usi. LEVEECOR

tendency for the residual head to increase with increasing bend angle, but the increase is relatively small, less than 0.5 ft for the example investigated. Effects may be more pronounced for shorter entrance distances, different permeability ratios, etc; however, time did not afford a complete investigation of every parameter. As the radius was increased to 500 ft, the head increased; the head decreased after the radius exceeded this value. Such variation may be related to the fact that the model geometry changes as the radius changes. Ideally, all the curves should pass through the point labeled "hand solution"; however, discrepancies arise because the numerical solutions for different radii generate different grid geometries. Some degradation of results is apparent for relatively large and small radii and for bend angles greater than 90 deg.

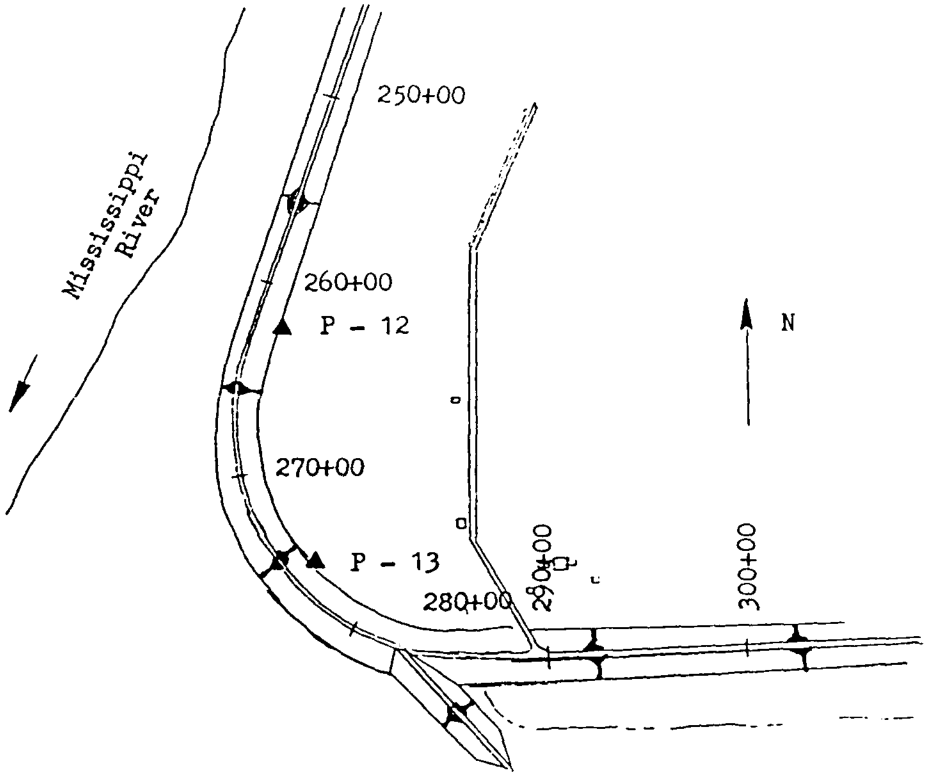
43. Although the study seems to indicate that the bend angle may have only a slight effect on the residual head for a symmetric problem, the program LEVEECOR should be useful for analysis of asymmetric problems because of its ability to model different distances to the river on either side of the bend. LEVEECOR should be used for radii greater than 500 ft since the model failed to produce reasonable trends or agree with the closed form solution.

Actual Versus Predicted Performance

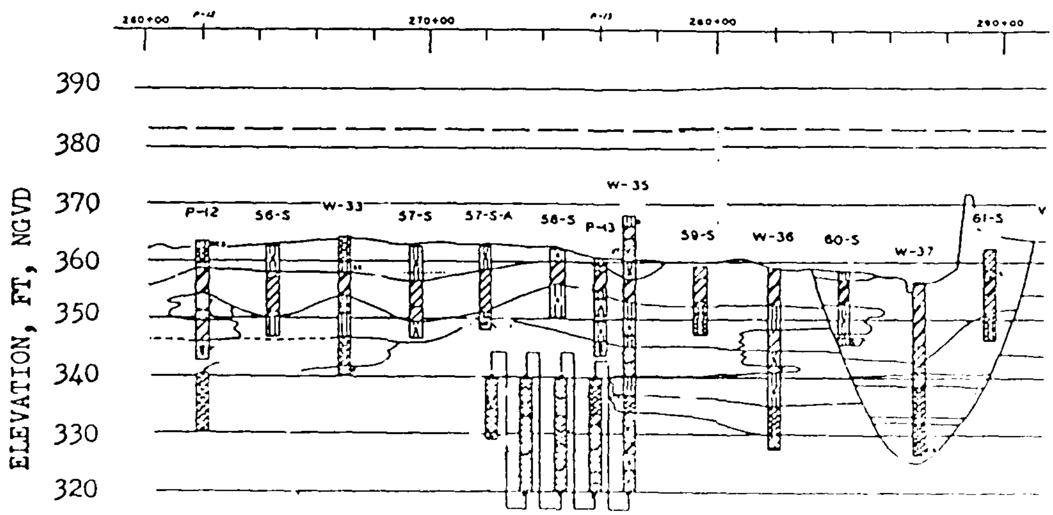
44. The program LEVEECOR was used to analyze a set of corner reaches where piezometric data were available. Performance predictions obtained from the program were compared to predictions based on conventional analysis and to actual piezometer readings. A discussion of these analyses and results follows.

St. Louis District, Degognia, Station 260-290

45. This piezometer range is located in the Degognia Levee and Drainage District adjacent to a near-right-angle bend in the Mississippi River called Liberty Bend. A plan of the levee and a foundation profile are shown in Figure 46. On the upstream side of the bend, the Mississippi River is about 650 ft from the levee. On the downstream side of the bend, a chute separates the floodplain from Wilkinson Island, and the Mississippi River is on the opposite sided of the island. Underseepage performance at this location during the 1973 flood was described by the USAED, St. Louis (1976).



Plan



Profile

Figure 46. Plan and profile of St. Louis District, Degognia, Station 260-290 (after WES 1956a)

Piezometer P-12 at the upstream end of the bend flowed over a 4-ft extension; the estimated head exceeded 5.2 ft, and the estimated gradient exceeded 0.43.

46. Three analyses were performed, one using the conventional method and two using the program LEVEECOR: analysis assumptions are summarized in Table 7. The conventional analysis is based on parameters obtained and inferred from TM 3-430 (WES 1956b). The permeability ratio for the conventional analysis was reduced from 1,000 to 500 to better fit the observed data. The entrance distance of 1,000 ft is a judgmental average of the widely varying distances on either side of the bend. Computer analysis "A" was performed using the same permeability ratio as the conventional analysis, but the distances to the river, L1A and L1B, represent prototype conditions. For computer analysis "B" the permeability ratio was varied to get the best match with the observed data. Performance predictions from the three analyses are compared to observed data in Figure 47. For the dimensions modeled, it was found that a permeability ratio of 150 provided the best match to observed performance. Using the program LEVEECOR provides a convenient method for back-calculating the permeability ratio in this case where an appropriate single value for the distance to the river required for conventional analysis is difficult to assess.

St. Louis District,
East Cape, Station 94

47. This piezometer range is located at an abrupt 50-deg bend at Station 94 of the East Cape Girardeau levee, which is across the river from Cape Girardeau, Mo. The data used are from the 1973 flood and were previously analyzed by USAED, St. Louis (1976). A plan view and foundation profile are shown in Figure 48.

48. Three analyses were performed; assumptions are summarized in Table 8. The conventional analysis is based on parameters obtained and inferred from TM 3-430 (WES 1956b). Computer analysis "A" was performed using the same permeability ratio as the conventional analysis, but the geometry is more completely described. For computer analysis "B" the same geometry was used, but the permeability ratio was varied to get the best match with the observed data. Performance predictions from the three analyses are compared to observed data in Figure 49. It was found that the permeability ratio had to be lowered to 25 to match observed performance. The USAED, St. Louis (1976) reported that numerous pin boils were present in the fields landside of

Table 7

Parameters Used for Analyses, St. Louis District,

Degognia, Station 260-290

Analysis Parameter	Conventional Analysis	LEVEECOR Computer Analysis "A"	LEVEECOR Computer Analysis "B"
L_{1A} (ft)	--	5,000	5,000
L_{1B} (ft)	--	650	650
s (ft)	1,000	--	--
L_2 (ft)	--	300	300
THETA (deg)	--	110	110
RADIUS (ft)	--	1,120	1,120
D (ft)	70	70	70
z (ft)	14.0	14.0	14.0
k_f/k_{b1}	500	500	150
x_3 (ft)	990	--	--
Levee crest el	382.7	382.7	382.7
Ground el	360.7	362.7	362.7
H_{max}	22.0	22.0	22.0
h_o at H_{max}	9.06	10.38	7.8

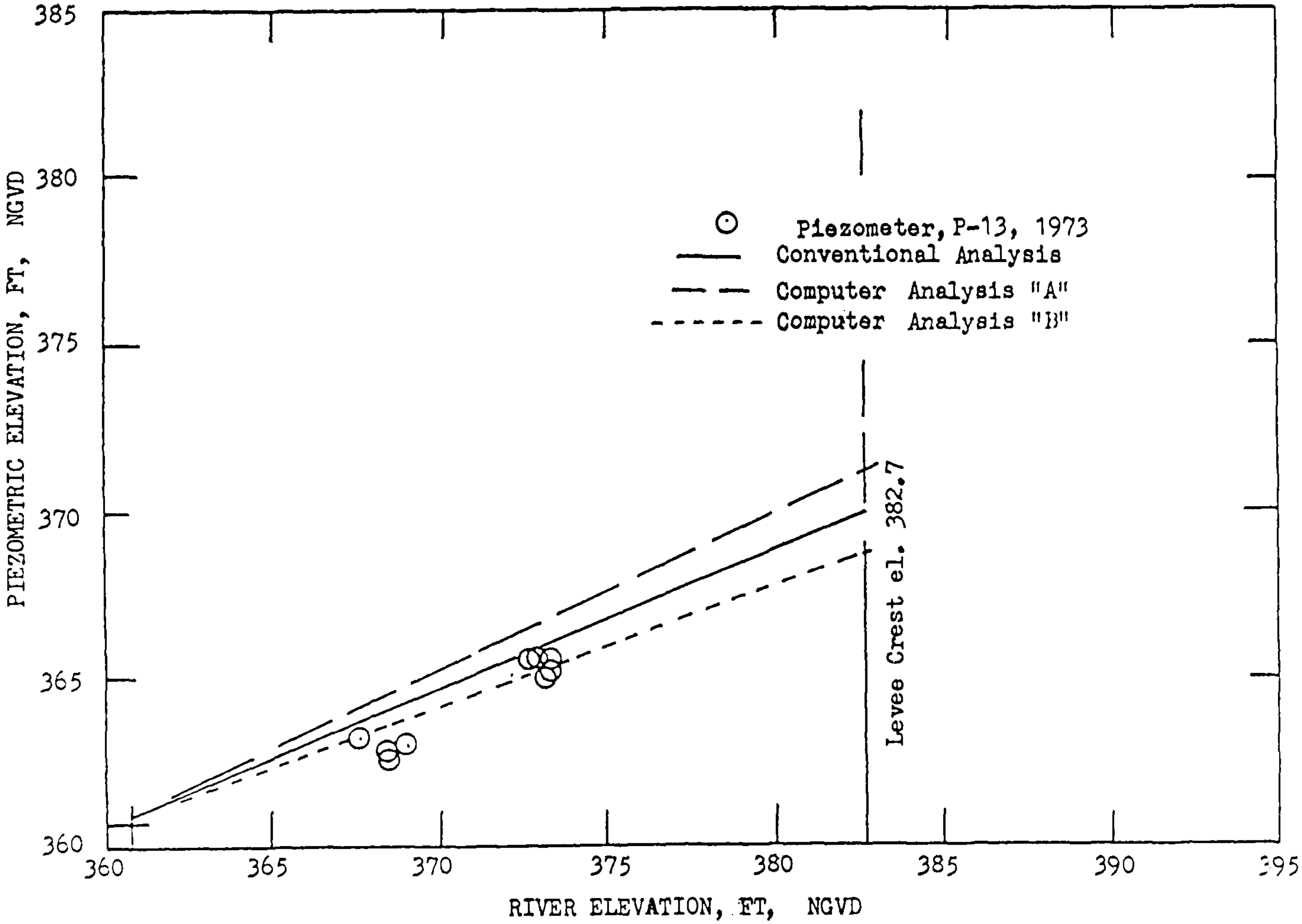
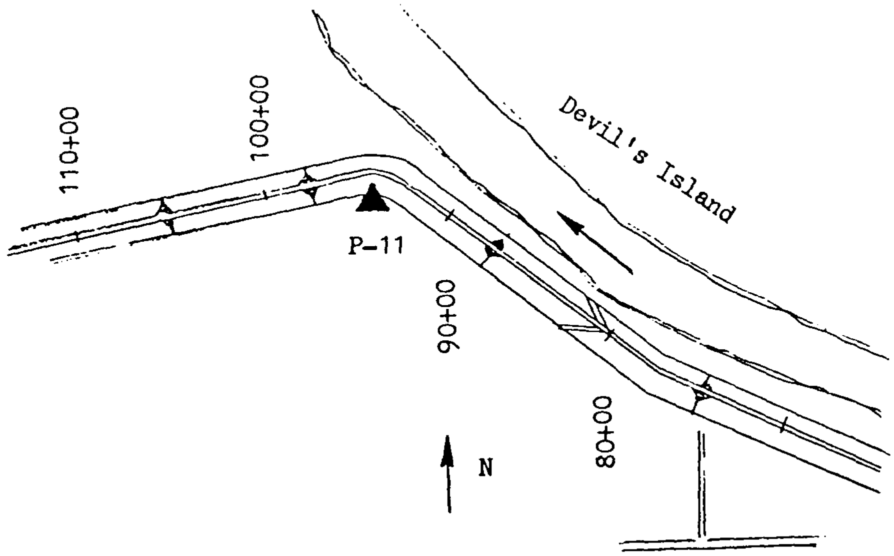
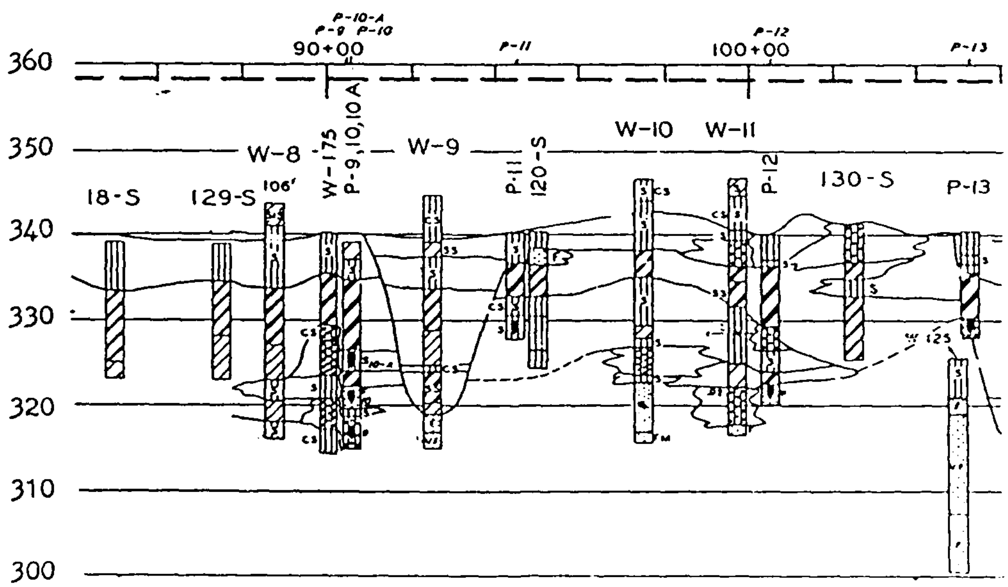


Figure 47. Results of analyses, St. Louis District, Degognia, Station 260-290



Plan

Levee Station



Profile

Figure 48. Plan and profile of St. Louis District, East Cape, Station 94 (after WES 1956b)

Table 8

Parameters Used for Analyses, St. Louis District, East Cape, Station 94

Analysis Parameter	Conventional Analysis	LEVEECOR Computer Analysis "A"	LEVEECOR Computer Analysis "B"
L_{1A} (ft)	--	850	850
L_{1B} (ft)	--	400	400
L_2 (ft)	--	290	290
s	850	--	--
THETA (deg)	--	50	50
RADIUS (ft)	--	290	290
d (ft)	70	70	70
z (ft)	12.0	12.0	12.0
k_f/k_{b1}	1,000	1,000	25
x_3 (ft)	916	--	--
Levee crest el	358.5	358.5	358.5
Ground el	340.3	340.3	340.3
H_{max}	18.2	18.2	18.2
h_o at H_{max}	9.5	9.2	4.0

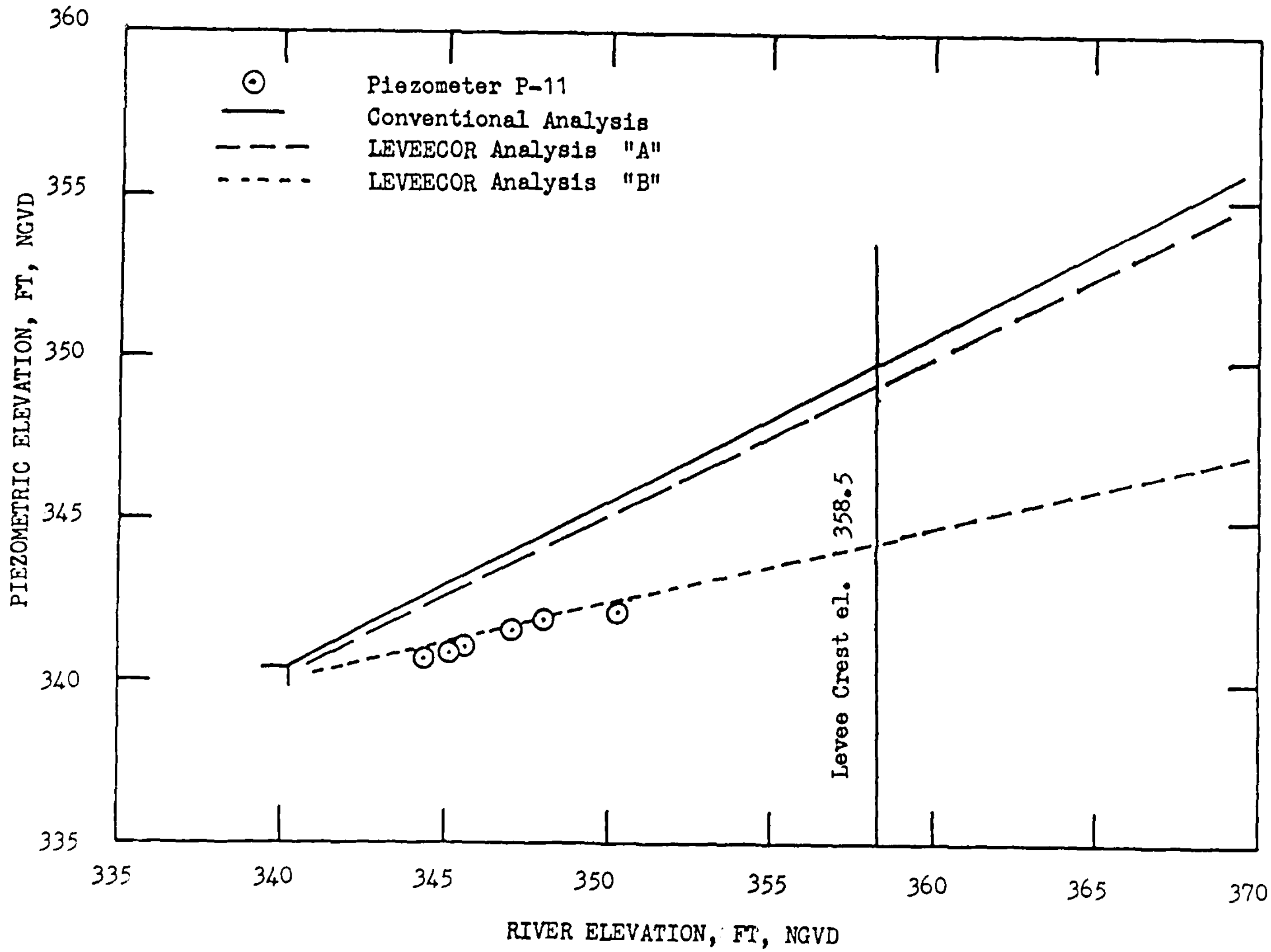


Figure 49. Results of analyses, St. Louis District, East Cape, Station 94

this location. These observations are consistent with the unusually low permeability ratio indicated.

PART VII: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

49. The "conventional method" of underseepage analysis is restricted to the special case of foundations consisting of two layers, each of uniform thickness and with horizontal boundaries. For this special case, there is a closed-form solution for the governing differential flow equation. Where actual foundation conditions are complex, considerable engineering judgment must be used to assign equivalent or "effective" values for the parameters describing the foundation geometry. Analysis results can be very dependent on the judgments made and may vary considerably among different engineers analyzing the same soil profile. Using numerical methods and microcomputers, the differential equation can be solved for more general cases of foundation and levee geometry. This reduces uncertainty introduced in the analysis regarding the geometry and allows the analyst to focus on the effects of other variables, in particular the material permeabilities and landside water elevations.

50. Three microcomputer programs were developed to perform underseepage analysis for three special cases of foundation conditions that are representative of many locations in the Mississippi Valley. Using these programs, predictions of piezometric head were made and compared to observed piezometric data at eight locations. The field permeability ratios were estimated by varying values of the program input parameters until predictions matched observed performance. Although the programs were evaluated by reanalyzing past performance, they would be equally useful for new analyses. Because grid size effects on the numerical solution were not parametrically investigated . the grid size cannot be varied by the user, the reader is cautioned that exit gradients computed by these programs may not be conservative. Experiences with the programs and findings from these studies are summarized below.

Foundations characterized by three layers

51. Where foundation sands are significantly different in the upper and lower parts of the substratum, a three-layer model provides a more consistent or general representation of prevailing conditions than the conventional two-layer analysis. The program LEVEE3L allows modeling of such conditions and

allows for different vertical and horizontal permeabilities in each of the three layers. Some of the effects of variations in the middle stratum have been demonstrated by parametric studies.

52. The program LEVEE3L should be useful to predict underseepage conditions where three-layer conditions are known to exist and reasonable estimates can be made of the six required permeabilities. A second case of a three-layer foundation not studied herein is the case of a sandy or silty top blanket overlying a clay layer. LEVEE3L would be applicable to such conditions. Because of its ability to account for six permeabilities, LEVEE3L is less useful for back-calculation of permeability values or ratios because five values must be assumed to calculate the sixth.

53. The analysis at Sny Island illustrates how a thin top blanket of clay overlying a silty middle stratum can lead to boils while piezometers at the base of the middle stratum indicate only moderate residual heads.

54. The analysis at Eutaw, Miss., illustrates that irregularities in the elevations and thicknesses of the soil deposits may dominate the problem more than the effect of the middle layer. Assigning appropriate effective ground elevations may be critical to accurately predict landside heads, and these elevations may differ significantly at different points along the profile.

Foundations characterized by two layers of irregular shape

55. Using conventional analysis techniques, the calculated residual head is a function of both the assumed equivalent geometry and the permeability ratio. Calculated residual heads may be highly uncertain because of the uncertainty introduced in the representation of foundation geometry. Using the program LEVEEIRR, a two layer foundation geometry can be represented as precisely as it is known. Thus, the permeability values and ratio can be isolated as the independent variables. The program is applicable to many common conditions of irregular foundation geometry, including borrow pits, ditches, and clay-filled channels. It should be particularly useful in assessing the impact of proposed changes adjacent to levees, such as construction of new ditches or elargement of borrow areas, problems that commonly occur and are not conveniently assessed using conventional methods. A particularly useful feature of LEVEEIRR is its capability to predict or assess performance (residual head and gradient) at any desired distance from the levee

or any piezometer location by appropriate specification of segment boundaries. In the author's opinion, LEVEEIRR probably has the greatest potential of the three programs for extensive use in routine practice.

56. The above comments on calculating residual heads apply as well to back-calculation of permeability ratios from observed residual heads. As the foundation geometry can be precisely described using LEVEEIRR, back-calculated permeability values should be more reliable than those related to "transformed" geometry.

Angles or "corners" in levee alignment

57. Using program LEVEECOR, underseepage conditions at bends in levee alignment or levee corners can be analyzed. Because of the problem complexity, the program employs more approximations than the other two programs. For typical problems investigated, the increase in residual head due to the corner effect is relatively small, typically less than a foot. This effect alone would not seem to warrant using the program in lieu of conventional methods. However, the program may be useful in practice because it allows the analyst to model actual distances to the river on either side of levee rather than assuming an "effective distance" that somehow averages widely different conditions. LEVEECOR should be used with caution, particularly for radii less than 500 ft since the model failed to produce reasonable trends or agree with the closed form solution in that range.

Permeability ratios

58. Permeability ratios cannot be reliably back-calculated using LEVEE3L. Back-calculated permeability ratios obtained using LEVEEIRR and LEVEECOR varied from 25 to 1,000 and were typically 500 or less. The low ratio of 25 at East Cape was for a site where pin boils were occurring, indicating that the apparently high top blanket permeability was due to open pathways or defects in the blanket. For the most part, the ratios calculated using the programs were consistent with those obtained by experienced analysts using conventional analysis. However, the programs allow a less experienced analyst to model the geometry and foundation conditions as they are perceived without the assignment of effective dimensions.

Comparison of programs and results

59. The three programs and the conventional method were used to analyze a common problem, and the results are compared in Appendix D. Variation among the solutions for the problem analyzed was several feet, a range somewhat

larger than expected at the outset of the research. Some reasons for the variation are suggested in the appendix, they include the use of fundamentally different assumptions in deriving the flow equations and truncation error. It is expected that some of this variation could be reduced by using finer grids or higher order approximations for the derivatives. Such improvements would require a second iteration in program development. The intent of the present research was to demonstrate the applicability of special-purpose microcomputer programs (as compared with general-purpose computer programs) for the problems of interest. Based on the parametric studies performed and the case histories analyzed, it is believed that the present versions of the programs are suitable and should be recommended for comparison studies to evaluate the effects of borrow areas, ditches, varying permeabilities, etc.

Recommendations

60. Based in the results of this research, the following recommendations are made:

- a. The developed programs should be used as a supplement to conventional analysis where geometry warrants.
- b. Modifications should be made to LEVEE3L to provide for variable grid spacing.
- c. Assuming that LEVEEIRR would be the most used of the three programs, improvements should be made to allow for different landside and riverside blanket permeabilities, to provide for expedient data input and file building, to provide a graphic display of foundation geometry, and to provide for more than one landside water level.
- d. A three-layer version of LEVEEIRR should be developed that incorporates features of LEVEE3L.
- e. By analyzing additional reaches and systematically assessing all results, better guidelines should be developed for estimating the field permeability ratio as a function of material types and thicknesses.
- f. The extension of the programs to analyze reaches where relief wells are present should be investigated.
- g. The programs should be field tested to determine the need for additional changes and improvements.

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APPENDIX A: COMPUTER PROGRAM LEVEE3L: UNDERSEEPAGE ANALYSIS FOR FOUNDATIONS CHARACTERIZED BY THREE LAYERS

1. The program LEVEE3L performs underseepage analysis for levee foundations consisting of three layers of uniform thickness with horizontal boundaries. The program was written in FORTRAN77 and runs on IBM PCs or compatible microcomputers using the MS-DOS operating system.

2. Input to the program is from a seven line data file without line numbers. This file can be created using any word processing or text-editing program that produces a standard ASCII file. An example input file is shown in Figure A1. Program variables are defined in Figure A2.

3. The program is executed by typing the command LEVEE3L with the file LEVEE3L.EXE resident on the default drive. The program will then ask for the name of the input file and the name of the output file. If the output file already exists, it will be written over; otherwise, it will be created. A sample run of LEVEE3L is shown in Figure A3.

4. The program provides output to two devices: the console (screen) and the output file. Output to the screen includes the number of iterations, the residual head at the levee toe, and the gradient at the levee toe. If the user desires more detailed output, the output file can be displayed or printed using any word processing or text-editing program that works with standard ASCII files. The output file contains the final calculated heads at each node point as shown in Figure A4.

5. The program source listing is presented in Figure 5.

EXAMPLE INPUT FILE FOR LEVEE3L

Values	Variable Names
Example Problem	TITLE
20.00 0.00	HR, HL
1000.00 50.00 3000.00	L1, L2, L3
10.0 20.0 60.0	Z1, Z2, D
.0002 0.0100 0.0400	KV1, KV2, KV3
.00100 0.0500 0.2000	KH1, KH2, KH3
.005 500	TOL TRIES

›les are defined as follows:

lescriptive title for the problem (80 characters maximum).

distance from the riverside levee toe to the river or an open ntrance.

distance from the riverside levee toe to the landside levee toe.

distance from the landside levee toe to an open seepage exit. This very long (e.g. twice the effective exit distance) when modeling ns of infinite extent.

elevation of water on the riverside of the levee. If the landside landside ground is taken as the datum, HR is the net head on the

elevation of water on the landside of the levee or the elevation of ground if no water is present. This level is often taken as the which case HL is 0.0.

thickness of the top blanket in feet or any consistent units.

thickness of the middle stratum in feet or any consistent units.

Figure A1. Example input file, program LEVEE3L (Continued)

D is the thickness of the substratum in feet or any consistent units.

KV1, KV2, and KV3 are the vertical permeabilities of the top blanket, middle stratum, and substratum, respectively, in feet per minute or any consistent units.

KH1, KH2, and KH3 are the horizontal permeabilities of the top blanket, middle stratum, and substratum, respectively, in feet per minute or any consistent units.

TOL is the maximum tolerance, or maximum difference in head at any node between successive iterations. The iteration process will stop when the maximum residual is smaller than TOL. This value should be smaller than the desired accuracy of the solution by a factor of 10 or more. For an answer accurate to 0.1 ft, a value for TOL of 0.003 is recommended.

TRIES is the maximum number of iterations that the program will be allowed to make. It is provided to stop the program in the event of non-converging solutions. Generally the program should terminate because TOL is reached before TRIES. A value of 500 is suggested.

Figure A1. (Concluded)

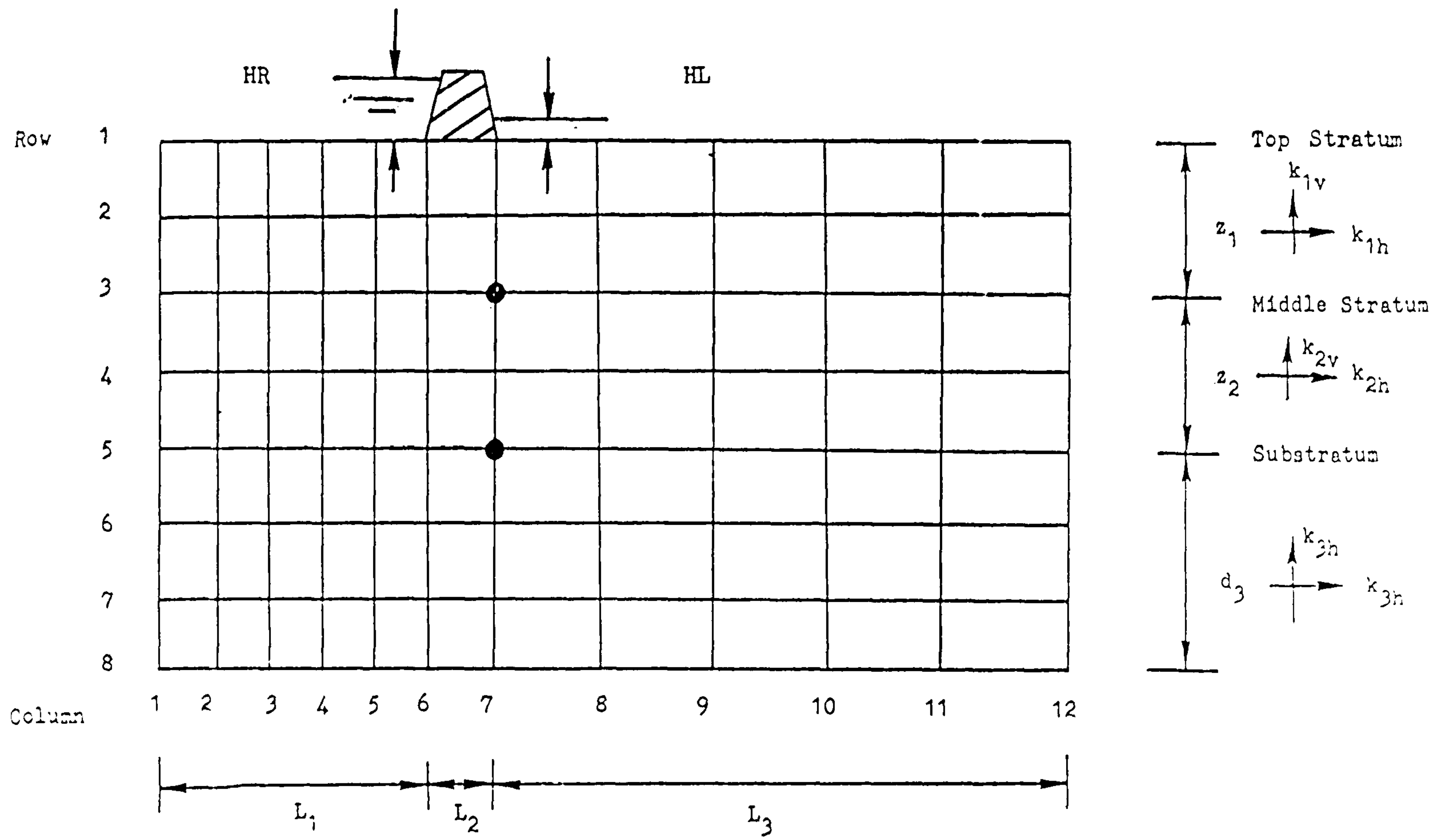

Figure A2. Definition of variables, program LEVEE3L

```
C>
C>LEVEE3L

PROGRAM LEVEE3L ---
UNDERSEEPAGE ANALYSIS FOR 3-LAYER PROFILES

Written by Thomas F. Wolff and H. A. Al-Moussawi
Michigan State University

For the U. S. Army Corps of Engineers
Release 1.0   September 1987



 ----------------
.     XXXXXX      .          XXXX  XXXXX  XXXX
.     X           .           XX    XXX    XX
.     XXXXXX      .           XXXXXXXIIXXXXXX
.          X      .           XXI IXI  IXI IX
.     XXXXXX      .          XXXXXXXI  IXXXXXX
 ----------------


 ENTER INPUT FILE NAME
DATA3L
 ENTER OUTPUT FILE NAME
OUT3L

Example Problem


INPUT DATA

RIVERSIDE HEAD        LANDSIDE HEAD
   20.00                   .00

L1                    L2                    L3
  1000.00                 50.00               3000.00

Z1                    Z2                    D
    10.00                 20.00                 60.00

KY1                   KY2                   KY3
KX1                   KX2                   KX3
RATIO                 RATIO                 RATIO

  .000200               .010000              .040000
  .001000               .050000              .200000
     5.00                  5.00                 5.00

TOLERANCE               MAX ITERATIONS
   .00500                  500

 JUST A MOMENT, I AM THINKING

SOLUTION COMPLETE AFTER    191 ITERATIONS
MAXIMUM RESIDUAL =     .00498



RESIDUAL HEAD AT BASE OF TOP BLANKET =    9.68
GRADIENT THROUGH TOP BLANKET =             .97

HEAD LOSS THROUGH MIDDLE STRATUM =         .35
GRADIENT THROUGH MIDDLE STRATUM =          .02

OUTPUT SAVED IN FILE OUT3L


WANT TO RUN ANOTHER PROBLEM ? Y OR N
N
Stop - Program terminated.

C>
```

Figure A3. Example run for program LEVEE3L

EXAMPLE OUTPUT FILE FOR LEVEE3L

```
  Example Problem


 INPUT DATA

 RIVERSIDE HEAD       LANDSIDE HEAD
     20.00                 .00

 L1                   L2                   L3
   1000.00               50.00              3000.00

 Z1                   Z2                   D
     10.00               20.00                60.00

 KY1                  KY2                  KY3
 KX1                  KX2                  KX3
 RATIO                RATIO                RATIO

   .000200              .010000              .040000
   .001000              .050000              .200000
     5.00                 5.00                 5.00

 TOLERANCE            MAX ITERATIONS
   .00500                 500

 INITIAL HEADS
  20.00  20.00  20.00  20.00  20.00  20.00    .00    .00    .00    .00
 .00   .00
  20.00  16.67  15.00  13.33  11.67  10.00   8.33   6.67   5.00   3.33
 1.67   .00
  20.00  16.67  15.00  13.33  11.67  10.00   8.33   6.67   5.00   3.33
 1.67   .00
  20.00  16.67  15.00  13.33  11.67  10.00   8.33   6.67   5.00   3.33
 1.67   .00
  20.00  16.67  15.00  13.33  11.67  10.00   8.33   6.67   5.00   3.33
 1.67   .00
  20.00  16.67  15.00  13.33  11.67  10.00   8.33   6.67   5.00   3.33
 1.67   .00
  20.00  16.67  15.00  13.33  11.67  10.00   8.33   6.67   5.00   3.33
 1.67   .00
  20.00  16.67  15.00  13.33  11.67  10.00   8.33   6.67   5.00   3.33
 1.67   .00

 SOLUTION COMPLETE AFTER   191 ITERATIONS
 MAXIMUM RESIDUAL =     .00498

 FINAL HEADS
  20.00  20.00  20.00  20.00  20.00  20.00    .00    .00    .00    .00
```

Figure A4. Example output file, program LEVEE3L (Continued)

```
.00     .00
  20.00  19.24  18.46  17.62  16.68  15.44    4.88   2.65   1.66   1.04
.51     .00
  20.00  18.48  16.92  15.24  13.36  11.08    9.68   5.30   3.32   2.09
1.03     .00
  20.00  18.45  16.86  15.14  13.23  10.92    9.86   5.40   3.39   2.13
1.05     .00
  20.00  18.43  16.80  15.06  13.10  10.80  10.03   5.50   3.45   2.17
1.07     .00
  20.00  18.41  16.78  15.02  13.05  10.75  10.10   5.54   3.48   2.18
1.07     .00
  20.00  18.41  16.76  15.00  13.03  10.74  10.15   5.56   3.49   2.19
1.08     .00
  20.00  18.41  16.76  14.99  13.01  10.74  10.17   5.57   3.50   2.19
1.08     .00

 RESIDUAL HEAD AT BASE OF TOP BLANKET =    9.68
 GRADIENT THROUGH TOP BLANKET =             .97

 HEAD LOSS THROUGH MIDDLE STRATUM =         .35
 GRADIENT THROUGH MIDDLE STRATUM =          .02
```

Figure A4. (Concluded)

```
      PROGRAM LEVEE3L

C$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C                                                                      $
C    THIS PROGRAM WAS WRITTEN BY:-                                     $
C         DR. THOMAS F. WOLFF; ASSISTANT PROFESSOR                     $
C         AND                                                          $
C         HASSAN M. ALMOUSSAWI; PH.D CANDIDATE                         $
C                                                                      $
C         USING THE A. H. CASE CENTER                                  $
C         COMPUTER AIDED ENGINEEING FACILITY AT                        $
C         MICHIGAN STATE UNIVERSITY , 1987                             $
C                                                                      $
C$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C
C     VERSION 1.0   SEPTEMBER 10, 1987
C
C***********************************************************************
C                                                                      *
C THIS PROGRAM USES THE FINITE DIFFERENCE METHOD TO ANALYZE SEEPAGE    *
C THROUGH A LEVEE FOUNDATION CONSISTING OF THREE LAYERS, EACH WITH     *
C DIFFERENT HORIZONTAL AND VERTICAL PERMEABILITIES.                    *
C                                                                      *
C***********************************************************************
C
C  VARIABLES
C
C  GR1      Gradient at levee toe through top blanket
C  GR2      Gradient at levee toe through middle stratum
C  H(R,C)   Head at row R and column C
C  HL       Head on landside of levee (ground or tw)
C  HR       Head on riverside of levee
C  KX1      Horizontal permeability in top blanket
C  KX2      Horizontal permeability in middle stratum
C  KX3      Horizontal permeability in substratum
C  KY1      Vertical permeability in top blanket
C  KY2      Vertical permeability in middle stratum
C  KY3      Vertical permeability in substratum
C  L1       Distance from RS levee toe to river
C  L2       Base width of levee
C  L3       Distance from LS levee toe to point of zero head
C  MR       Maximum residual
C  PR1      Permeability ratio in top blanket
C  PR2      Permeability ratio in middle stratum
C  PR3      Permeability ratio in substratum
C  TOL      Tolerance
C  TRIES    Maximum number of iterations
C  Z1       Thickness of top blanket
C  Z2       Thickness of middle stratum
C  Z3       Thickness of substratum (d)
C***********************************************************************
```

Figure A5. Listing of program LEVEE3L (Sheet 1 of 8)

```
      CHARACTER*64 FILEIN
      CHARACTER*64 FILEOUT
      CHARACTER*80 TITLE
      CHARACTER*1 ANS
      REAL L1,L2,L3,HR,HL,Z1,Z2,Z3
      REAL KX1,KX2,KX3,KY1,KY2,KY3,TOL
      REAL DX1,DX2,DX3,DZ1,DZ2,DZ3
      REAL M1,M2,M3,M4,M5,M6,MR,MRN
      REAL H(8,12),OLDH(8,12)
      REAL PR1,PR2,PR3,RHO1,RHO2,GR1,GR2,CFLOAT
      INTEGER R,C,TRIES,ITT,I,J

C DISPLAY INTRODUCTION
      CALL INTRO

C OPEN DATA FILES

100   WRITE (*,*) ' ENTER INPUT FILE NAME'
      READ (*,'(A)') FILEIN
      OPEN(UNIT=10,FILE=FILEIN, ERR=100, STATUS='OLD')
      REWIND (10)

      WRITE (*,*) ' ENTER OUTPUT FILE NAME'
      READ (*, '(A)') FILEOUT
      OPEN (UNIT=20,FILE=FILEOUT)
      REWIND (20)

C READ DATA
      READ(10,'(A)')TITLE
      READ(10,*) HR,HL,L1,L2,L3,Z1,Z2,Z3,KY1,KY2,KY3,
     1KX1,KX2,KX3,TOL,TRIES

C  INITIALIZE HEADS

      DO 140 C=1,6
140   H(1,C)=HR

      DO 150 C=7,12
150   H(1,C)=HL

      DO 160 R=2,8
      H(R,1)=HR
160   H(R,12)=HL

      DO 170 C=2,11
      DO 170 R=2,8
        CFLOAT=C
170   H(R,C)=HR-(CFLOAT/12)*(HR-HL)


C THE PERMEABILITY RATIOS ARE

      PR1=KX1/KY1
```

Figure A5. (Sheet 2 of 8)

```
      PR2=KX2/KY2
      PR3=KX3/KY3


C PRINT INPUT DATA AND WRITE TO FILE

      WRITE(20,*) TITLE
      WRITE(*,*)
      WRITE(*,*) TITLE

      WRITE(20,910)
      WRITE(*,910)
910   FORMAT(/' INPUT DATA')

      WRITE(20,912)
      WRITE(*,912)
912   FORMAT(/' RIVERSIDE HEAD      LANDSIDE HEAD')
      WRITE(20,914) HR,HL
      WRITE(*,914) HR,HL
914   FORMAT(2(F9.2,11X))

      WRITE(20,916)
      WRITE(*,916)
916   FORMAT(/' L1                  L2                  L3')
      WRITE(20,918) L1,L2,L3
      WRITE(*,918) L1,L2,L3
918   FORMAT(1X,3(F9.2,11X))

      WRITE(20,920)
      WRITE(*,920)
920   FORMAT(/' Z1                  Z2                  D')
      WRITE(20,922) Z1,Z2,Z3
      WRITE(*,922) Z1,Z2,Z3
922   FORMAT(1X,3(F9.2,11X))

      WRITE(20,924)
      WRITE(*,924)
924   FORMAT(/' KY1                 KY2                 KY3'
     1/' KX1                 KX2                 KX3'
     2/' RATIO               RATIO               RATIO')
      WRITE(20,926) KY1,KY2,KY3,KX1,KX2,KX3,PR1,PR2,PR3
      WRITE(*,926) KY1,KY2,KY3,KX1,KX2,KX3,PR1,PR2,PR3
926   FORMAT(/,1X,3(F9.6,11X),/,1X,3(F9.6,11X),/,1X,3(F9.2,11X))

      WRITE(20,928)
      WRITE(*,928)
928   FORMAT(/' TOLERANCE           MAX ITERATIONS')
      WRITE(20,930) TOL,TRIES
      WRITE(*,930) TOL,TRIES
930   FORMAT(1X,F9.5,15X,I5)

      WRITE(20,932)
932   FORMAT(/' INITIAL HEADS')
      WRITE(20,934) ((H(R,C),C=1,12),R=1,8)
```

Figure A5. (Sheet 3 of 8)

```
934   FORMAT(12(1X,F6.2))

C CALCULATE DIFFERENTIAL DISTANCES

      DZ1=Z1/2
      DZ2=Z2/2
      DZ3=Z3/3
      DX1=L1/5
      DX2=L2
      DX3=L3/5
      M1=DX1/DZ3
      M2=DX3/DZ3
      M3=DX1/DZ2
      M4=DX3/DZ2
      M5=DX1/DZ1
      M6=DX3/DZ1

C **********************************
C  ITERATION
C **********************************

C INITIALIZE
      ITT=0
      WRITE(*,*)
      WRITE(*,*) ' JUST A MOMENT, I AM THINKING'

C BEGIN NEXT ITERATION

300     ITT=ITT+1
C       WRITE (*,301) ITT
C 301   FORMAT(1X' ITERATION  ', I5)
        IF(ITT+1.GT.TRIES) GO TO 2400

C RESET OLD HEADS

      DO 400  R=1,8
      DO 400  C=1,12
400   OLDH(R,C)=H(R,C)

C  ROW EIGHT - IMPERMEBLE BOUNDARY

      DO 500 C=2,5
500   H(8,C)=(((KX3*(H(8,C-1)+H(8,C+1)))/M1)+(2*KY3*H(7,C)*M1))/
     1 (2*KX3/M1+2*KY3*M1)

      DO 600  C=8,11
600   H(8,C)=(((KX3*(H(8,C-1)+H(8,C+1)))/M2)+(2*KY3*H(7,C)*M2))/
     1 ((2*KX3)/M2+2*KY3*M2)

      H(8,6)=(.5*KY3*((DX2+DX1)/DZ3)*H(7,6)+KX3*((DZ3/DX1)*
     1 H(8,5)+(DZ3/DX2)*H(8,7)))/(.5*KY3*((DX2+DX1)/DZ3)+KX3*
     1 (DZ3/DX2+DZ3/DX1))

       H(8,7)=(.5*KY3*((DX2+DX3)/DZ3)*H(7,7)+KX3*((DZ3/DX2)*
```

Figure A5. (Sheet 4 of 8)

```
     1 H(8,6)+(DZ3/DX3)*H(8,8)))/(.5*KY3*((DX2+DX3)/DZ3)+KX3*
     1 (DZ3/DX2+DZ3/DX3))

C  ROWS SIX AND SEVEN - INTERIOR NODES

      DO 700 I=6,7
      DO 700 C=2,5
700   H(I,C)=(((KX3*(H(I,C+1)+H(I,C-1)))/M1)+(KY3*(H(I-1,C)+
     1 H(I+1,C))*M1))/(2*KX3/M1+2*KY3*M1)

      DO 800   J=6,7
      DO 800 C=8,11
800   H(J,C)=(((KX3*(H(J,C+1)+H(J,C-1)))/M2)+(KY3*(H(J-1,C)+
     1 H(J+1,C))*M2))/(2*KX3/M2+2*KY3*M2)

      DO 900 I=6,7
      H(I,6)=(KX3*(DZ3/DX2)*H(I,7)+KX3*(DZ3/DX1)*H(I,5)+KY3*
     1 ((DX1+DX2)/(2*DZ3))*(H(I-1,6)+H(I+1,6)))/(KX3*(DZ3/
     1 DX1+DZ3/DX2)+KY3*((DX1+DX2)/DZ3))

      H(I,7)=(KX3*(DZ3/DX3)*H(I,8)+KX3*(DZ3/DX2)*H(I,6)+KY3*
     1 ((DX2+DX3)/(2*DZ3))*(H(I-1,7)+H(I+1,7)))/(KX3*(DZ3/
     1 DX3+DZ3/DX2)+KY3*((DX2+DX3)/DZ3))
900     CONTINUE

C ROW FIVE - INTERFACE NODES

      DO 1000 C=2,5
1000  H(5,C)=(KY3*(DX1/DZ3)*H(6,C)+KY2*(DX1/DZ2)*H(4,C)+
     1 (((KX3+KX2)/2)*((DZ2+DZ3)/2)*H(5,C+1))/DX1+((KX3+KX2)/
     1 2)*((DZ2+DZ3)/(2*DX1))*H(5,C-1))/(KY3*(DX1/DZ3)+KY2*
     1 (DX1/DZ2)+(((KX3+KX2)/2)*(DZ2+DZ3))/DX1)

      DO 1100 C=8,11
1100  H(5,C)=((KY3*(DX3/DZ3)*H(6,C)+KY2*(DX3/DZ2)*H(4,C)+
     1 (((KX3+KX2)/2)*((DZ2+DZ3)/2)*H(5,C+1))/DX3+((KX3+KX2)/
     1 (2*DX3))*H(5,C-1)*(DZ2+DZ3)/2))/((KY3*(DX3/DZ3))+KY2*
     1 (DX3/DZ2)+(((KX3+KX2)/2)*(DZ2+DZ3))/DX3)

      H(5,6)=(KY3*H(6,6)*((DX1+DX2)/DZ3)+KY2*((DX1+DX2)/
     1 DZ2)*H(4,6)+((KX3+KX2)/2)*.5*((DZ2+DZ3)/DX2)*H(5,7)+
     1 ((KX3+KX2)/2)*.5*((DZ2+DZ3)/DX1)*H(5,5))/((KY3/DZ3)*
     1 (DX1+DX2)+(KY2/DZ2)*(DX1+DX2)+(((KX3+KX2)/2)*.5*
     1 (DZ2+DZ3))/DX2+(((KX3+KX2)/2)*.5*(DZ2+DZ3))/DX1)

      H(5,7)=(KY3*H(6,7)*((DX2+DX3)/DZ3)+KY2*((DX2+DX3)/
     1 DZ2)*H(4,7)+((KX3+KX2)/2)*.5*((DZ2+DZ3)/DX3)*H(5,8)+
     1 ((KX3+KX2)/2)*.5*((DZ2+DZ3)/DX2)*H(5,6))/((KY3/DZ3)*
     1 (DX2+DX3)+(KY2/DZ2)*(DX2+DX3)+(((KX3+KX2)/2)*.5*
     1 (DZ2+DZ3))/DX3+(((KX3+KX2)/2)*.5*(DZ2+DZ3))/DX2)

C  ROW FOUR - INTERIOR NODES

      DO 1200 C=2,5
```

Figure A5. (Sheet 5 of 8)

```
1200  H(4,C)=((KX2*(H(4,C+1)+H(4,C-1)))/M3+KY2*(H(3,C)+H(5,C))*
     1 M3)/(2*KX2/M3+2*KY2*M3)

      DO 1400 C=8,11
1400   H(4,C)=((KX2*(H(4,C+1)+H(4,C-1)))/M4+KY2*(H(3,C)+H(5,C))*
     1 M4)/(2*KX2/M4+2*KY2*M4)

      H(4,6)=(KX2*(DZ2/DX2)*H(4,7)+KX2*(DZ2/DX1)*H(4,5)+KY2*
     1 ((DX1+DX2)/(2*DZ2))*(H(3,6)+H(5,6)))/(KX2*(DZ2/DX2+DZ2/
     1 DX1)+(KY2*(DX1+DX2))/DZ2)

       H(4,7)=(KX2*(DZ2/DX3)*H(4,8)+KX2*(DZ2/DX2)*H(4,6)+KY2*
     1 ((DX2+DX3)/(2*DZ2))*(H(3,7)+H(5,7)))/(KX2*(DZ2/DX3+DZ2/
     1 DX2)+(KY2*(DX2+DX3))/DZ2)


C ROW THREE - INTERFACE  NODES

      DO 1500 C=2,5
1500  H(3,C)=(KY2*(DX1/DZ2)*H(4,C)+KY1*(DX1/DZ1)*H(2,C)+
     1 (((KX2+KX1)/2)*((DZ1+DZ2)/2)*H(3,C+1))/DX1+((KX2+KX1)/
     1 2)*(((DZ1+DZ2)/2)/DX1)*H(3,C-1))/(KY2*(DX1/DZ2)+KY1*
     1 DX1/DZ1+(((KX2+KX1)/2)*(DZ1+DZ2))/DX1)

      DO 1600 C=8,11
1600  H(3,C)=(KY2*(DX3/DZ2)*H(4,C)+KY1*(DX3/DZ1)*H(2,C)+
     1 (((KX2+KX1)/2)*((DZ1+DZ2)/2)*H(3,C+1))/DX3+((KX1+KX2)/
     1 2)*((DZ1+DZ2)/(2*DX3))*H(3,C-1))/(KY2*(DX3/DZ2)+KY1*
     1 (DX3/DZ1)+(((KX1+KX2)/2)*(DZ1+DZ2))/DX3)

      H(3,6)=(KY2*H(4,6)*((DX1+DX2)/DZ2)+KY1*((DX1+DX2)/
     1 DZ1)*H(2,6)+((KX1+KX2)/2)*.5*((DZ1+DZ2)/DX2)*H(3,7)+
     1 ((KX2+KX1)/2)*.5*((DZ1+DZ2)/DX1)*H(3,5))/((KY2/DZ2)*
     1 (DX1+DX2)+KY1*((DX1+DX2)/DZ1)+((KX1+KX2)/2)*.5*
     1 ((DZ1+DZ2)/DX1)+((KX1+KX2)/2)*.5*((DZ2+DZ1)/DX2))

      H(3,7)=(KY2*H(4,7)*((DX2+DX3)/DZ2)+KY1*((DX2+DX3)/
     1 DZ1)*H(2,7)+((KX1+KX2)/2)*.5*((DZ1+DZ2)/DX3)*H(3,8)+
     1 ((KX2+KX1)/2)*.5*((DZ1+DZ2)/DX2)*H(3,6))/((KY2/DZ2)*
     1 (DX2+DX3)+KY1*((DX2+DX3)/DZ1)+((KX1+KX2)/2)*.5*
     1 ((DZ1+DZ2)/DX3)+((KX1+KX2)/2)*.5*((DZ2+DZ1)/DX2))

C   ROW TWO - INTERIOR NODES

      DO 1700 C=2,5
1700    H(2,C)=((KX1*(H(2,C+1)+H(2,C-1)))/M5+KY1*(H(3,C)+H(1,C))*
     1  M5)/((2*KX1)/M5+2*KY1*M5)

      DO   1800  C=8,11
1800    H(2,C)=((KX1*(H(2,C-1)+H(2,C+1)))/M6+KY1*(H(3,C)+H(1,C))*
     1  M6)/((2*KX1)/M6+2*KY1*M6)

        H(2,6)=(KX1*(DZ1/DX2)*H(2,7)+KX1*(DZ1/DX1)*H(2,5)+KY1*
     1((DX1+DX2)/(2*DZ1))*(H(1,6)+H(3,6)))/(KX1*(DZ1/DX2+
```

Figure A5. (Sheet 6 of 8)

```
     1  DZ1/DX1)+KY1*((DX1+DX2)/DZ1))

        H(2,7)=(KX1*(DZ1/DX3)*H(2,8)+KX1*(DZ1/DX2)*H(2,6)+KY1*
     1  ((DX2+DX3)/(2*DZ1))*(H(1,7)+H(3,7)))/(KX1*(DZ1/DX3+
     1  DZ1/DX2)+KY1*((DX2+DX3)/DZ1))

C SEARCH FOR MAXIMUM RESIDUAL MR

      MR=0.0
      DO 2200 R=1,8
      DO 2200 C=1,12
        MRN=ABS(H(R,C)-OLDH(R,C))
        IF(MRN.GT.MR) MR=MRN
2200  CONTINUE

C  RETURN FOR NEXT ITERATION
      IF(MR.GT.TOL) GO TO 300

C  PRINT COMPLETION MESSAGE

      WRITE(20,950) ITT, MR
      WRITE(*,950) ITT,MR
950   FORMAT(/' SOLUTION COMPLETE AFTER ',I5,' ITERATIONS'
     1/' MAXIMUM RESIDUAL = 'F9.5)
      GO TO 2450

C TERMINATION FOR MAXIMUM TRIES

2400  WRITE(20,952) ITT, MR
      WRITE(*,952) ITT,MR
952   FORMAT(/' NO SOLUTION  AFTER MAXIMUM OF ',I5,' ITERATIONS'
     1/' MAXIMUM RESIDUAL = 'F9.5)
      GO TO 2450

C  CALCULATE FINAL HEADS AND GRADIENTS

2450    RHD1=(H(3,7)-H(1,7))
        RHD2=(H(5,7)-H(3,7))
        GR1=RHD1/Z1
        GR2=RHD2/Z2

C  WRITE FINAL HEADS TO FILE

      WRITE(20,940) ((H(R,C),C=1,12),R=1,8)
940   FORMAT(/' FINAL HEADS',/,12(1X,F6.2))


C  PRINT RESIDUAL HEADS AND GRADIENTS

      WRITE(20,960) RHD1,GR1,RHD2,GR2
      WRITE(*,960) RHD1,GR1,RHD2,GR2

960   FORMAT(/' RESIDUAL HEAD AT BASE OF TOP BLANKET = 'F6.2
     1/' GRADIENT THROUGH TOP BLANKET =          'F6.2
```

Figure A5. (Sheet 7 of 8)

```
     2//' HEAD LOSS THROUGH MIDDLE STRATUM =      'F6.2
     3/' GRADIENT THROUGH MIDDLE STRATUM =       'F6.2)

C CLOSE FILES AND CHECK FOR NEW PROBLEM

      REWIND 10
      REWIND 20
      CLOSE (10)
      CLOSE (20)
      WRITE (*,970) FILEOUT
970   FORMAT(/' OUTPUT SAVED IN FILE ',A)

      WRITE(*,980)
980   FORMAT(/' WANT TO RUN ANOTHER PROBLEM ? Y OR N')
      READ(*,'(A)') ANS
      IF((ANS.EQ.'Y').OR.(ANS.EQ.'y')) GOTO 100

      STOP
      END

C INTRODUCTION SUBROUTINE

      SUBROUTINE INTRO
      WRITE(*,20)
20    FORMAT(/,
     1' PROGRAM LEVEE3L --- '/
     2' UNDERSEEPAGE ANALYSIS FOR 3-LAYER PROFILES'//
     3' Written by Thomas F. Wolff and H. A. Al-Moussawi'/
     4' Michigan State University'//
     5' For the U. S. Army Corps of Engineers'/
     6' Release 1.0   September 1987')
      WRITE(*,30)
30    FORMAT(///,
     1/' -----------------'
     2/' .    XXXXXX     .             XXXX  XXXXX  XXXX  '
     3/' .    X          .              XX    XXX    XX   '
     4/' .    XXXXXX     .              XXXXXXXIIXXXXXX   '
     5/' .         X     .              XXI IXI  IXI IX   '
     6/' .    XXXXXX     .             XXXXXXXI  IXXXXXX  '
     7/' ----------------- '
     8//)
      RETURN
      END
```

Figure A5. (Sheet 8 of 8)

APPENDIX B: COMPUTER PROGRAM LEVEEIRR: UNDERSEEPAGE ANALYSIS FOR FOUNDATIONS CHARACTERIZED BY TWO LAYERS OF IRREGULAR SHAPE

1. The program LEVEEIRR performs underseepage analysis for levee foundations consisting of two layers of variable thickness with irregular boundaries. The program was written in FORTRAN77 and runs on IBM PCs or compatible microcomputers using the MS-DOS operating system.

2. Input to the program is from a data file without line numbers. The geometry of the two foundation layers is described by dividing the foundation into a series of horizontal segments. At x-coordinates of the lines defining the segments, the elevations of the top of the top blanket, top of the substratum, and bottom of the substratum are specified. Up to 30 segments can be specified, and it is recommended that minimum of 3 segments be specified on each side of the levee. Node points at which the flow equation is solved are generated at the specified top-of-substratum coordinates at a nine additional points between each set of adjacent specified points. The input file can be created using any word processing or text-editing program that produces a standard ASCII file. An example input file is shown in Figure B1. The cross section represented by the example is shown in Figure B2.

3. The program is executed by typing the command LEVEEIRR with the file LEVEEIRR.EXE resident on the default drive. The program will then ask for the name of the input file and the name of the output file. If the output file already exists, it will be written over; otherwise, it will be created. A sample run of LEVEEIRR is shown in Figure B3. An example output file is shown in Figure B4. A program source listing of LEVEEIRR is shown in Figure B5.

4. The program provides output to two devices: the console (screen) and the output file. Output to the screen includes the number of iterations, the residual head at the levee toe, and the gradient at the levee toe. If the user desires more detailed output, the output file can be displayed or printed using any word processing or text editing program that works with standard ASCII files. The output file contains the values of the x-coordinates, y-coordinates, layer thicknesses, heads, and gradients at each node point.

EXAMPLE INPUT FILE FOR LEVEEIRR

The section analyzed using this data file is illustrated in Figure B2. Although a minimum of three segments on each side of the levee are recommended, only four segments total are used in this example for simplicity.

Values	Variable Names
IRREGULAR FOUNDATION TEST PROBLEM	TITLE
175.0 160.0	HR HL
4 2	NSEGS, LSEG
.2 .0002	KF, KB
1000 .003	TRIES, TOL
750.0 60.0 140.0 158.0	X(1), Y1(1), Y2(1), Y3(1)
1750.0 60.0 140.0 160.0	X(2), Y1(2), Y2(2), Y3(2)
1900.0 60.0 140.0 160.0	X(3), Y1(3), Y2(3), Y3(3)
2400.0 60.0 120.0 158.33	X(4), Y1(4), Y2(4), Y3(4)
4900.0 60.0 140.0 150.0	X(LAST), Y1(LAST) Y2(LAST) Y3(LAST)

The variables are defined as follows:

TITLE is descriptive title for the problem (80 characters maximum).

HR is the elevation of water on the riverside of the levee. Actual elevations are usually most convenient.

HL is the elevation of water on the landside of the levee or the elevation of landside ground if no water is present.

NSEGS is the number of segments used to describe the problem geometry.

LSEG is the segment number under the levee. One and only one segment must be under the levee. For the example shown, LSEG equals 2.

Figure B1. Example input file, program LEVEEIRR (Continued)

KF is the horizontal permeability of the substratum, in feet per minute or other consistent units.

KB is the vertical permeability of the top blanket, in feet per minute or other consistent units.

TRIES is the maximum number of iterations that the program will be allowed to make. It is provided to stop the program in the event of non-converging solutions. Generally the program should terminate because TOL is reached before TRIES. A value of 500 is suggested.

TOL is the maximum tolerance, or maximum difference in head at any node between successive iterations. The iteration process will stop when the maximum residual is smaller than TOL. A value of 0.001 is suggested.

X(1), Y1(1), Y2(1), Y3(1) are the x-coordinate, the y-coordinate of the base of the substratum, the y-coordinate of the base of the top blanket, and the y-coordinate of the ground surface, respectively, at the riverside of the first segment. This line is repeated for the riverside of each segment.

X(LAST), Y1(LAST), Y2(LAST), Y3(LAST) are the x-coordinate, the y-coordinate of the base of the substratum, the y-coordinate of the base of the top blanket, and the y-coordinate of the ground surface, respectively, at the land side of the last segment.

Figure B1. (Concluded)

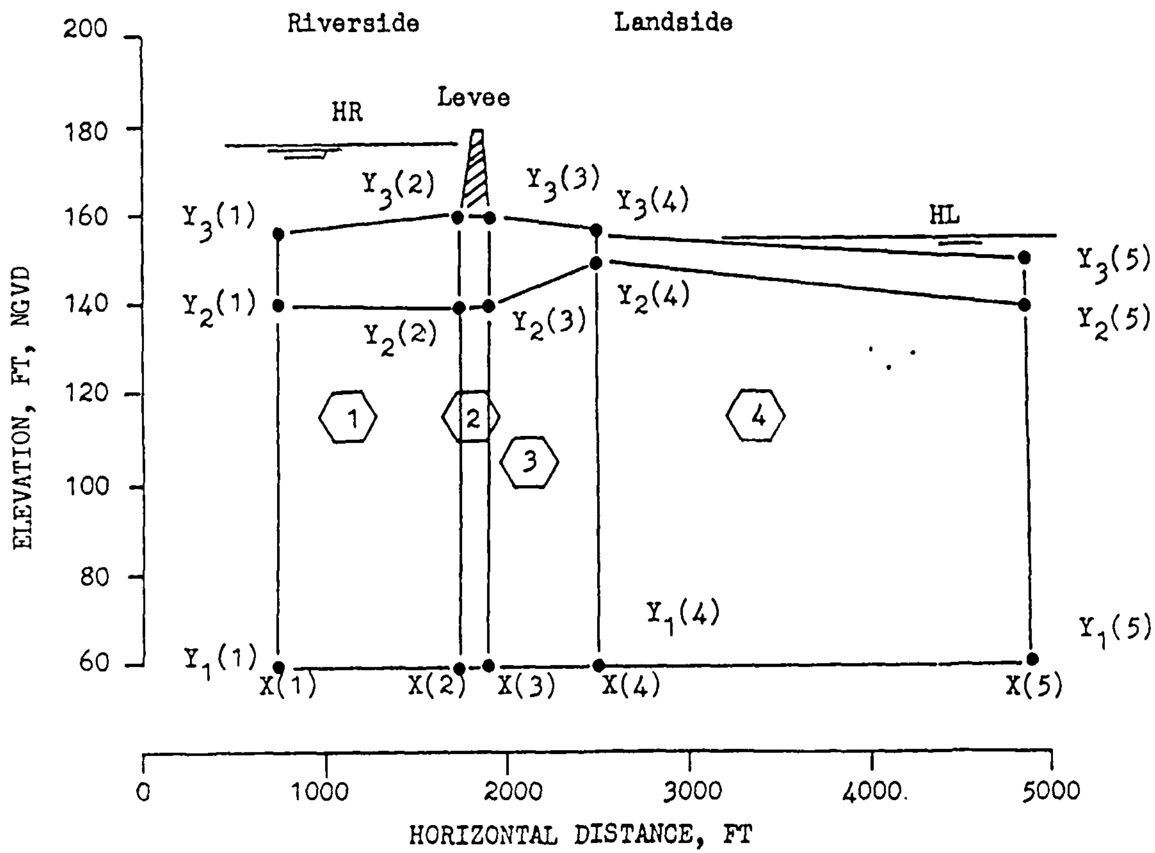

Figure B2. Definition of variables, LEVEEIRR

```
C>
C>LEVEEIRR

PROGRAM LEVEEIRR ---
UNDERSEEPAGE ANALYSIS FOR IRREGULAR PROFILES

Written by Thomas F. Wolff and H. A. Al-Moussawi
Michigan State University

For the U. S. Army Corps of Engineers Release 1.0   September 1987


 ---------------
.     XXXXXX      .          XXXX  XXXXX  XXXX
.     X           .           XX    XXX    XX
.     XXXXXX      .           XXXXXXXIIXXXXXX
.         X       .           XXI IXI  IXI IX
.     XXXXXX      .          XXXXXXXI  IXXXXXX
 ---------------


ENTER INPUT FILE NAME
DATAIRR
ENTER OUTPUT FILE NAME
OUTIRR

IRREGULAR FOUNDATION TEST PROBLEM


INPUT DATA

RIVERSIDE HEAD       LANDSIDE HEAD
    175.00               160.00

NO OF SEGMENTS       SEGMENT AT LEVEE
  4                    2

SUBSTRATUM KF         BLANKET KB
    .200000              .000200

MAX ITERATIONS       TOLERANCE
 1000                   .003000

X DISTANCE     BASE OF SUBSTRATUM  BASE OF BLANKET    TOP OF BLANKET
    750.00           60.00          140.00          158.00
  1750.00          60.00          140.00          160.00
  1900.00          60.00          140.00          160.00
  2400.00          60.00          120.00          158.33
  4900.00          60.00          140.00          150.00

JUST A MOMENT, I AM THINKING

THE SOLUTION IS COMPLETE
TOTAL ITTERATIONS=  298
MAXIMUM RESIDUAL=  .0030


HEAD AT LEVEE TOE =        7.38
MAXIMUM HEAD =             7.38 AT X =  1900.00

GRADIENT AT LEVEE TOE =        .37
MAXIMUM GRADIENT =             .37 AT X =  1900.00

DETAILED OUTPUT SAVED IN FILE OUTIRR


WANT TO RUN ANOTHER PROBLEM ?  Y OR N
N
Stop - Program terminated.

C>
```

Figure B3. Example run for program LEVEEIRR

EXAMPLE OUTPUT FILE FOR LEVEEIRR

```
IRREGULAR FOUNDATION TEST PROBLEM

INPUT DATA

RIVERSIDE HEAD      LANDSIDE HEAD
    175.00              160.00

NO OF SEGMENTS      SEGMENT AT LEVEE
  4                   2

SUBSTRATUM KF        BLANKET KB
    .200000              .000200

MAX ITERATIONS      TOLERANCE
 1000                  .003000

X DISTANCE     BASE OF SUBSTRATUM  BASE OF BLANKET     TOP OF BLANKET
   750.00             60.00          140.00            158.00
  1750.00             60.00          140.00            160.00
  1900.00             60.00          140.00            160.00
  2400.00             60.00          120.00            158.33
  4900.00             60.00          140.00            150.00

X VALUES
 750.00  850.00  950.00 1050.00 1150.00 1250.00 1350.00 1450.00 1550.00 1650.00
1750.00 1765.00 1780.00 1795.00 1810.00 1825.00 1840.00 1855.00 1870.00 1885.00
1900.00 1950.00 2000.00 2050.00 2100.00 2150.00 2200.00 2250.00 2300.00 2350.00
2400.00 2650.00 2900.00 3150.00 3400.00 3650.00 3900.00 4150.00 4400.00 4650.00
4900.00

D VALUES
 80.00  80.00  80.00  80.00  80.00  80.00  80.00  80.00  80.00  80.00
 80.00  80.00  80.00  80.00  80.00  80.00  80.00  80.00  80.00  80.00
 80.00  78.00  76.00  74.00  72.00  70.00  68.00  66.00  64.00  62.00
 60.00  62.00  64.00  66.00  68.00  70.00  72.00  74.00  76.00  78.00
 80.00

Z VALUES
 18.00  18.20  18.40  18.60  18.80  19.00  19.20  19.40  19.60  19.80
 20.00  20.00  20.00  20.00  20.00  20.00  20.00  20.00  20.00  20.00
 20.00  21.83  23.67  25.50  27.33  29.17  31.00  32.83  34.66  36.50
 38.33  35.50  32.66  29.83  27.00  24.17  21.33  18.50  15.67  12.83
 10.00

HEADS AT TOP OF BLANKET
175.00 175.00 175.00 175.00 175.00 175.00 175.00 175.00 175.00 175.00
```

Figure B4. Example output file, program LEVEEIRR (Continued)

```
175.00 173.50 172.00 170.50 169.00 167.50 166.00 164.50 163.00 161.50
160.00 160.00 160.00 160.00 160.00 160.00 160.00 160.00 160.00 160.00
160.00 160.00 160.00 160.00 160.00 160.00 160.00 160.00 160.00 160.00
160.00

INITIAL HEADS
175.00 174.50 174.00 173.50 173.00 172.50 172.00 171.50 171.00 170.50
170.00 169.50 169.00 168.50 168.00 167.50 167.00 166.50 166.00 165.50
165.00 164.50 164.00 163.50 163.00 162.50 162.00 161.50 161.00 160.50
160.00 159.50 159.00 158.50 158.00 157.50 157.00 156.50 156.00 155.50
160.00

THE SOLUTION IS COMPLETE
TOTAL ITTERATIONS=  298
MAXIMUM RESIDUAL=  .0030

X DISTANCE
PIEZ EL
RESIDUAL HEAD
GRADIENT


  750.0   850.0   950.0  1050.0  1150.0  1250.0  1350.0  1450.0  1550.0  1650.0
 175.00  174.40  173.80  173.19  172.57  171.94  171.28  170.61  169.91  169.17
    .00     .00     .00     .00     .00     .00     .00     .00     .00     .00
    .00     .00     .00     .00     .00     .00     .00     .00     .00     .00

 1750.0  1765.0  1780.0  1795.0  1810.0  1825.0  1840.0  1855.0  1870.0  1885.0
 168.41  168.29  168.18  168.07  167.96  167.85  167.75  167.65  167.56  167.46
    .00     .00     .00     .00     .00     .00     .00     .00     .00     .00
    .00     .00     .00     .00     .00     .00     .00     .00     .00     .00

 1900.0  1950.0  2000.0  2050.0  2100.0  2150.0  2200.0  2250.0  2300.0  2350.0
 167.38  167.09  166.82  166.56  166.32  166.08  165.85  165.63  165.43  165.23
   7.38    7.09    6.82    6.56    6.32    6.08    5.85    5.63    5.43    5.23
    .37     .32     .29     .26     .23     .21     .19     .17     .16     .14

 2400.0  2650.0  2900.0  3150.0  3400.0  3650.0  3900.0  4150.0  4400.0  4650.0
 165.04  164.16  163.41  162.76  162.19  161.70  161.28  160.91  160.58  160.28
   5.04    4.16    3.41    2.76    2.19    1.70    1.28     .91     .58     .28
    .13     .12     .10     .09     .08     .07     .06     .05     .04     .02

HEAD AT LEVEE TOE =      7.38
MAXIMUM HEAD =           7.38 AT X =  1900.00

GRADIENT AT LEVEE TOE =       .37
MAXIMUM GRADIENT =            .37 AT X =  1900.00
```

Figure B4. (Concluded)

```
      PROGRAM LEVEEIRR

C$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C                                                                       $
C    THIS PROGRAM WAS WRITTEN BY:                                       $
C                                                                       $
C         DR. THOMAS F. WOLFF; ASSISTANT PROFESSOR                      $
C         AND                                                           $
C         HASSAN M. ALMOUSSAWI; PH.D CANDIDATE                          $
C                                                                       $
C         USING THE A. H. CASE CENTER                                   $
C         COMPUTER AIDED ENGINEEING FACILITY AT                         $
C         MICHIGAN STATE UNIVERSITY , 1987                              $
C                                                                       $
C$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$$
C                                                                       *
C   THIS PROGRAM USES THE FINITE DIFFERENCE METHOD TO ANALYZE           *
C   SEEPAGE THROUGH TWO SOIL LAYERS BENEATH A LEVEE.                    *
C   THE TOP SOIL LAYER HAS PERMEABILITY KB AND THICKNESS Z              *
C   THE BOTTOM LAYER HAS PERMEABILITY KF AND THICKNESS D                *
C   Z AND D ARE FUNCTIONS OF THE DISTANCE X FROM THE LEFT.              *
C                                                                       *
C************************************************************************
C
C   VARIABLES:
C
C   A            Segment Number under levee
C   CLEFT(C)     Left side head coefficient
C   CRIGHT(C)    Right side head coefficient
C   CLEV1        Column no. at riverside levee toe
C   CLEV2        Column no. at landside levee toe
C   CTOP(c)      Top side head coefficient
C   DX(C)        Differential foundation width at node C
C   HL           Landside water elevation
C   HR           Riverside water elevation
C   H(R,C)       Head (row 1 is ground, row 2 is base of blanket)
C   ITT          Iteration
C   KB           Permeability of blanket
C   KF           Permeability of substratum
C   LENGTH       Segment Length
C   MR           Maximum residual
C   N            Number of foundation segments
C   NN           Node subscript
C   OLDH(R,C)    Head from previous iteration
C   TOL          Tolerance
C   TRIES        Maximum number of iterations
C   X(R,C)       X coordinate at column C
C   Y1(C)        Y coordinate at base of substratum
C   Y2(C)        Y coordinate at base of blanket
C   Y3(C)        Y coordinate at ground surface
C   Z            Top blanket thickness
C************************************************************************
```

Figure B5. Listing of program LEVEEIRR (Sheet 1 of 8)

```
C DECLARE VARIABLES

      CHARACTER ANS*1, FILEIN*64, FILEOUT*64, TITLE*80
      INTEGER A,C,C1,C2,CLEV1,CLEV2,ITT,J,N,NN,NN10,TRIES
      REAL HR,HL,H(2,300),RHMAX,DH,DH1,OLDH(300)
      REAL X(300),DX(300),DXCTR(300),Y1(300),Y2(300),Y3(300)
      REAL Z(300),D(300),RESHD(300),GRAD(300),GRMAX
      REAL CLEFT(300),CRIGHT(300),CTOP(300),CSUM(300)
      REAL KB,KF,MRN,MR,TOL
      REAL FC,FJ,FNN,LENGTH
      REAL XHMAX, XGRMAX

C DISPLAY INTRODUCTION
      CALL INTRO

C OPEN DATA FILES

100   WRITE (*,*) 'ENTER INPUT FILE NAME'
      READ (*,'(A)') FILEIN
      OPEN (UNIT=10, FILE=FILEIN, ERR=100, STATUS='OLD')
      REWIND (10)

      WRITE (*,*) 'ENTER OUTPUT FILE NAME'
      READ(*,'(A)') FILEOUT
      OPEN (20,FILE=FILEOUT)
      REWIND (20)

C READ DATA

      READ(10,'(A)')TITLE
      READ(10,*) HR,HL,N,A,KF,KB,TRIES,TOL
      NN=N*10
      NN10=NN+10
      READ(10,*) (X(J),Y1(J),Y2(J),Y3(J),J=10,NN10,10)

C PRINT INPUT DATA AND WRITE TO FILE

      WRITE(20,*) TITLE
      WRITE(*,*)
      WRITE(*,*) TITLE

      WRITE(20,910)
      WRITE(*,910)
910   FORMAT(/' INPUT DATA ')

      WRITE(20,912)
      WRITE(*,912)
912   FORMAT(/,' RIVERSIDE HEAD      LANDSIDE HEAD')
      WRITE(20,914) HR,HL
      WRITE(*,914) HR,HL
914   FORMAT(1X,F10.2,10X,F10.2)

      WRITE(20,916)
      WRITE(*,916)
```

Figure B5. (Sheet 2 of 8)

```
916   FORMAT(/,' NO OF SEGMENTS      SEGMENT AT LEVEE')
      WRITE(20,918) N,A
      WRITE(*,918) N,A
918   FORMAT(1X,I3,17X,I3)

      WRITE(20,920)
      WRITE(*,920)
920   FORMAT(/,' SUBSTRATUM KF        BLANKET KB')
      WRITE(20,922) KF,KB
      WRITE(*,922) KF,KB
922   FORMAT(1X,F12.6,8X,F12.6)

      WRITE(20,924)
      WRITE(*,924)
924   FORMAT(/,' MAX ITERATIONS      TOLERANCE')
      WRITE(20,926) TRIES,TOL
      WRITE(*,926) TRIES,TOL
926   FORMAT(1X,I5,15X,F10.6)

      WRITE(20,928)
      WRITE(*,928)
928   FORMAT(/,' X DISTANCE     BASE OF SUBSTRATUM  BASE OF BLANKET
     1TOP OF BLANKET')
      WRITE(20,930) (X(J),Y1(J),Y2(J),Y3(J),J=10,NN10,10)
      WRITE(*,930) (X(J),Y1(J),Y2(J),Y3(J),J=10,NN10,10)
930   FORMAT(1X,4(F10.2,6X))


C   CALCULATE THE  X VALUES FOR ALL NODES

      DO 200 C=10,NN,10
         LENGTH=X(C+10)-X(C)
         DX(C)=LENGTH/10.0
      DO 200 J=1,9
         DX(C+J)=DX(C)
         X(C+J)=X(C+J-1)+DX(C+J-1)
200   CONTINUE

C  WRITE THE X VALUES TO FILE

      WRITE (20,935) (X(C), C=10,NN+10)
935   FORMAT (/,' X VALUES',/,10(1XF7.2))

C CALCULATE THE D, Z, AND Y3 VALUES
      DO 350 C=10,NN,10
        D(C)=Y2(C)-Y1(C)
        Z(C)=Y3(C)-Y2(C)
      DO 340 J=1,9
        FJ=FLOAT(J)/10.0
        D(C+J)=Y2(C)-Y1(C)+FJ*(Y2(C+10)-Y2(C))-FJ*(Y1(C+10)-Y1(C))
        Z(C+J)=Y3(C)-Y2(C)+FJ*(Y3(C+10)-Y3(C))-FJ*(Y2(C+10)-Y2(C))
        Y3(C+J)=Y3(C)+FJ*(Y3(C+10)-Y3(C))
340   CONTINUE
350   CONTINUE
```

Figure B5. (Sheet 3 of 8)

```
      D(NN10)=Y2(NN10)-Y1(NN10)
      Z(NN10)=Y3(NN10)-Y2(NN10)

C WRITE THE D AND Z VALUES TO FILE

     WRITE(20,940)
940  FORMAT(/,' D VALUES')
     WRITE(20,941) (D(C), C=10,NN+10)
941  FORMAT(10(1XF6.2))

     WRITE(20,942)
942  FORMAT(/,' Z VALUES')
     WRITE(20,941) (Z(C), C=10,NN+10)

C FIND THE COLUMNS UNDER THE LEVEE -- CLEV1 TO CLEV2

     CLEV1 = A*10
     CLEV2 = CLEV1 + 10

C  CALCUALATE HEAD CHANGES AT LEVEE/BLANKET INTERFACE

     IF(Y3(CLEV2).GT.HL) THEN
       DH=(HR-Y3(CLEV2))/10.0
     ELSE
       DH=(HR-HL)/10.0
     ENDIF

C CALCULATE THE HEAD AT TOP OF BLANKET

     DO 400 C=10,NN10

C       RIVERSIDE
        IF(C.LE.CLEV1) THEN
          H(1,C)=HR

C       LEVEE
        ELSEIF((C.GT.CLEV1).AND.(C.LT.CLEV2)) THEN
          H(1,C)=H(1,C-1)-DH

C       LANDSIDE - WATER ABOVE GROUND
        ELSEIF((C.GE.CLEV2).AND.(HL.GT.Y3(C))) THEN
          H(1,C)=HL

C       LANDSIDE - GROUND ABOVE WATER
        ELSE
          H(1,C)=Y3(C)
        ENDIF

C       LANDSIDE  - HIGH GROUND ABOVE HR
        IF((C.GE.CLEV2).AND.(H(1,C).GT.HR)) THEN
          H(1,C) = H(1,C-1)
        ENDIF

400  CONTINUE
```

Figure B5. (Sheet 4 of 8)

```
C WRITE HEADS AT TOP OF BLANKET TO FILE

      WRITE(20,945)
945   FORMAT(/,' HEADS AT TOP OF BLANKET')
      WRITE(20,941) (H(1,C), C=10,NN10)

C INITIALIZE HEADS AT BASE OF BLANKET

      H(2,10)=HR
      H(2,NN10)=HL
      FNN=FLOAT(NN)

      DO 450 C=11,NN+9
        FC=FLOAT(C)
        H(2,C)=H(2,10)-((FC-10.0)/(FNN-10.0))*(HR-HL)
450   CONTINUE

C WRITE INITIAL HEADS AT BASE OF BLANKET TO FILE

      WRITE(20,950)
950   FORMAT(/,' INITIAL HEADS')
      WRITE(20,941) (H(2,C), C=10,NN10)

C CALCULATE DIFFERENCE COEFFICIENTS

      DO 470 C=11, NN+9
        CLEFT(C)=KF*D(C)/DX(C-1)
        DXCTR(C)=(DX(C-1)+DX(C))/2
        CTOP(C)=KB*DXCTR(C)/Z(C)
        CRIGHT(C)=KF*D(C)/DX(C)
        CSUM(C)=CLEFT(C)+CRIGHT(C)+CTOP(C)
470   CONTINUE

C****************************************
C   ITTERATION PROCESS
C****************************************

C INITIALIZE
      ITT=0
      WRITE (*,*)
      WRITE (*,*) 'JUST A MOMENT, I AM THINKING'

C BEGIN NEXT ITERATION

500   ITT=ITT+1
C     WRITE(*,960) ITT
C 960 FORMAT(1X,'ITERATION NO ',I5)
      IF(ITT+1.GT.TRIES) GO TO 2400

C     RESET OLD HEADS
      DO 510 C=11,NN+9
510   OLDH(C)=H(2,C)
```

Figure B5. (Sheet 5 of 8)

```
C   CALCULATE HEADS AT ROW TWO

      DO 520  C=11,NN+9
      H(2,C)=(H(2,C-1)*CLEFT(C)+H(1,C)*CTOP(C)+H(2,C+1)*CRIGHT(C))
     1 /CSUM(C)
520   CONTINUE

C  SEARCH FOR MAXIMUM RESIDUAL -MR-

      MR=0.0
      DO 600  C=11,NN+9
        MRN=ABS(H(2,C)-OLDH(C))
        IF(MRN.GT.MR) MR=MRN
600   CONTINUE

C  RETURN FOR NEXT ITERATION
      IF(MR.GT.TOL) GO TO 500

C  NORMAL TERMINATION

      WRITE(20,970)ITT,MR
      WRITE(*,970) ITT,MR
970   FORMAT(/,' THE SOLUTION IS COMPLETE'
     1/' TOTAL ITTERATIONS= ',I4
     2/' MAXIMUM RESIDUAL= ',F6.4)

C CALCULATE FINAL RESIDUAL HEADS AND GRADIENTS

620   DO 650, C=CLEV2,NN+9
      RESHD(C)=H(2,C)-H(1,C)
      GRAD(C)=RESHD(C)/Z(C)
650   CONTINUE

C CALCULATE MAX LANDSIDE RESIDUAL HEAD

      RHMAX=RESHD(CLEV2)
      XHMAX=X(CLEV2)
      DO 660 C=CLEV2,NN+9
        IF (RESHD(C).GT.RHMAX) THEN
          RHMAX=RESHD(C)
          XHMAX=X(C)
        ENDIF
660   CONTINUE

C CALCULATE MAX LANDSIDE GRADIENT
      GRMAX=GRAD(CLEV2)
      XGRMAX=X(CLEV2)
      DO 670 C=CLEV2,NN+9
        IF (GRAD(C).GT.GRMAX) THEN
          GRMAX=GRAD(C)
          XGRMAX=X(C)
        ENDIF
670   CONTINUE
```

Figure B5. (Sheet 6 of 8)

```
C WRITE X, PIEZ EL, HEAD, AND GRADIENT TO FILE

      WRITE(20,975)
975   FORMAT(/,' X DISTANCE',/,' PIEZ EL',/,' RESIDUAL HEAD',/
     1' GRADIENT',/)
      DO 700 I=1,N
        C1=I*10
        C2=I*10+9
        WRITE(20,980) (X(C), C=C1,C2)
        WRITE(20,982) (H(2,C), C=C1,C2)
        WRITE(20,982) (RESHD(C), C=C1,C2)
        WRITE(20,982) (GRAD(C), C=C1,C2)
700   CONTINUE
980   FORMAT(/,10(1XF7.1))
982   FORMAT(10(1XF7.2))

C PRINT TOE AND MAXIMUM RESIDUAL HEADS AND GRADIENTS
      WRITE(20,990) RESHD(CLEV2), RHMAX, XHMAX
      WRITE(*,990)  RESHD(CLEV2), RHMAX, XHMAX
990   FORMAT(/,' HEAD AT LEVEE TOE = ',F8.2,/
     1' MAXIMUM HEAD =       ',F8.2,' AT X = ',F8.2)

      WRITE(20,994) GRAD(CLEV2), GRMAX, XGRMAX
      WRITE(*,994)  GRAD(CLEV2), GRMAX, XGRMAX
994   FORMAT(/,' GRADIENT AT LEVEE TOE = ',F8.2,/
     1' MAXIMUM GRADIENT =       ',F8.2,' AT X = ',F8.2)

C CLOSE FILES AND CHECK FOR NEW PROBLEM
      REWIND 10
      REWIND 20
      CLOSE (10)
      CLOSE (20)
      WRITE (*,1000) FILEOUT
1000  FORMAT(/' DETAILED OUTPUT SAVED IN FILE ',A)

      WRITE(*,1010)
1010  FORMAT(/,' WANT TO RUN ANOTHER PROBLEM ?  Y OR N ')
      READ(*,'(A)') ANS
      IF (ANS.EQ.'Y') GOTO 100
      GO TO 99

C TERMINATION FOR MAXIMUM TRIES

2400  WRITE(20,995) ITT,MR
      WRITE(*,995) ITT,MR
995   FORMAT(//, 'SOLUTION INCOMPLETE STOPPED BY MAXIMUM
     1 POSSIBLE NUMBER OF TRIES= ',I4,/10X,'MAXIMUM RESIDUAL=
     1  ',F6.3)
      GO TO 620

99    STOP

      END
```

Figure B5. (Sheet 7 of 8)

```
C INTRODUCTION SUBROUTINE
      SUBROUTINE INTRO
      WRITE(*,20)
20    FORMAT(/,
     1' PROGRAM LEVEEIRR --- '/
     2' UNDERSEEPAGE ANALYSIS FOR IRREGULAR PROFILES'//
     3' Written by Thomas F. Wolff and H. A. Al-Moussawi'/
     4' Michigan State University'//
     5' For the U. S. Army Corps of Engineers'
     6' Release 1.0   September 1987')
      WRITE(*,30)
30    FORMAT(///,
     1/'  -----------------'
     2/' .     XXXXXX      .              XXXX  XXXXX  XXXX  '
     3/' .     X           .               XX    XXX    XX   '
     4/' .     XXXXXX      .               XXXXXXXIIXXXXXX   '
     5/' .          X      .               XXI IXI  IXI IX   '
     6/' .     XXXXXX      .              XXXXXXXI  IXXXXXX  '
     7/'  ----------------- '
     8//)
      RETURN
      END
```

Figure B5. (Sheet 8 of 8)

APPENDIX C: COMPUTER PROGRAM LEVEECOR: UNDERSEEPAGE ANALYSIS AT ANGLES OR "CORNERS" IN LEVEE ALIGNMENT

1. The program LEVEECOR performs underseepage analysis at bends or corners in levee alignment. The program was written in FORTRAN77 and runs on IBM PCs or compatible microcomputers using the MSD-DOS operating system.

2. Input to the program is from a 15 line data file without line numbers. This file can be created using any word processing or text-editing program that produces a standard ASCII file. An example input file is shown in Figure C1. Program variables are defined in Figure C2.

3. The program is executed by typing the command LEVEECOR with the file LEVEECOR.EXE resident on the default drive. The program will then ask for the name of the input file and the name of the output file. If the output file already exists, it will be written over; otherwise, it will be created. A sample run of LEVEECOR is shown in Figure C3. An example output file is shown in Figure C4. A program source listing of LEVEECOR is shown in Figure C5.

4. The program provides output to two devices: the console (screen) and the output file. Output to the screen includes the number of iterations, the residual head at the levee toe, and the gradient at the levee toe. If the user desires more detailed output, the output file can be displayed or printed using any word processing or text-editing program that works with standard ASCII files. The output file contains the approximate distances to adjacent nodes, equation coefficients, and initial and final heads at each node point.

EXAMPLE INPUT FILE FOR LEVEECOR

Values	Variable Names
TEST PROBLEM	TITLE
12.58	HR
0	HL
5000	L1A
650	L1B
300	L2
80	THETA
.089	KF
.0000908	KBL
.0000908	KBR
1100.0	RADIUS
75	D
.005	TOL
2000	TRIES
14	Z

The variables are defined as follows:

TITLE is descriptive title for the problem (80 characters maximum).

HR is the elevation of water on the riverside of the levee. If the landside water or landside ground is taken as the datum, HR is the net head on the levee.

HL is the elevation of water on the landside of the levee or the elevation of landside ground if no water is present. This level is often taken as the datum, in which case HL is 0.0.

L1A is the distance from the riverside levee toe to the river or source of seepage on the left side of the bend if one is facing the river.

Figure C1. Example input file, program LEVEECOR (Continued)

L1B is the distance from the riverside levee to to the river or source of seepage on the right side of the bend if one is facing the river.

L2 is the base width of the levee.

THETA is the deflection angle between two levee tangents (analogous to the delta angle in surveying).

KF is the horizontal permeability of the substratum, in feet per minute or other consistent units.

KBL is the upward vertical permeability of the landside top blanket, in feet per minute or other consistent units.

KBR is the downward vertical permeability of the riverside top blanket, in feet per minute or other consistent units.

RADIUS is the radius of curvature of the landside levee toe, in feet or other consistent units.

D is the thickness of the substratum in feet or any consistent units.

TRIES is the maximum number of iterations that the program will be allowed to make. It is provided to stop the program in the event of non-converging solutions. Generally the program should terminate because TOL is reached before TRIES. Because LEVEECOR may converge slowly, a value of 1,000 is suggested.

TOL is the maximum tolerance, or maximum difference in head at any node between successive iterations. The iteration process will stop when the maximum residual is smaller than TOL. Because LEVEECOR may converge slowly, a value of 0.001 is suggested.

Z is the total thickness of the top stratum.

Figure C1. (Concluded)

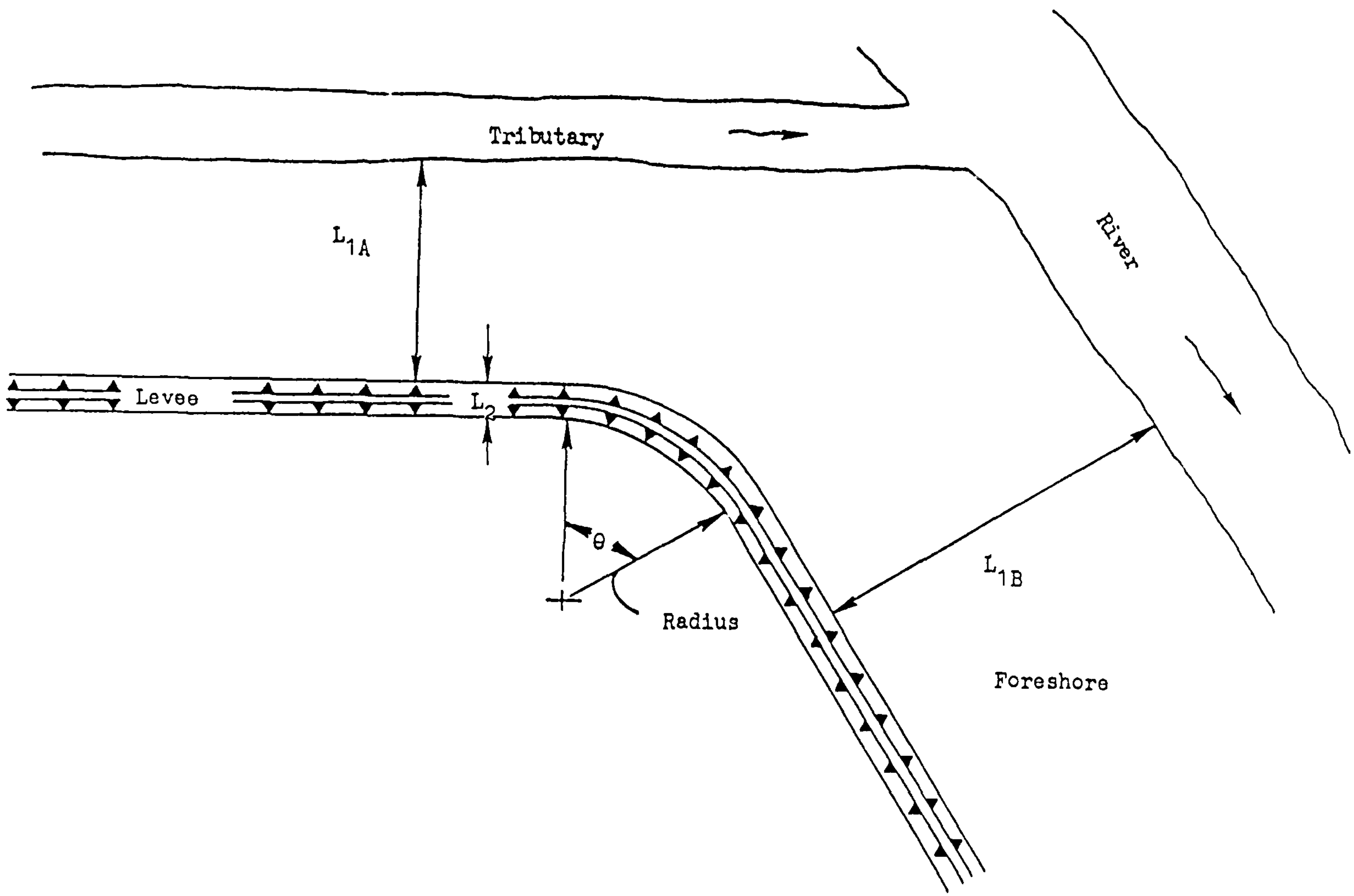

Figure C2. Definition of variables, program LEVEECOR

```
C>
C>LEVEECOR
PROGRAM LEVEECOR
SEEPAGE ANALYSIS AT LEVEE CORNERS

ENTER INPUT FILE NAME
DATACOR
ENTER OUTPUT FILE NAME
OUTCOR



 INPUT PARAMETERS OF THE PROGRAM

------------------------------

TEST PROBLEM


 HR VALUE:   12.580

HL VALUE:     .000

 L1A VALUE: 5000.000

 L1B VALUE:  650.000

 L2 VALUE:  300.000

 THETA VALUE:   80.000

 KF VALUE:

 KBL VALUE:  .000091

 KBR VALUE:  .000091

 RADIuS VALUE: 1100.000

 D VALUE:   75.000

 TOL VALUE:  .005000

 TOTAL NUMBER OF TRIES: 2000

 THICKNESS VALUE:   14.000000
 ITERATION     1  HEAD =   6.05448  MAX RES =  -5.54076 AT   2, 14
 ITERATION     2  HEAD =   5.95314  MAX RES =   1.56634 AT   5,  9
 ITERATION     3  HEAD =   5.89575  MAX RES =    .94499 AT   5,  7
 ITERATION     4  HEAD =   5.91959  MAX RES =    .64477 AT   5,  6
 ITERATION     5  HEAD =   6.00586  MAX RES =    .39485 AT   5,  6
```

Figure C3. Example run for program LEVEECOR (Continued)

```
ITERATION    13  HEAD =   6.34391  MAX RES =   -.04920 AT   2, 10
ITERATION    14  HEAD =   6.35871  MAX RES =   -.03832 AT   2, 10
ITERATION    15  HEAD =   6.37394  MAX RES =   -.02976 AT   2,  6
ITERATION    16  HEAD =   6.38382  MAX RES =   -.02307 AT   2,  6
ITERATION    17  HEAD =   6.39376  MAX RES =   -.01784 AT   2,  6
ITERATION    18  HEAD =   6.40037  MAX RES =   -.01376 AT   2, 10
ITERATION    19  HEAD =   6.40693  MAX RES =   -.01058 AT   2, 10
ITERATION    20  HEAD =   6.41137  MAX RES =   -.00811 AT   2, 10
ITERATION    21  HEAD =   6.41577  MAX RES =   -.00620 AT   2,  6

 TOTAL NUMBER OF ITERATIONS        21
TEST PROBLEM




 VALUE OF THE GRADIENT AT H(3,8) =      .4583

  VALUE OF THE H(3,8) =    6.4158
Stop - Program terminated.


C>
```

Figure C3. (Concluded)

```
EXAMPLE OUTPUT FILE FOR LEVEECOR

 INPUT PARAMETERS OF THE PROGRAM
--------------------------------

 TEST PROBLEM

 HR VALUE:   12.580
HL VALUE:     .000
L1A VALUE: 5000.000
L1B VALUE:  650.000
L2 VALUE:  300.000
THETA VALUE:   80.000
KF VALUE:  .089000
KBL VALUE:  .000091
KBR VALUE:  .000091
RADIuS VALUE: 1100.000
D VALUE:   75.000
TOL VALUE:  .005000
TOTAL NUMBER OF TRIES: 2000
THICKNESS VALUE:   14.000000
INITIAL MATRIX
******* ******
  .0000    .0000    .0000    .0000    .0000    .0000    .0000    .0000
    .0000    .0000    .0000    .0000    .0000    .0000    .0000
  6.290    6.290    6.290    6.290    6.290    6.290    6.290    6.290
    6.290    6.290    6.290    6.290    6.290    6.290    6.290
  6.290    6.290    6.290    6.290    6.290    6.290    6.290    6.290
    6.290    6.290    6.290    6.290    6.290    6.290    6.290
  6.290    6.290    6.290    6.290    6.290    6.290    6.290    6.290
    6.290    6.290    6.290    6.290    6.290    6.290    6.290
  6.290    6.290    6.290    6.290    6.290    6.290    6.290    6.290
    6.290    6.290    6.290    6.290    6.290    6.290    6.290
  12.58    12.58    12.58    12.58    12.58    12.58    12.58    12.58
    12.58    12.58    12.58    12.58    12.58    12.58    12.58

DXLEFT  MATRIX
  .0000    1100.    1100.    1100.    1100.    1037.    20.00    20.00
    20.00    20.00    1037.    1100.    1100.    1100.    1100.
  .0000    1100.    1100.    1100.    1100.    1100.    20.00    20.00
    20.00    20.00    1100.    1100.    1100.    1100.    1100.
  .0000    1100.    1100.    1100.    1100.    1100.    384.0    384.0
    384.0    384.0    1100.    1100.    1100.    1100.    1100.
  .0000    1100.    1100.    1100.    1100.    1100.    488.7    488.7
    488.7    488.7    1100.    1100.    1100.    1100.    1100.
  .0000    1100.    1100.    1100.    1100.    1100.    1172.    981.7
    791.9    602.1    1100.    1100.    1100.    1100.    1100.
  .0000    1100.    1100.    1100.    1100.    1100.    1854.    1475.
    1095.    715.6    1100.    1100.    1100.    1100.    1100.

DXRIGHT MATRIX
```

Figure C4. Example output file, program LEVEECOR
(Sheet 1 of 5)

1100.	1100.	1100.	1100.	1037.	20.00	20.00	20.00
20.00	1037.	1100.	1100.	1100.	1100.	.0000	
1100.	1100.	1100.	1100.	1100.	20.00	20.00	20.00
20.00	1100.	1100.	1100.	1100.	1100.	.0000	
1100.	1100.	1100.	1100.	1100.	384.0	384.0	384.0
384.0	1100.	1100.	1100.	1100.	1100.	.0000	
1100.	1100.	1100.	1100.	1100.	488.7	488.7	488.7
488.7	1100.	1100.	1100.	1100.	1100.	.0000	
1100.	1100.	1100.	1100.	1100.	602.1	791.9	981.7
1172.	1100.	1100.	1100.	1100.	1100.	.0000	
1100.	1100.	1100.	1100.	1100.	715.6	1095.	1475.
1854.	1100.	1100.	1100.	1100.	1100.	.0000	

DYTOP MATRIX

75.00	75.00	75.00	75.00	75.00	97.91	97.91	97.91
97.91	97.91	75.00	75.00	75.00	75.00	75.00	
1100.	1100.	1100.	1100.	1100.	1100.	1100.	1100.
1100.	1100.	1100.	1100.	1100.	1100.	1100.	
300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0
300.0	300.0	300.0	300.0	300.0	300.0	300.0	
2500.	2500.	2500.	2500.	2500.	2500.	4456.	3913.
3369.	325.0	325.0	325.0	325.0	325.0	325.0	
2500.	2500.	2500.	2500.	2500.	2500.	4456.	3913.
3369.	325.0	325.0	325.0	325.0	325.0	325.0	
.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
.0000	.0000	.0000	.0000	.0000	.0000	.0000	

DYBOT MATRIX

.0000	.0000	.0000	.0000	.0000	.0000	.0000	.0000
.0000	.0000	.0000	.0000	.0000	.0000	.0000	
75.00	75.00	75.00	75.00	75.00	97.91	97.91	97.91
97.91	97.91	75.00	75.00	75.00	75.00	75.00	
1100.	1100.	1100.	1100.	1100.	1100.	1100.	1100.
1100.	1100.	1100.	1100.	1100.	1100.	1100.	
300.0	300.0	300.0	300.0	300.0	300.0	300.0	300.0
300.0	300.0	300.0	300.0	300.0	300.0	300.0	
2500.	2500.	2500.	2500.	2500.	2500.	4456.	3913.
3369.	325.0	325.0	325.0	325.0	325.0	325.0	
2500.	2500.	2500.	2500.	2500.	2500.	4456.	3913.
3369.	325.0	325.0	325.0	325.0	325.0	325.0	

DYCTR MATRIX

37.50	37.50	37.50	37.50	37.50	48.95	48.95	48.95
48.95	48.95	37.50	37.50	37.50	37.50	37.50	
587.5	587.5	587.5	587.5	587.5	599.0	599.0	599.0
599.0	599.0	587.5	587.5	587.5	587.5	587.5	
550.0	550.0	550.0	550.0	550.0	550.0	550.0	550.0
550.0	550.0	550.0	550.0	550.0	550.0	550.0	
1250.	1250.	1250.	1250.	1250.	1250.	2228.	1956.
1684.	162.5	162.5	162.5	162.5	162.5	162.5	
2500.	2500.	2500.	2500.	2500.	2500.	4456.	3913.
3369.	325.0	325.0	325.0	325.0	325.0	325.0	

Figure C4. (Sheet 2 of 5)

```
  1250.    1250.    1250.    1250.    1250.    1250.    2228.    1956.
    1684.    162.5    162.5    162.5    162.5    162.5    162.5

DXCTR MATRIX
  550.0    1100.    1100.    1100.    1069.    528.5    20.00    20.00
    20.00    528.5    1069.    1100.    1100.    1100.    550.0
  550.0    1100.    1100.    1100.    1100.    560.0    20.00    20.00
    20.00    560.0    1100.    1100.    1100.    1100.    550.0
  550.0    1100.    1100.    1100.    1100.    742.0    384.0    384.0
    384.0    742.0    1100.    1100.    1100.    1100.    550.0
  550.0    1100.    1100.    1100.    1100.    794.3    488.7    488.7
    488.7    794.3    1100.    1100.    1100.    1100.    550.0
  550.0    1100.    1100.    1100.    1100.    851.1    981.7    981.7
    981.7    851.1    1100.    1100.    1100.    1100.    550.0
  550.0    1100.    1100.    1100.    1100.    907.8    1475.    1475.
    1475.    907.8    1100.    1100.    1100.    1100.    550.0

CLT MATRIX
  .0000    .0000    .0000    .0000    .0000    .0000    .0000    .0000
    .0000    .0000    .0000    .0000    .0000    .0000    .0000
  .0000    3.565    3.565    3.565    3.565    3.635    199.9    199.9
    199.9    199.9    3.565    3.565    3.565    3.565    3.565
  .0000    4.248    4.248    4.248    4.248    4.248    12.17    12.17
    12.17    12.17    4.248    4.248    4.248    4.248    4.248
  .0000    8.495    8.495    8.495    8.495    8.495    32.48    28.77
    25.06    4.268    1.896    1.896    1.896    1.896    1.896
  .0000    15.17    15.17    15.17    15.17    15.17    25.39    26.60
    28.39    3.603    1.972    1.972    1.972    1.972    1.972
  .0000    .0000    .0000    .0000    .0000    .0000    .0000    .0000
    .0000    .0000    .0000    .0000    .0000    .0000    .0000

CT MATRIX
  .0000    .0000    .0000    .0000    .0000    .0000    .0000    .0000
    .0000    .0000    .0000    .0000    .0000    .0000    .0000
  3.338    6.675    6.675    6.675    6.675    3.398    .1214    .1214
    .1214    3.398    6.675    6.675    6.675    6.675    3.338
  12.24    24.48    24.48    24.48    24.48    16.51    8.543    8.543
    8.543    16.51    24.48    24.48    24.48    24.48    12.24
  1.469    2.937    2.937    2.937    2.937    2.121    .7320    .8337
    .9683    16.31    22.59    22.59    22.59    22.59    11.30
  1.469    2.937    2.937    2.937    2.937    2.272    1.471    1.675
    1.945    17.48    22.59    22.59    22.59    22.59    11.30
  .0000    .0000    .0000    .0000    .0000    .0000    .0000    .0000
    .0000    .0000    .0000    .0000    .0000    .0000    .0000

CRT MATRIX
  .0000    .0000    .0000    .0000    .0000    .0000    .0000    .0000
    .0000    .0000    .0000    .0000    .0000    .0000    .0000
  3.565    3.565    3.565    3.565    3.565    199.9    199.9    199.9
    199.9    3.635    3.565    3.565    3.565    3.565    .0000
  4.248    4.248    4.248    4.248    4.248    12.17    12.17    12.17
    12.17    4.248    4.248    4.248    4.248    4.248    .0000
```

Figure C4. (Sheet 3 of 5)

```
 8.495    8.495    8.495    8.495    8.495    19.12    32.48    28.77
   25.06    1.896    1.896    1.896    1.896    1.896    .0000
 15.17    15.17    15.17    15.17    15.17    27.71    37.56    26.60
   19.19    1.972    1.972    1.972    1.972    1.972    .0000
 .0000    .0000    .0000    .0000    .0000    .0000    .0000    .0000
   .0000    .0000    .0000    .0000    .0000    .0000    .0000

CB MATRIX
 .0000    .0000    .0000    .0000    .0000    .0000    .0000    .0000
   .0000    .0000    .0000    .0000    .0000    .0000    .0000
 48.95    97.90    97.90    97.90    97.90    38.18    1.364    1.364
   1.364    38.18    97.90    97.90    97.90    97.90    48.95
 3.338    6.675    6.675    6.675    6.675    4.503    2.330    2.330
   2.330    4.503    6.675    6.675    6.675    6.675    3.338
 12.24    24.48    24.48    24.48    24.48    17.67    10.87    10.87
   10.87    17.67    24.48    24.48    24.48    24.48    12.24
 1.469    2.937    2.937    2.937    2.937    2.272    1.471    1.675
   1.945    17.48    22.59    22.59    22.59    22.59    11.30
 .0000    .0000    .0000    .0000    .0000    .0000    .0000    .0000
   .0000    .0000    .0000    .0000    .0000    .0000    .0000

CD MATRIX
 .0000    .0000    .0000    .0000    .0000    .0000    .0000    .0000
   .0000    .0000    .0000    .0000    .0000    .0000    .0000
 2.096    4.191    4.191    4.191    4.191    2.175    .7769E-01 .7769E-01
   .7769E-01 2.175  4.191    4.191    4.191    4.191    2.096
 1.962    3.924    3.924    3.924    3.924    2.647    1.370    1.370
   1.370    2.647    3.924    3.924    3.924    3.924    1.962
 4.459    8.918    8.918    8.918    8.918    6.440    7.062    6.200
   5.339    .8372    1.159    1.159    1.159    1.159    .5797
 8.918    17.84    17.84    17.84    17.84    13.80    28.37    24.91
   21.45    1.794    2.319    2.319    2.319    2.319    1.159
 .0000    .0000    .0000    .0000    .0000    .0000    .0000    .0000
   .0000    .0000    .0000    .0000    .0000    .0000    .0000

FINAL H MATRIX
 1.910    1.910    1.910    1.910    1.910    1.910    1.910    1.910
   1.910    1.910    1.910    1.910    1.910    1.910    1.910
 2.091    2.091    2.092    2.093    2.098    2.176    2.176    2.176
   2.176    2.176    2.109    2.106    2.105    2.105    2.105
 6.087    6.088    6.092    6.106    6.151    6.293    6.377    6.416
   6.416    6.405    6.338    6.319    6.315    6.313    6.313
 8.157    8.158    8.163    8.179    8.231    8.405    8.625    8.668
   8.631    8.599    8.505    8.486    8.482    8.481    8.481
 12.03    12.03    12.03    12.04    12.07    12.13    12.22    12.14
   11.83    10.78    10.65    10.63    10.63    10.63    10.63
 12.58    12.58    12.58    12.58    12.58    12.58    12.58    12.58
   12.58    12.58    12.58    12.58    12.58    12.58    12.58

TOTAL NUMBER OF ITERATIONS         21

TEST PROBLEM
```

Figure C4. (Sheet 4 of 5)

```
VALUE OF THE GRADIENT AT H(3,8) =      .4583
VALUE OF THE H(3,8) =    6.4158
```

Figure C4. (Sheet 5 of 5)

```
      PROGRAM LEVEECOR

C     Corrections 8-12-87
C___________________________________________________________________________.
C               THE FOLLOWING PROGRAM IS WRITTEN BY:                         !
C                  -DR. THOMAS F. WOLFF, ASSISTANT PROFESSOR                 !
C                AND                                                         !
C                  -MAGDAL N. HAJI, PH.D CANDIDATE                           !
C                                                                            !
C                  ----------------------------                              !
C                                                                            !
C                  DEVELOPED AT THE A. H. CASE CENTER                        !
C                 COMPUTER AIDED ENGINEERING FACILITY AT                     !
C                MICHIGAN STATE UNIVERSITY . SPRING 1987                     !
C                                                                            !
C                  ----------------------------                              !
C                                                                            !
C                                                                            !
C     THE PURPOSE OF THIS PROGRAM IS TO ANALYZE GROUND WATER FLOW BENEATH    !
C  FLOOD CONTROL LEVEES. THE PROGRAM SOLVES FOR THE DISTRIBUTION OF HEAD     !
C  FOR A THREE DIMENSIONAL POROUS MEDIA FLOW DESCRIBED BY LAPLACE EQUATION.  !
C     THE FINITE DIFFERENCE METHOD IS USED AS A MATHEMATICAL TOOL FOR A      !
C  6 BY 15 GRID MESH TO REACH THE DESIRED SOLUTION.                          !
C___________________________________________________________________________!

       CHARACTER*64 FILEIN
       CHARACTER*64 FILEOUT
       CHARACTER*80 TITLE
       INTEGER TRIES,ITT,R,RM,C,CM
       INTEGER DONE
       REAL*4  THETA
       REAL  GRADIENT,X3
       REAL  TEMP,TOPHN,BOTHN
       REAL  L1A,L1B,L2,HR,HL,KF,KBL,KBR,RADIUS,D,COEFF
       REAL  Z,DXLEFT(0:7,0:16)
       REAL  DXRIGHT(0:7,0:16)
       REAL  DYTOP(0:7,0:16)
       REAL  DYBOT(0:7,0:16),DXCTR(0:7,0:16)
       REAL  DYCTR(0:7,0:16)
       DOUBLE PRECISION CLT(0:7,0:16),CD(0:7,0:16)
       DOUBLE PRECISION CT(0:7,0:16),CRT(0:7,0:16),CB(0:7,0:16)
       DOUBLE PRECISION HN(0:7,0:16),H(0:7,0:16),HD(0:7),HO
       REAL  MR,MRN,MRX,MRA,TOL
C____________________________________________________________________________.
C                                                                             !
C    VARIABLE DICTIONARY                                                      !
C    -------- ----------                                                      !
C                                                                             !
C                                                                             !
C             C        INCREMENTAL INDEX                                      !
```

Figure C5. Listing of program LEVEECOR (Sheet 1 of 12)

```
C          CB      STORES INTERMIDIATE VALUE TO BE USED IN MAIN EQU.     !
C          CD      STORES INTERMIDIATE VALUE TO BE USED IN MAIN EQU.     !
C          CLT     STORES INTERMIDIATE  VALUE TO BE USED IN MAIN EQU.    !
C          CRT     STORES INTERMEDIATE VALUE TO BE USED IN MIAN EQU.     !
C          CT      STORES INTERMEDIATE VALUE TO BE USED IN MIAN EQU.     !
C          D       AQUIFER THICKNESS
C                  DISTANCE BETWEEN CONSECUTIVE COLUMNS AT THE BOTTOM    !
C                  OF THE MATRIX.                                        !
C          DXCTR   AVERAGE HORIZENTAL DIST. BETWEEN TWO CONSECUTIVE COL. !
C          DXLEFT  THE HORIZANTAL DISTANCE AT THE LEFT OF A GRID MESH.   !
C          DXRIGHT THE HORIZANTAL DISTANCE AT THE RGHT OF A GRID MESH    !
C          DYCTR   AVERAGE VERTICAL DIST. BETWEEN TWO CONSECUTIVE ROWS.  !
C          DYBOT   VERTICAL DISTANCE FROM ONE NODE TO THE NEXT LOWER NODE!
C          DYTOP   VERTICAL DISTANCE FROM ONE NODE TO THE NEXT UPPER NODE!
C          HR      INITIAL HEAD OF THE RIVER                             !
C          HL      INITIAL HEAD BEYOND THE LEVEE (LANDWARD)              !
C          HN      STORES NEW HEAD OF EACH NODE PRODUCED BY THE LAST     !
C                  ITERATION                                             !
C          HO      STORES OLD HEAD VALUES OF EACH NODE PRODUCES BY       !
C                  PREVIOUS ITERATION.                                   !
C          ITT     ITERATION NUMBER                                      !
C          KBL     HYDRULIC CONDUCTIVITY                                 !
C          KBR     HYDRULIC CONDUCTIVITY                                 !
C          KF      HYDRULIC CONDUCTIVITY                                 !
C          L1A     DISTANCE BETWEEN THE LEFT SIDE OF THE LEVEE AND THE   !
C                  RIVER                                                 !
C          L1B     DISTANCE BETWEEN THE RIGHT SIDE OF THE LEVEE AND THE  !
C                  RIVER                                                 !
C          L2      WIDTH OF THE LEVEE                                    !
C          MR      RESIDUAL HEAD                                         !
C          MRN     THE NEW RESIDUAL HEAD                                 !
C          RADIUS  RADIUS OF THE CURVATURE                               !
C          THETA   ANGLE BETWEEN THE RIVER AND THE LEVEE CURVATURE       !
C          TRIES   NUMBER OF TRIES                                       !
C          I       HYDRULIC GRADIENT                                     !
C          Z       THICKNESS OF SOIL LAYERS                              !
C______________________________________________________________________!

C     PROGRAM HEADING

      WRITE (*,*) 'PROGRAM LEVEECOR'
      WRITE (*,*) 'SEEPAGE ANALYSIS AT LEVEE CORNERS'
      WRITE (*,*)

C     OPEN DATA FILES

      WRITE (*,*) 'ENTER INPUT FILE NAME'
      READ (*,'(A)') FILEIN
      OPEN (20,FILE=FILEIN)
      REWIND (20)
```

Figure C5. (Sheet 2 of 12)

```
      WRITE (*,*) 'ENTER OUTPUT FILE NAME'
      READ(*,'(A)') FILEOUT
      OPEN (10.FILE=FILEOUT)
      REWIND (10)
C_______________________________________________________________________
C                                                                       |
C    INPUT PHASE OF THE PROGRAM                                         |
C_______________________________________________________________________|

       WRITE(10,11)
       WRITE(*,11)
11     FORMAT(1H1,' INPUT PARAMETERS OF THE PROGRAM')
       WRITE(10,12)
       WRITE(*,12)
12     FORMAT(1H0,'-------------------------------',/)
       READ (20,'(A)') TITLE
       WRITE(*,*) TITLE
       WRITE (10,*) TITLE
       READ (20,*) HR
       WRITE(10,21) HR
       WRITE(*,21) HR
21     FORMAT(1H0,' HR VALUE:' ,F9.3,)
       READ (20,*) HL
       WRITE(10,22) HL
       WRITE(*,22) HL
22     FORMAT(1H0,'HL VALUE:' ,F9.3,)
       READ (20,*) L1A
       WRITE(10,23) L1A
       WRITE(*,23) L1A
23     FORMAT(1H0,' L1A VALUE:' ,F9.3,)
       READ (20,*) L1B
       WRITE(10,24) L1B
       WRITE(*,24) L1B
24     FORMAT(1H0,' L1B VALUE:' ,F9.3,)
       READ (20,*) L2
       WRITE(10,25) L2
       WRITE(*,25) L2
25     FORMAT(1H0,' L2 VALUE:' ,F9.3,)
       READ (20,*) THETA
       WRITE(10,26) THETA
       WRITE(*,26) THETA
26     FORMAT(1H0,' THETA VALUE:' ,F9.3,)
       READ (20,*) KF
       WRITE(10,27) KF
       WRITE(*,27)
27     FORMAT(1H0,' KF VALUE:' ,F9.6,)
       READ (20,*) KBL
       WRITE(10,28) KBL
       WRITE(*,28) KBL
28     FORMAT(1H0,' KBL VALUE:' ,F9.6,)
       READ (20,*) KBR
```

Figure C5. (Sheet 3 of 12)

```
      WRITE(10,29) KBR
      WRITE(*,29) KBR
29    FORMAT(1H0,' KBR VALUE:' ,F9.6,)
      READ (20,*) RADIUS
      WRITE(10,30) RADIUS
      WRITE(*,30) RADIUS
30    FORMAT(1H0,' RADIuS VALUE:' ,F9.3,)
      READ (20,*) D
      WRITE(10,31) D
      WRITE(*,31) D
31    FORMAT(1H0,' D VALUE:' ,F9.3,)
      READ (20,*) TOL
      WRITE(10,32) TOL
      WRITE(*,32) TOL
32    FORMAT(1H0,' TOL VALUE:' ,F9.6,)
      READ (20,*) TRIES
      WRITE(10,33) TRIES
      WRITE(*,33) TRIES
33    FORMAT(1H0,' TOTAL NUMBER OF TRIES:',I5,)
      READ (20,*) Z
      WRITE (10,34) Z
      WRITE(*,34) Z
34    FORMAT(1H0,' THICKNESS VALUE:' ,F12.6,)

C_________________________________________________________________
C
C INITIALIZATION PHASE OF THE PROGRAM
C_________________________________________________________________

C CONVERT THETA TO RADIANS
    THETA=THETA/57.29578

C INITIALIZE HEADS

    DO 40 R=0,7
      H(R,0)=0
      H(R,16)=0

    IF (R.LE.3) THEN
         HD(R)=HL
      ELSE
         HD(R)=HR
      ENDIF


40  CONTINUE

    DO 44, C=1,15
      H(7,C)=0
      H(6,C)=HR
      H(1,C)=HL
```

Figure C5. (Sheet 4 of 12)

```
      H(0,C)=0
     DO 42, R=2,5
      H(R,C)=(HR+HL)/2
42     CONTINUE
44     CONTINUE


C INITIALIZE DXLEFT

     DO 46,R=1,6
      DXLEFT(R,1)=0
       DO 45 C=2,5
        DXLEFT(R,C)=RADIUS
45       CONTINUE
46     CONTINUE

     X3=SQRT((KF/KBL)*Z*D)

     IF (RADIUS.GT.X3) THEN
       DXLEFT(1,6) = RADIUS-D*TAN(THETA/2)
     ELSE
       DXLEFT(1,6) = RADIUS-(RADIUS-X3)*TAN(THETA/2)
     ENDIF

     DO 47,R=2,6
       DXLEFT(R,6)=RADIUS
47     CONTINUE

     DO 50,R=1,2
     DO 49,C=7,10
       DXLEFT(R,C)=20
49     CONTINUE
50     CONTINUE

     DO 55,C=7,10
      DXLEFT(3,C)=RADIUS*(THETA/4)
55     CONTINUE

     DO 60,C=7,10
       DXLEFT(4,C)=((RADIUS+L2)*(THETA/4))
60     CONTINUE

     DXLEFT(5,7)=(RADIUS+L2+0.5*L1A+.125*(L1B-L1A))*(THETA/4)
     DXLEFT(5,8)=(RADIUS+L2+0.5*L1A+.25*(L1B-L1A))*(THETA/4)
     DXLEFT(5,9)=(RADIUS+L2+0.5*L1A+.375*(L1B-L1A))*(THETA/4)
     DXLEFT(5,10)=(RADIUS+L2+0.5*L1B)*(THETA/4)

     DXLEFT(6,7)=(RADIUS+L2+L1A+.25*(L1B-L1A))*(THETA/4)
     DXLEFT(6,8)=(RADIUS+L2+L1A+.5*(L1B-L1A))*(THETA/4)
     DXLEFT(6,9)=(RADIUS+L2+L1A+.75*(L1B-L1A))*(THETA/4)
     DXLEFT(6,10)=(RADIUS+L2+L1B)*(THETA/4)
```

Figure C5. (Sheet 5 of 12)

```
      DXLEFT(1,11)=DXLEFT(1,6)

      DO 85,R=2,6
        DXLEFT(R,11)=RADIUS
85    CONTINUE

      DO 90,R=1,6
      DO 89,C=12,15
        DXLEFT(R,C)=RADIUS
89    CONTINUE
90    CONTINUE

C INITIALIZE DXRIGHT

      DO 105,R=1,6
      DO 100,C=14,1,-1
         DXRIGHT(R,C)=DXLEFT(R,16-C)
100   CONTINUE
105   CONTINUE

      DO 110,R=1,6
        DXRIGHT(R,15)=0
110   CONTINUE

C_____________________________________________________________________
C
C THIS PART OF THE PROGRAM COMPUTES DYTOP
C_____________________________________________________________________

      DO 115,C=1,5
        DYTOP(1,C)=X3-RADIUS
        IF (DYTOP(1,C).LT.1.0) THEN
         DYTOP(1,C)=D
        ENDIF
 115  CONTINUE


      DO 120,C=11,15
        DYTOP(1,C)=X3-RADIUS
        IF (DYTOP(1,C).LT.1.0) THEN
         DYTOP(1,C)=D
        ENDIF
120   CONTINUE

      DO 125,C=6,10
         DYTOP(1,C)=DYTOP(1,11)/COS(THETA/2)
125   CONTINUE

      DO 126,C=1,15
         DYTOP(2,C)=RADIUS
```

Figure C5. (Sheet 6 of 12)

```
        DYTOP(3,C)=L2
126   CONTINUE

      DO 135,R=4,5
      DO 127,C=1,6
        DYTOP(R,C)=L1A/2
127   CONTINUE

      DYTOP(R,7)=L1A + (0.25*(L1B-L1A)/2)
      DYTOP(R,8)=L1A + (0.5*(L1B-L1A)/2)
      DYTOP(R,9)=L1A + (0.75*(L1B-L1A)/2)

      DO 134,C=10,15
       DYTOP(R,C)=L1B/2
134   CONTINUE

135   CONTINUE

      DO 140,C=1,15
      DYTOP(6,C)=0
140   CONTINUE

C_________________________________________________________________
C
C   THIS PART OF THE PROGRAM CALCULATES THE DYBOT VALUES
C_________________________________________________________________

      DO 150,C=1,15
        DYBOT(1,C)=0
150   CONTINUE

      DO 155,R=2,6
      DO 152,C=1,15
        DYBOT(R,C)=DYTOP(R-1,C)
152   CONTINUE
155   CONTINUE

C_________________________________________________________________
C
C   THE FOLLOWING PART CALCULATES DXCTR AND DYCTR

C_________________________________________________________________

      DO 160,C=1,15
        DXCTR(3,C)=(DXLEFT(3,C)+DXRIGHT(3,C))/2
        DYCTR(3,C)=DYBOT(3,C)/2
160   CONTINUE

      DO 170,C=1,15
        DXCTR(4,C)=(DXLEFT(4,C)+DXRIGHT(4,C))/2
        DYCTR(4,C)=DYTOP(4,C)/2
```

Figure C5. (Sheet 7 of 12)

```
170   CONTINUE

      DO 180,C=1,15
       DO 175,R=1,2
        DXCTR(R,C)=(DXLEFT(R,C)+DXRIGHT(R,C))/2
        DYCTR(R,C)=(DYTOP(R,C)+DYBOT(R,C))/2
175    CONTINUE
180   CONTINUE

      DO 190,C=1,15
       DO 185,R=5,6
        DXCTR(R,C)=(DXLEFT(R,C)+DXRIGHT(R,C))/2
        DYCTR(R,C)=(DYTOP(R,C)+DYBOT(R,C))/2
185    CONTINUE
190   CONTINUE

C_____________________________________
C
C   PRINT MATRICES
C_____________________________________

      WRITE(10,191)
191     FORMAT(1H1,'INITIAL MATRIX')
      WRITE(10,192)
192     FORMAT(1H0,'******* ******')
      CALL DECHO_MAT(H)
      WRITE(10,193)
193     FORMAT(1H1,'DXLEFT  MATRIX')
      CALL ECHO_MAT(DXLEFT)
      WRITE(10,194)
194     FORMAT(1H1,'DXRIGHT MATRIX')
      CALL ECHO_MAT(DXRIGHT)
      WRITE(10,195)
195     FORMAT(1H1,'DYTOP MATRIX')
      CALL ECHO_MAT(DYTOP)
      WRITE(10,196)
196     FORMAT(1H1,'DYBOT MATRIX')
      CALL ECHO_MAT(DYBOT)
      WRITE(10,197)
197     FORMAT(1H1,'DYCTR MATRIX')
      CALL ECHO_MAT(DYCTR)
      WRITE(10,199)
199     FORMAT(1H1,'DXCTR MATRIX')
      CALL ECHO_MAT(DXCTR)

C_____________________________________
C
C CALCULATE C COEFFICIENTS
C
C_____________________________________
```

Figure C5. (Sheet 8 of 12)

```
      DO 240, C=2,14
      DO 230,R=2,5

        CLT(R,1)=0
        CLT(R,C)=D*KF*(DYTOP(R,C)+DYBOT(R,C))/(DXLEFT(R,C)*2)
        CLT(R,15)=D*KF*(DYTOP(R,15)+DYBOT(R,15))/(DXLEFT(R,15)*2)

        CT(R,1)=D*KF*DXRIGHT(R,1)/(DYTOP(R,1)*2)
        CT(R,C)=D*KF*(DXLEFT(R,C)+DXRIGHT(R,C))/(DYTOP(R,C)*2)
        CT(R,15)=D*KF*DXLEFT(R,15)/(DYTOP(R,15)*2)

        CRT(R,1)=D*KF*(DYTOP(R,1)+DYBOT(R,1))/(DXRIGHT(R,1)*2)
        CRT(R,C)=D*KF*(DYTOP(R,C)+DYBOT(R,C))/(DXRIGHT(R,C)*2)
        CRT(R,15)=0

        CB(R,1)=D*KF*DXRIGHT(R,1)/(DYBOT(R,1)*2)
        CB(R,C)=D*KF*(DXLEFT(R,C)+DXRIGHT(R,C))/(DYBOT(R,C)*2)
        CB(R,15)=D*KF*DXLEFT(R,C)/(DYBOT(R,C)*2)

        IF (R.LE.3) THEN
          COEFF=KBL
        ELSE
          COEFF=KBR
        ENDIF

        CD(R,1)=(COEFF*DXCTR(R,1)*DYCTR(R,1))/Z
        CD(R,C)=(COEFF*DXCTR(R,C)*DYCTR(R,C))/Z
        CD(R,15)=(COEFF*DXCTR(R,15)*DYCTR(R,15))/Z


230   CONTINUE
240   CONTINUE

      WRITE(10,224)
224   FORMAT(1H1,'CLT MATRIX')
      CALL DECHO_MAT(CLT)

      WRITE(10,225)
225   FORMAT(1H1,'CT MATRIX')
      CALL DECHO_MAT(CT)

      WRITE(10,226)
226   FORMAT(1H1,'CRT MATRIX')
      CALL DECHO_MAT(CRT)

      WRITE(10,227)
227   FORMAT(1H1,'CB MATRIX')
      CALL DECHO_MAT(CB)

      WRITE(10,228)
```

Figure C5. (Sheet 9 of 12)

```
228   FORMAT(1H1,'CD MATRIX')
      CALL DECHO_MAT(CD)

      ITT=0
      DONE=0

C_________________________
C
C SET NEW HEADS EQUAL TO OLD HEADS AT EDGES OF MATRIX
C_________________________

      DO 247,C=1,15
        HN(1,C)=H(1,C)
        HN(6,C)=H(6,C)
247   CONTINUE

      DO 248,R=1,6
        HN(R,1)=H(R,1)
        HN(R,15)=H(R,15)
248   CONTINUE

C________________________
C
C MAIN ITERATION LOOP
C________________________

2481  CONTINUE

      DO 250,R=2,5
      DO 249,C=1,15

      IF (R.EQ.2.AND.C.GE.7.AND.C.LE.10) THEN
        HN(R,C) = HN(2,6)
      ELSE
       TEMP = CLT(R,C)*H(R,C-1)+ CT(R,C)*H(R+1,C) + CRT(R,C)*H(R,C+1)
       TOPHN = TEMP + CD(R,C)*HD(R) + CB(R,C)*H(R-1,C)
       BOTHN = CLT(R,C) + CT(R,C) + CB(R,C)+ CD(R,C) + CRT(R,C)
       HN(R,C) = TOPHN/BOTHN
      ENDIF

249   CONTINUE
250   CONTINUE

C-----------------------------------
C  RESET ROW 1 HEADS
C-----------------------------------
      HO=H(3,1)-HL
      DO 251,C=1,15
       HN(1,C)=HL+HO*EXP(-1*(DYTOP(1,1)+DYTOP(2,1))/X3)
251   CONTINUE
```

Figure C5. (Sheet 10 of 12)

```
C____________________________________
C
C CHECK FOR MAXIMUM RESIDUAL
C____________________________________

      MR=0.0
      DO 255,R=1,6
       DO 253,C=2,14
         MRN=(HN(R,C)-H(R,C))
         MRA=ABS(MRN)
         IF (MRA.GT.MR) THEN
           MRX=MRN
           MR=MRA
           RM=R
           CM=C
         ENDIF
253    CONTINUE
255   CONTINUE


C_________________________________
C
C CHECK FOR END DUE TO TOLERANCE OR TRIES
C_________________________________

      IF ((MR.LT.TOL).OR.(ITT.GT.TRIES)) THEN
      WRITE(10,270)
270   FORMAT(1H1,'FINAL H MATRIX')
      CALL DECHO_MAT(H)

      WRITE(10,275) ITT
      WRITE(*,275) ITT
275   FORMAT(1H0,' TOTAL NUMBER OF ITERATIONS ',I10)

      WRITE(10,*) TITLE
      WRITE(*,*) TITLE
      WRITE(*,*)

      GRADIENT=H(3,8)/Z
      WRITE(10,276) GRADIENT
      WRITE(*,276) GRADIENT
276   FORMAT(1H0,' VALUE OF THE GRADIENT AT H(3,8) = ',F9.4)

      WRITE(10,277) H(3,8)
      WRITE(*,277) H(3,8)
277   FORMAT(1H0,'  VALUE OF THE H(3,8) = ',F9.4)

        REWIND (20)
        CLOSE (20)
        REWIND (10)
        CLOSE (10)
```

Figure C5. (Sheet 11 of 12)

```
        DONE=1

      ELSE
        DO 400,R=1,5
        DO 300,C=1,15
          H(R,C)=HN(R,C)
300     CONTINUE
400     CONTINUE

        ITT=ITT+1

        WRITE(*,410) ITT, H(3,8), MRX, RM, CM
410     FORMAT (1X,' ITERATION ',I5,
     &  '  HEAD = ',F9.5,'  MAX RES = ',F9.5,' AT ',I3,',',I3)

      ENDIF

      IF (DONE .EQ. 0) GOTO 2481

      STOP
      END

C--------------------------------------------------------------------
C
C THIS SUBROUTINE DISPLAYS THE CONTENT OF A MATRIX.
C
C--------------------------------------------------------------------

      SUBROUTINE ECHO_MAT(MAT)
      REAL MAT(0:7,0:16)
      INTEGER I,J

      DO 10,I=1,6
      WRITE(10,15) (MAT(I,J),J=1,15)
15       FORMAT(1X,15(G10.4))
10    CONTINUE
      RETURN
      END

      SUBROUTINE DECHO_MAT(MAT)
      DOUBLE PRECISION MAT(0:7,0:16)
      INTEGER I,J

      DO 10,I=1,6
      WRITE(10,15) (MAT(I,J),J=1,15)
15       FORMAT(1X,15(G10.4))
10    CONTINUE
      RETURN
      END
```

Figure C5. (Sheet 12 of 12)

APPENDIX D: COMPARISON OF PROGRAMS

Example Problem

1. In this appendix, a comparison is made among the solutions obtained for a common example problem using the computer programs LEVEE3L, LEVEEIRR, LEVEECOR, and the conventional method. The example selected is the same as that used for Figure 45 in the main text. Foundation conditions are assumed to consist of a 10-ft-thick top blanket overlying an 80-ft-thick substratum. The ratio of the horizontal substratum permeability to the vertical top blanket permeability is assumed to be 1,000. The foundation is assumed to extend 1,500 ft riverside of the levee to an open seepage entrance. The levee base width is assumed to be 300 ft. The foundation is assumed to extend infinitely in the landside direction. The calculated residual head at the levee toe using the conventional method is 8.97 ft.

Comparative Solutions

2. The heads obtained using the computer analyses and conventional analyses are plotted as a function of horizontal distance in Figure D1. Computer solutions for the residual head at the levee toe range from 6.6 to 8.9 ft, a difference of 2.3 ft. Two different segment assumptions are shown for LEVEEIRR in Figure D1. Computer solutions in this example reflect generally lower heads than the conventional solution, a trend also noted in the case studies cited in the main report. These variations are larger than was generally expected at the outset of the research. Reasons for these variations are not completely understood at the time of preparing this report; there are, a number of factors that may contribute. These are discussed below.

Differences in Program Assumptions

3. The programs and the conventional method employ certain fundamentally different assumptions to derive the flow equations. In the conventional method, flow is assumed to be horizontal in one direction in the substratum and is assumed to be vertical in the top stratum. In LEVEE3L, both

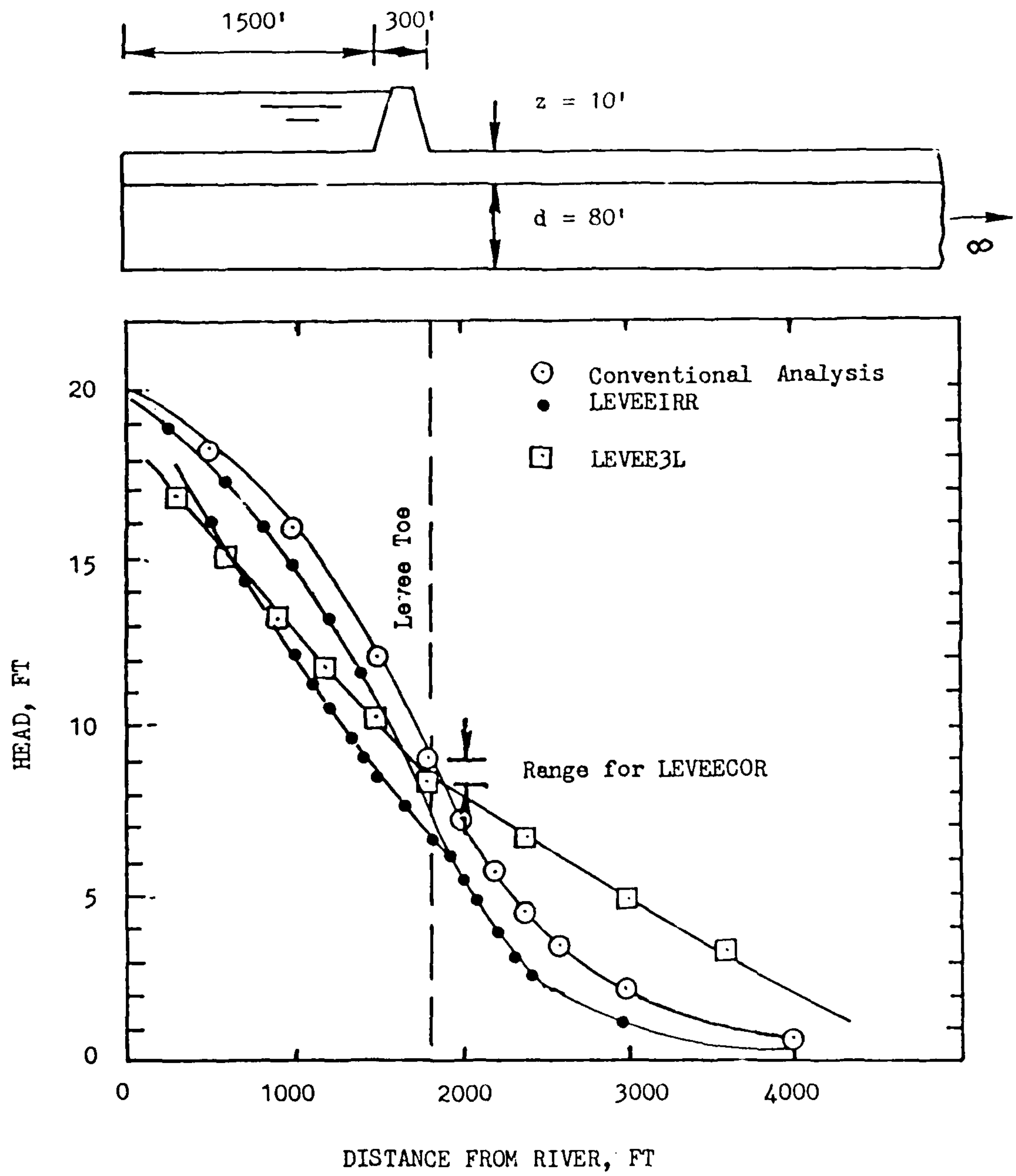

Figure D1. Comparison of results for example problem horizontal and vertical flow is accounted for in each of three layers. In LEVEEIRR, flow assumptions are generally the same as the conventional solution, but the flow equation is still satisfied only approximately at a finite number of points rather than exactly at all points. In LEVEECOR, flow in the substratum is horizontal only, but has two horizontal components, and flow in the top stratum is vertical only. In LEVEE3L and LEVEEIRR, boundaries at an infinite distance must be modeled by using rather large finite distances. Results will vary depending on the boundary distance specified. In LEVEECOR, which most closely matched the conventional solution at the levee toe, the head on the landside boundary is forced to be consistent with the conventional closed-form solution.

Numerical Problems Common to All Programs

4. In each of the three programs, the solution is obtained by iteration. As the tolerance is made smaller and the number of iterations is increased, a more accurate solution is expected. However, this may not always be the case as round-off errors may accumulate where the tolerance or maximum allowable residual is set extremely low. Recommended tolerance values based on limited experience with the programs are given in Appendices A through C. Associated with any finite difference solution is a discretization or truncation error, due to the fact that a continuous system is replaced with a finite system. For the three computer programs developed, the gradients at a node point are represented by a first-order approximation of the derivative of head with respect to distance. The truncation errors could conceivably be reduced and more accurate solutions obtained if higher order approximations were used or if node spacing was significantly reduced. Both of these approaches would increase program complexity or execution time. The present research was viewed as an initial evaluation of the utility of applying numerical methods to underseepage analysis and involved a deliberate effort to produce working versions of three different programs that were fundamentally as simple as possible.

APPENDIX E: NOTATION

c	A constant; inverse of the effective exit distance
d	Thickness of pervious substratum
h_o	Residual head at levee toe
h_x	Net head at distance x landward of levee toe
H	Net head on levee
k_b	Permeability of top blanket
k_{bl}	Permeability of landside top blanket
k_{br}	Permeability of riverside top blanket
k_f	Permeability of pervious substratum
k_{1h}	Horizontal permeability of top blanket in three layer system
k_{1v}	Vertical permeability of top blanket in three layer system
k_{2h}	Horizontal permeability of middle stratum in three layer system
k_{2v}	Vertical permeability of middle stratum in three layer system
k_{3h}	Horizontal permeability of substratum in three layer system
k_{3v}	Vertical permeability of substratum in three layer system
L_1	Distance from riverside toe of levee to open or blocked seepage entrance
L_2	Distance from riverside toe of levee to landside toe
L_3	Distance from landside toe of levee to open or blocked seepage exit
q	Flow
s	Distance from landside levee toe to effective seepage entrance
x_1	Distance from riverside toe of levee to effective seepage entrance
x_2	Distance from riverside toe of levee to landside toe
x_3	Distance from landside toe of levee to effective seepage exit
z	Thickness of top blanket
z_1	Thickness of top blanket in three-layer system
z_2	Thickness of middle stratum

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This report describes a research study in which techniques were developed for prediction of underseepage conditions for special cases of levee and foundation geometry. The differential equations for levee underseepage were derived and programmed in finite difference form for three special cases of boundary conditions. The developed programs allow analyses that are not restricted to the boundary conditions assumed in the conventional, closed form solution, i.e., two foundation layers of uniform thickness with horizontal boundaries.

The three special cases of foundation conditions that can be analyzed are as follow:

a. Foundations consisting of three layers of uniform thickness with horizontal boundaries and differing horizontal and vertical permeability in each layer.

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16. SUPPLEMENTARY NOTATION (Continued).

A report of the Geotechnical problem area of the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Programs. Available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

18. SUBJECT TERMS (Continued).

Analyses	Numerical methods
Foundations	Permeability
Geometry evaluation	Rehabilitation
Irregular boundaries	Underseepage
Levees	

19. ABSTRACT (Continued).

b. Foundations consisting of two layers of nonuniform thickness with irregular boundaries.

c. Levee reaches where the levee alignment bends or forms a corner. Capabilities of the techniques and programs are demonstrated by comparing theoretical solutions to observed performance at eight field locations where piezometric data are available. At each location, the field permeability ratio was estimated by varying program input and seeking a match between the program output and actual observed performance.

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