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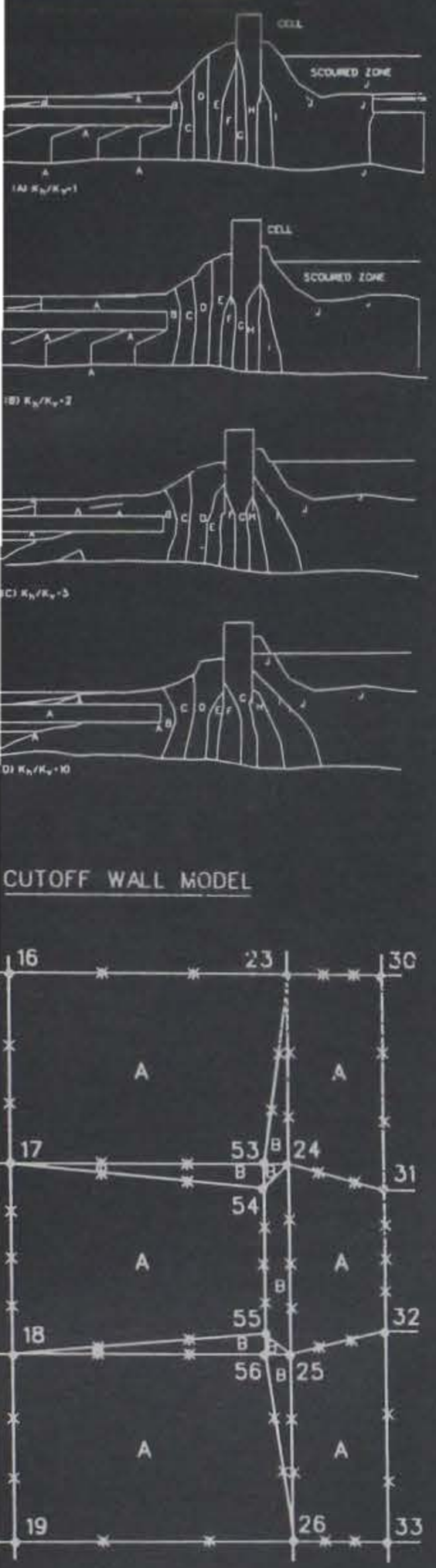


# GEOTECHNICAL ASPECTS OF COMPUTER-AIDED STRUCTURAL ENGINEERING (GCASE) PROJECT

TECHNICAL REPORT ITL-92-6

# APPLICATIONS OF THE FINITE ELEMENT SEEPAGE ANALYSIS CORPS PROGRAM CSEEP (X8202)

by

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Case studies are presented for various applications of the US Army Corps of Engineers (USACE) finite element seepage analysis program, CSEEP (X8202). This report is directed toward the new as well as experienced user of the seepage program and is intended to serve as a supplement to previous USACE Instructional Report, K-83-4, and Miscellaneous Papers, K-77-4 and K-77-5.

Five cases of seepage analyses from recent USACE projects are detailed to show the different aspects of modeling, analysis, and interpretation of results. A discussion of different problems noted by past users of the seepage program is highlighted by drawing upon the USACE projects as examples or for explanation.

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# PREFACE

This technical report documents the various applications of the US Army Corps of Engineers (USACE) seepage analysis program CSEEP (X8202) by using recent USACE projects as examples. The funding for this project was provided to the Information Technology Laboratory (ITL), US Army Engineer Waterways Experiment Station (WES), by Headquarters, Civil Works Directorate, US Army Corps of Engineers (HQUSACE), under the Geotechnical Aspects of Computer-Aided Structural Engineering (GCASE) Project and Numerical Model Maintenance Program.

CASE examples were selected and provided by the members of the GCASE Task Group. The members of the GCASE Task Group are:

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At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander and Deputy Director was COL Leonard G. Hassell, EN.

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## 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 |
|---|---|---|
| cubic feet | 0.02831685 | cubic metres |
| cubic yards | 0.7645549 | cubic metres |
| degrees (angle) | 0.01745329 | radians |
| feet | 0.3048000 | metres |

# APPLICATIONS OF THE FINITE ELEMENT SEEPAGE ANALYSIS CORPS PROGRAM CSEEP (X8202)

## PART I: INTRODUCTION

1. This report presents case studies of seepage analyses using the US Army Corps of Engineers (USACE) finite element (FE) seepage package. These programs were developed by Dr. Fred Tracy, Information Technology Laboratory (ITL), US Army Engineer Waterways Experiment Station (WES), and are documented by Miscellaneous Papers K-77-4 and K-77-5 and Instruction Report K-83-4 (Tracy 1977a, b, and 1983). These reports also contain the user manuals for the programs.

### Purpose

2. This report is directed toward the new and the experienced user of the seepage program, therefore some parts may seem trivial, while others are more difficult for the reader. It is assumed that the reader of this report and user of the seepage program is familiar with the contents of the program manuals listed in paragraph 1. Therefore, data file input and use of commands in the programs are not emphasized. This report is to serve as a supplement to the previously mentioned reports and is not intended or written for use as a replacement or substitute.

### Seepage Package

3. CSEEP is the term used for the personal computer version of the seepage package. In this report, the three programs which make up the package - the finite element preprocessor (X8200), postprocessor (X8201), and FE seepage analysis (X8202) - are referred to collectively as CSEEP, regardless of what computer system one uses. These programs are maintained on the CORPS (Conversationally Oriented, Real-time Programming System) Library at WES in versions for use on the IBM-compatable PC and the Intergraph Workstation.

## Report Content

4. Five examples of seepage analysis are presented in Part II. These cases are or have been projects of the USACE. Different aspects of modeling, analysis, or interpretation of results are presented in each example.

5. Part III is a discussion of different problems noted by past users of the programs. This discussion draws upon many of the cases in Part II as examples or for explanation.

## PART II: EXAMPLES OF FINITE ELEMENT SEEPAGE ANALYSES

6. This part contains five examples of seepage analyses performed for Corps of Engineer projects using the FE seepage package CSEEP. The example problems and their contributors are:

a. Seepage Analysis of Unconfined Flow Through an Earthen Dam (Pace 1983).

b. Old River Control Structure - Seepage Analysis of Cofferdam Embankment for Stilling Basin Dewatering (Mosher and Noddin 1987a).

c. S.A. Murray Hydroelectric Station - 2D Plan View Seepage Analysis (Mosher and Noddin 1987b).

d. Seepage Analysis at Cellular Cofferdam Section, Lock and Dam 26-R (Wolff 1989).

e. Seepage Under U-Frame Channel for Drainage System Design (Strohm 1990).

For each example, a description is given of the project, materials, grid development, data file development, analysis procedure, and results.

7. In Example Problem 1, details about preparing the input files and running the CSEEP programs are presented. Such detail is not repeated for the other examples. Each example has some unique characteristics dealing with modeling, analysis procedure, or results interpretation. It is suggested that each problem be read thoroughly for a full understanding of the different aspects and features of the seepage analysis.

### Example Problem 1

8. This is an analysis of unconfined flow through a multilayered earth dam founded on rock with inclined joints. The model includes drains, sand blankets, and a grout curtain below the core. More detail on data file preparation is given in this example than in the other examples.

#### Description of Problem 1

9. Figure 1 shows a section of the dam to be analyzed. Six different materials and their permeabilities are also listed. The horizontal permeabilities range from $9.84 \times 10^{-1}$ to $9.84 \times 10^{-5}$ ft/min.* Some of the materials are anisotropic. The rock has fractures and bedding planes angled at 140 deg

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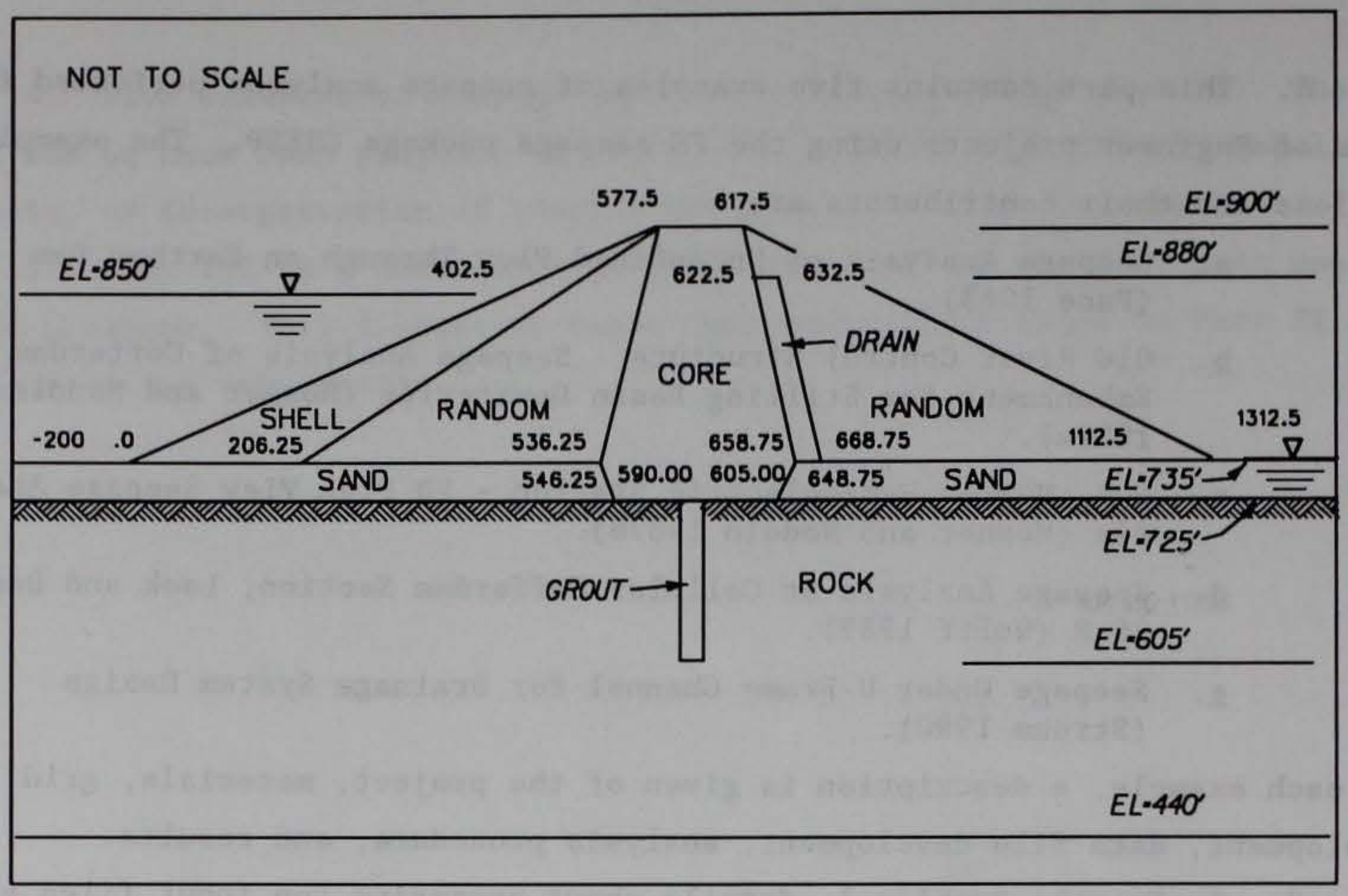
* A table for converting non-SI units of measurement to SI (metric) units is presented on 6.



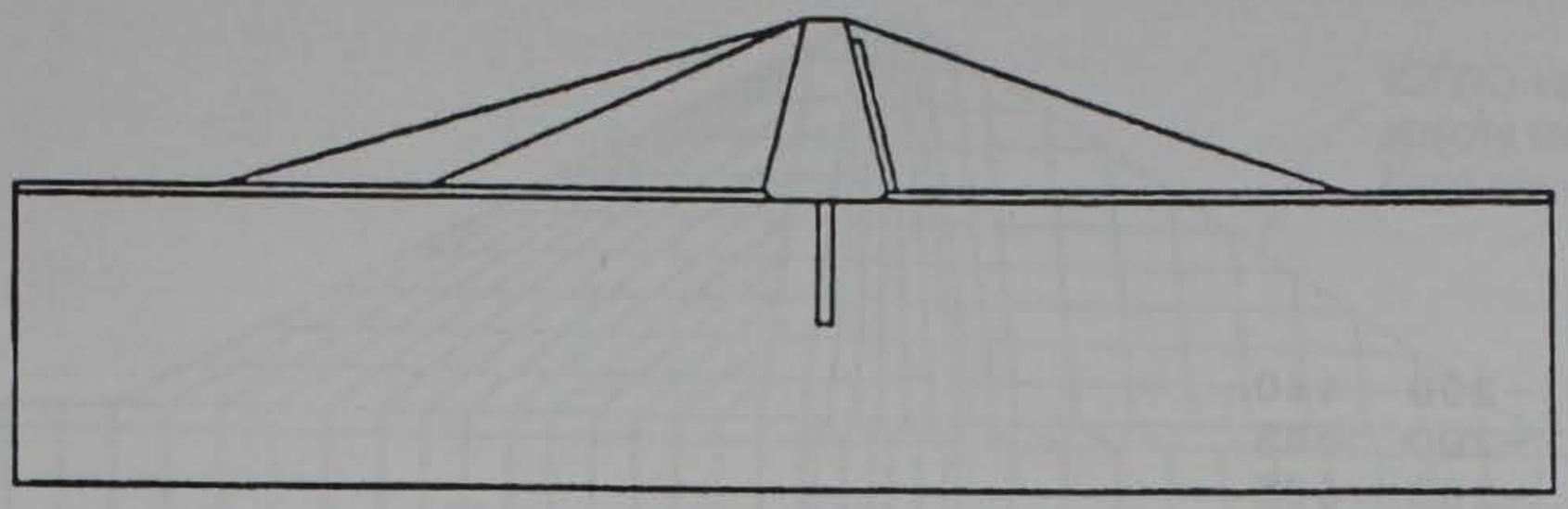

| MATERIAL NO. | MATERIAL | PERMEABILITIES (ft/min) $K_H$ | $K_V$ | ANGLE (deg) |
|---|---|---|---|---|
| 1 | ROCK | $9.843 \times 10^{-2}$ | $1.969 \times 10^{-2}$ | 140 |
| 2 | SAND & DRAIN | $9.843 \times 10^{-2}$ | $1.969 \times 10^{-2}$ | 0 |
| 3 | RANDOM | $9.843 \times 10^{-3}$ | $9.843 \times 10^{-3}$ | 0 |
| 4 | CORE | $9.843 \times 10^{-5}$ | $1.969 \times 10^{-5}$ | 0 |
| 5 | SHELL | $9.843 \times 10^{-1}$ | $9.843 \times 10^{-1}$ | 0 |
| 6 | GROUTED ZONE | $9.843 \times 10^{-3}$ | $1.969 \times 10^{-3}$ | 140 |

Figure 1. Dam section for example problem 1

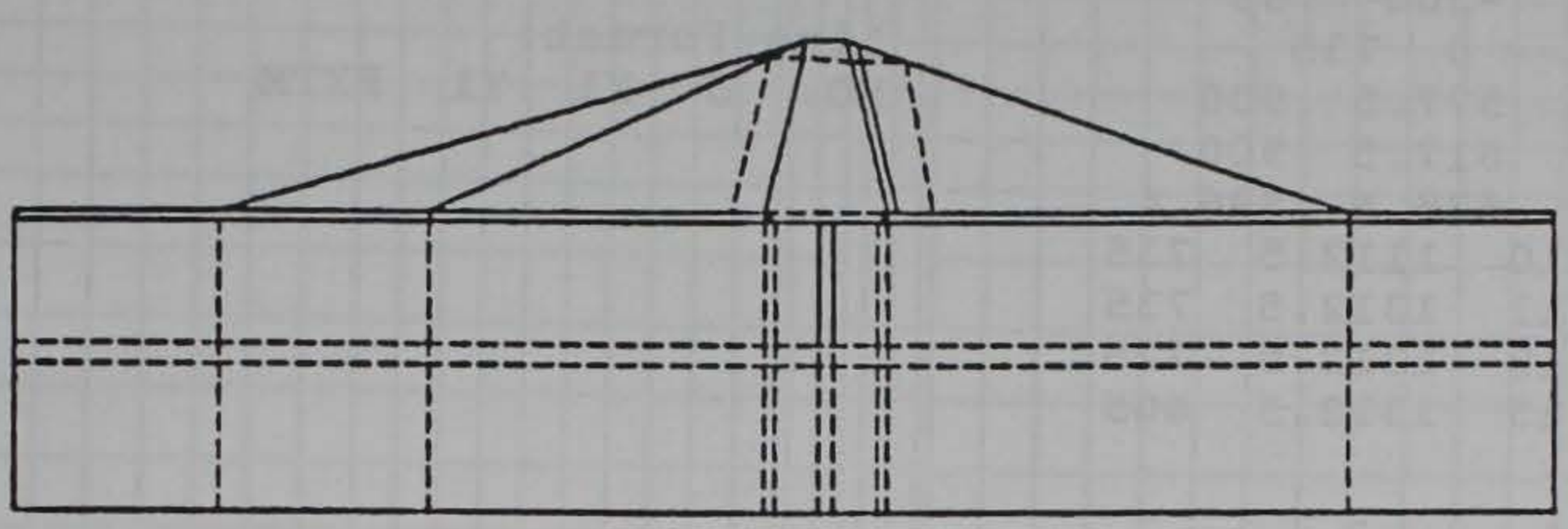
from the horizontal. CSEEP allows input of an angle for the "major" permeability. The "minor" permeability is taken at 90 deg from the major permeability angle. For the rock and grout, 140 deg is the major permeability angle. Total head difference for this dam is 115 ft.

FE grid

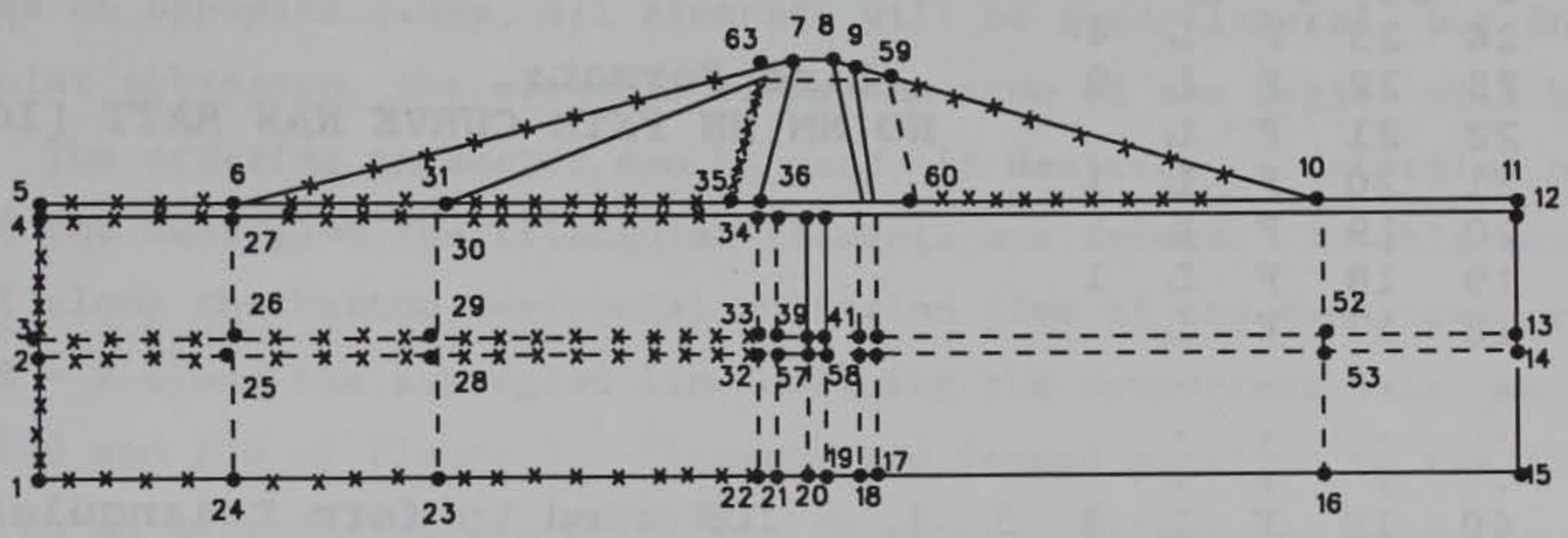
10. The section to be analyzed is partitioned into subdivisions shown in Figure 2. These partitions are simple geometric shapes which follow the material boundaries. Temporary lines are used in some places so that they may be moved slightly when the grid is smoothed. These are internal lines other than material boundaries or exterior borders which define the model. Figure 3 lists part of the input data file defining the subregion points and lines.



a. Profile outline



b. Partitions (temporary lines are dashed)




c. Some additional nodes and subregion points labeled

Figure 2. Partitions and nodes for section model

11. The generated grid is shown in Figure 4. Elements have roughly the same size throughout the grid. The elements in the dam on the left size of the core do not have the same pattern as those on the right side of the core. This will not affect the analysis results, but may look unusual. Generally, symmetric or "even" grids are desired. The grid here shows the function of the ordering parameter, IOR, an optional command in the input file. The ordering parameter allows the user to control the order in which the elements are formed in a subregion. In a quadrilateral subregion with an equal number

```
10   1   -200   440
20   2   -200   585
30   3   -200   605
40   4   -200   725
50   5   -200   735
60   6    0     735
70   7   577.5   900
80   8   617.5   900
90   9   628.4   896.4
100   10   1112.5   735
110   11   1312.5   735
120   12   1312.5   725
130   13   1312.5   605
 .    .      .       .
 .    .      .       .
 .    .      .       .
520   -1
530   1   24   F   L   4   1
540   24   23   F   L   4
550   23   22   F   L   9
560   22   21   F   L
570   21   20   F   L   1
580   20   19   F   L
590   19   18   F   L   1
600   18   17   F   L
 .    .    .    .   .
 .    .    .    .   .
 .    .    .    .   .
840   60   10   F   L   8   3   1
850   10   59   F   L   8   3   2
 .    .    .    .   .
 .    .    .    .   .
 .    .    .    .   .
1460   57   58   T   L
1470   58   43   T   L   1
1480   57   39   T   L
1490   58   41   T   L
1500   20   57   T   L   4
1510   19   58   T   L   4
```

**Line Format:**

**NO. J X1 Y1 FXTM**

**Line Format:**

**NO MM NN FXTM CURVE NAN MATT [IOR]**

IOR used to form triangular elements on downstream face.

**(See preprocessor user manual for description of line items)**

Figure 3. Input data file for problem 1

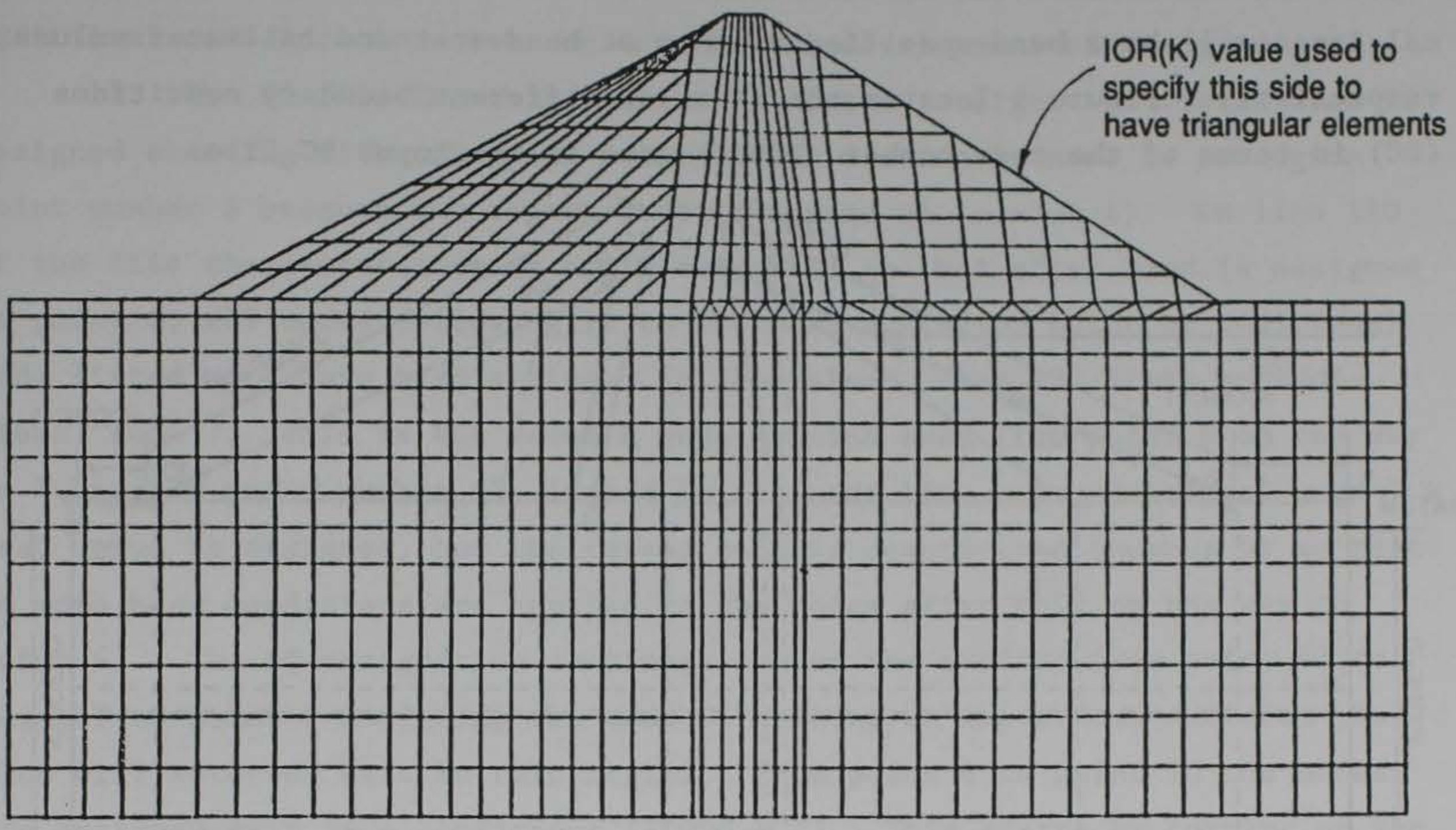



Figure 4. Grid generated for dam section of example problem 1

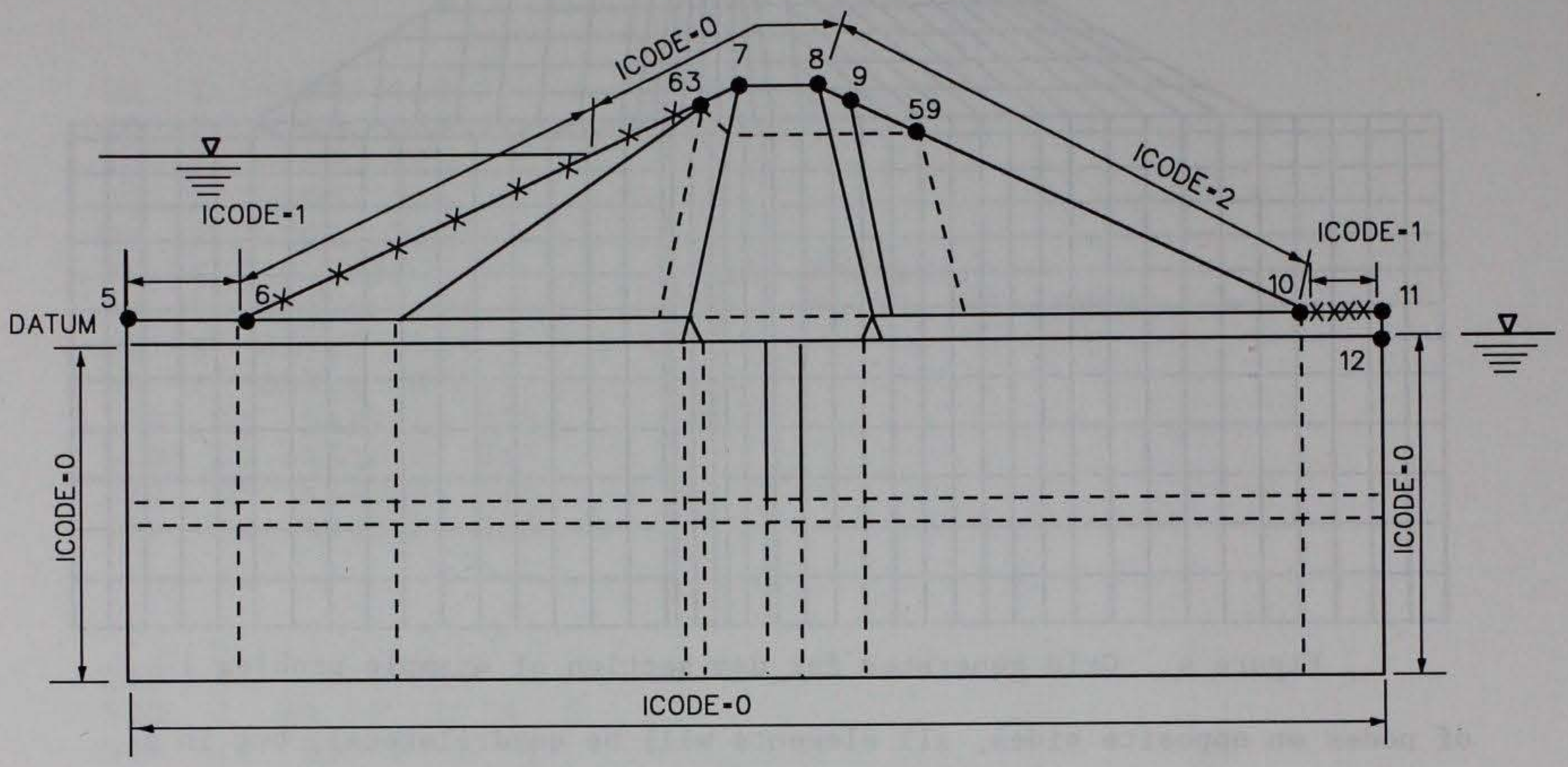
of nodes on opposite sides, all elements will be quadrilateral, but in a triangular subregion, the elements along one side of the region will be triangular. The ordering parameter can be used, if desired, to determine on which side of the subregion the triangular elements are formed. In this case, IOR = 1 along the bottom horizontal subregion line of the downstream region, and IOR = 2 along the subregion line defining the downstream face, as shown in lines 840 and 850 of Figure 3. Elements are formed parallel to the line segment with an ordering parameter of 1. Therefore, triangular elements in this subregion are formed adjacent to the line segment coded 2.

12. In the upstream triangular subregion the code 2 was assigned to the side adjacent to the core, so triangular elements were formed along this side.

Boundary conditions

13. This is an unconfined flow problem. Headwater, tailwater, and an exit surface must be specified. Headwater is modeled along the upstream surface of the sand and the dam face. Tailwater is modeled along the downstream sand surface. Total head, with respect to a predetermined datum, is the value used for input. An exit surface is represented along the downstream slope of the dam face since flow could possibly exit anywhere along this face. The bottom and the two sides of the rock base are modeled as impervious boundaries in this demonstration problem. Ordinarily, the region of flow extends well

beyond the dam in both the upstream and downstream directions, and the vertical faces will have head specified on them at headwater and tailwater values, respectively. Figure 5 locates the areas of different boundary conditions (BC) in terms of the code number (ICODE) used in the input BC file.




| ICODE | BOUNDARY CONDITION |
|---|---|
| 0 | IMPERVIOUS |
| 1 | HEAD |
| 2 | EXIT SURFACE |

Figure 5. Codes used in the preprocessor boundary conditions file

14. The boundary code for head (ICODE = 1) should be applied to each node along the exterior boundary where head occurs. In the BC data file this is usually accomplished by assigning total head from one subregion point to another and activating the repeat code so that each node between the two points will have this condition applied. However, in this problem the specified head condition ends between the two subregion points of the upstream dam face. To account for this, the number of additional nodes between these subregion points was selected so that one would be generated at the location where the water intersects the dam face. The grid generator spaces additional nodes evenly along a subregion line if the linear spacing option is used. By choosing the number of nodes appropriately, the user can determine their generated locations. In the BC data file for this problem, head is specified for nodes between (and including) the subregion point at the dam toe and the

additional node generated where the water meets the dam. Consideration of additional node locations must be done in the development of the grid.

15. The BC file for this problem is listed in Figure 6. Total head is assigned starting with subregion point number 5 and continues to subregion point number 6 because the repeat code is turned on (number 1). On line 110 of the file the repeat code is again activated so that after head is assigned at point 6, all nodes following it to the next subregion point or additional node listed will have head assigned to them also. Line 120 lists an additional node 7. This is the seventh node counted away from point 6 on the way to subregion point number 63, listed in the next line. At additional node 7 a head value is assigned, but the repeat code is deactivated (number 0) so that no more head conditions are applied to the nodes after this on the way to point 63. The BC designation continues around the surface from point 63 to point 7 to point 8 assigning the code 0, meaning an impervious surface. No flow will enter or exit in this region. From point 8 to point 10 the nodes are assigned exit face conditions (ICODE = 2). This starts by turning on the repeat code at point 8 in the BC file and keeping it on until point 10 is reached. The first additional node after point 10 on the way to point 11 is assigned a head condition. This is repeated to point 11 at which the repeat flag is turned off. All remaining boundary nodes are automatically assigned the boundary condition code 0, which is an impervious condition.

Seepage analysis input file

16. The output file from the preprocessor contains all the generated node x-y coordinates, generated element information (surrounding node numbers and material type number), and boundary conditions (code and value) for each node. This is done so the user does not have to type the file himself.

```
100   P   5   1   1   115
110   P   6   1   1   115
120   A   7   0   1   115
130   P   63   1   0
140   P   7   0   0
150   P   8   1   2
150   P   9   1   2
160   P   59   1   2
170   P   10   0   2
180   A   1   1   1   0
190   P   11   0   1   0
```

Figure 6. Boundary conditions data file for example problem 1

17. The file is not complete, however, as it comes out of the preprocessor. More information is required for the seepage analysis. This can be provided in one of two ways. One way is to use an editor or word processor to edit the file and add the required information in the proper format (as described in the user guide, Report K-83-4 (Tracy 1983)). The other, easier way is to enter the seepage analysis part of CSEEP and respond "Yes" to the question "DOES FILE NEED TO BE EDITED?". The user is prompted for the required information and types it in. It is then written by the CSEEP program to the input file in the proper format. The sequence of these editing questions for this example problem is shown in Figure 7.

Analysis procedure

18. Two cases for Problem 1 ware analyzed. Initially, the problem was analyzed with all materials having the same permeability in both the major and minor directions. This was done to check the grid and BC. For instance, if an impervious BC was accidentally applied to a flow region or exit surface, the plotted vectors and contours of the results would indicate this error. If a flow net of this simple case was plotted, curvilinear squares should result since homogeneous, isotropic conditions are modeled. After checking for correct modeling, the true permeability values were applied to all the materials and the problem was reanalyzed.

Results - homogeneous, isotropic case

19. After the seepage analysis is performed the postprocessor is used to view the results. It is usually helpful to look at the plots of vectors, head contours, and the flow net (if requested in the analysis program).

20. Vectors show the direction and relative velocity of flow in each element. The vector plot for the uniform permeability analysis is shown in Figure 8. The top outline of all plots shown in the postprocessor is the phreatic surface. It can be helpful to draw the outline of the section onto the plot by hand as shown in Figure 8. The vectors show fairly uniform velocity throughout the region, with exceptions at the upstream entrance near the top of the dam and the downstream exit at the toe. A "window" plot of the top of the dam enlarged using the "big" plot option, Figure 9, shows what is happening in this region. The largest vector, which appears to show flow from the phreatic surface sharply downward toward the sand blanket just above the toe, is actually an anomaly. The FE grid is adjusted to fit along the phreatic surface, and this sometimes created skewed elements. While most of these are eliminated, sometimes one remains that generates poor discharge

```
ENTER INPUT FILENAME (PREPROCESSOR OUTPUT FILE)
= P1OUT

DOES FILE NEED TO BE EDITED?
= YES
```

[Answering YES causes the following questions to be asked, otherwise it is assumed this information has already been put in the input file and the query sequence skips to the last two questions shown on this page.]

```
ENTER IDENTIFICATION LINE
= UNCONFINED FLOW THROUGH DAM

ENTER NUMBER OF DISCHARGE VELOCITY CARDS
= 0  [This will almost always be zero since this option is
      rarely used.  It could, however, be used to specify
      an infiltration rate or the flow from a well or
      slot.]

ENTER AXSY OR PLNE
= PLNE  [Plane flow problem, not axisymmetric]

ENTER ELEVATION OF DATUM
= 735  [Datum is arbitrary, but the boundary
        condition file must be written with respect
        to this datum]

DO YOU WANT A FLOW NET?
= N  [a flow net cannot always be computed for more
      than one material]

ENTER SOIL TYPE DATA
NSOIL,  K1,  K2,  ANGLE  [mat. #, major permeability,
                          minor perm., angle of major
                          perm.]

= 1  9.843E-2  1.969E-2   140
= 2  9.843E-2  1.969E-2   0
= 3  9.843E-3  9.843E-3   0
= 4  9.843E-4  1.969E-5   0
= 5  9.843E-1  9.843E-1   0
= 6  9.843E-3  1.969E-3   140

WHAT IS PRINT-OUT OUTPUT FILE NAME?
= P1PRT

WHAT IS OUTPUT FILENAME (POSTPROCESSOR INPUT FILE)?
= P1PP
```

Figure 7. Question-and-answer sequence for editing the input file in the Seepage Analysis Program

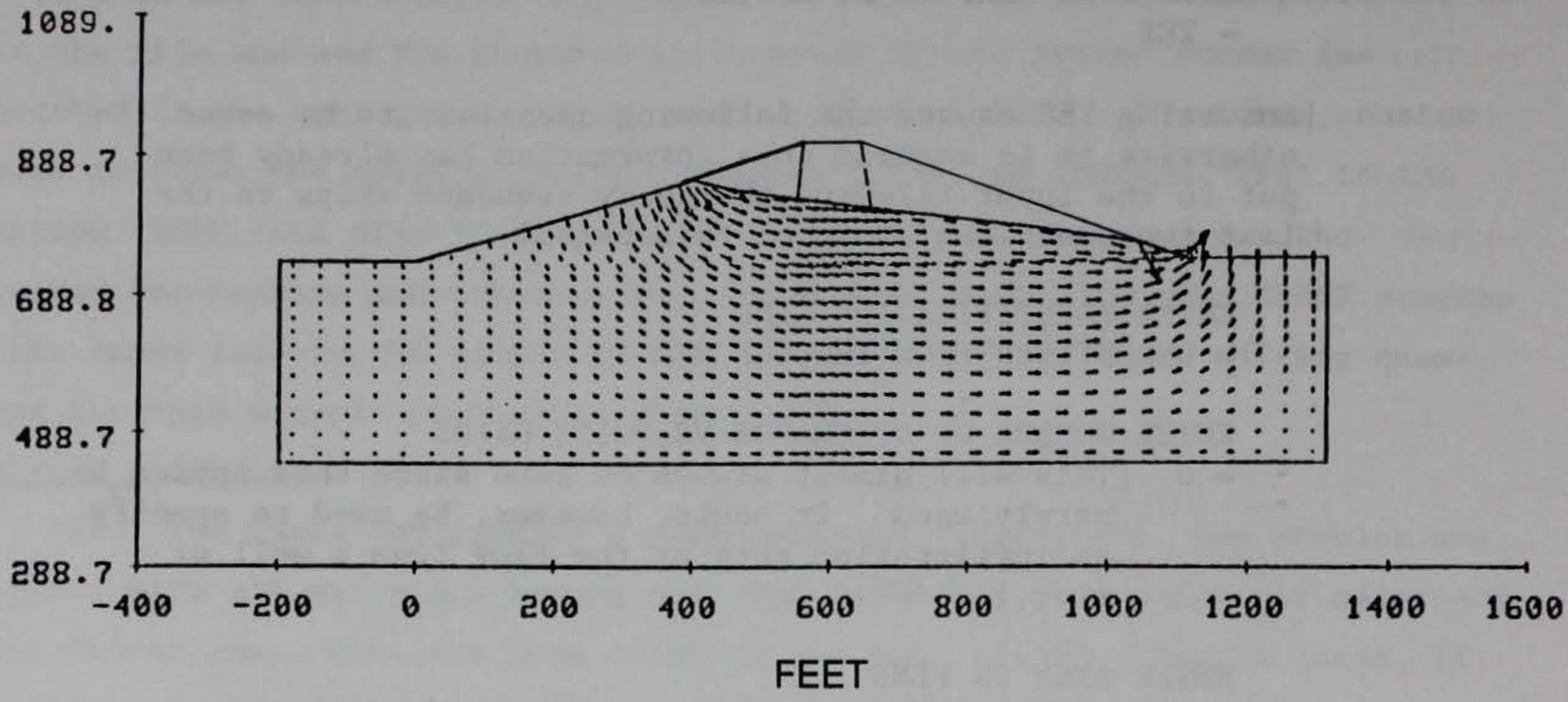



Figure 8. Velocity vectors for homogeneous, isotropic conditions, example problem 1

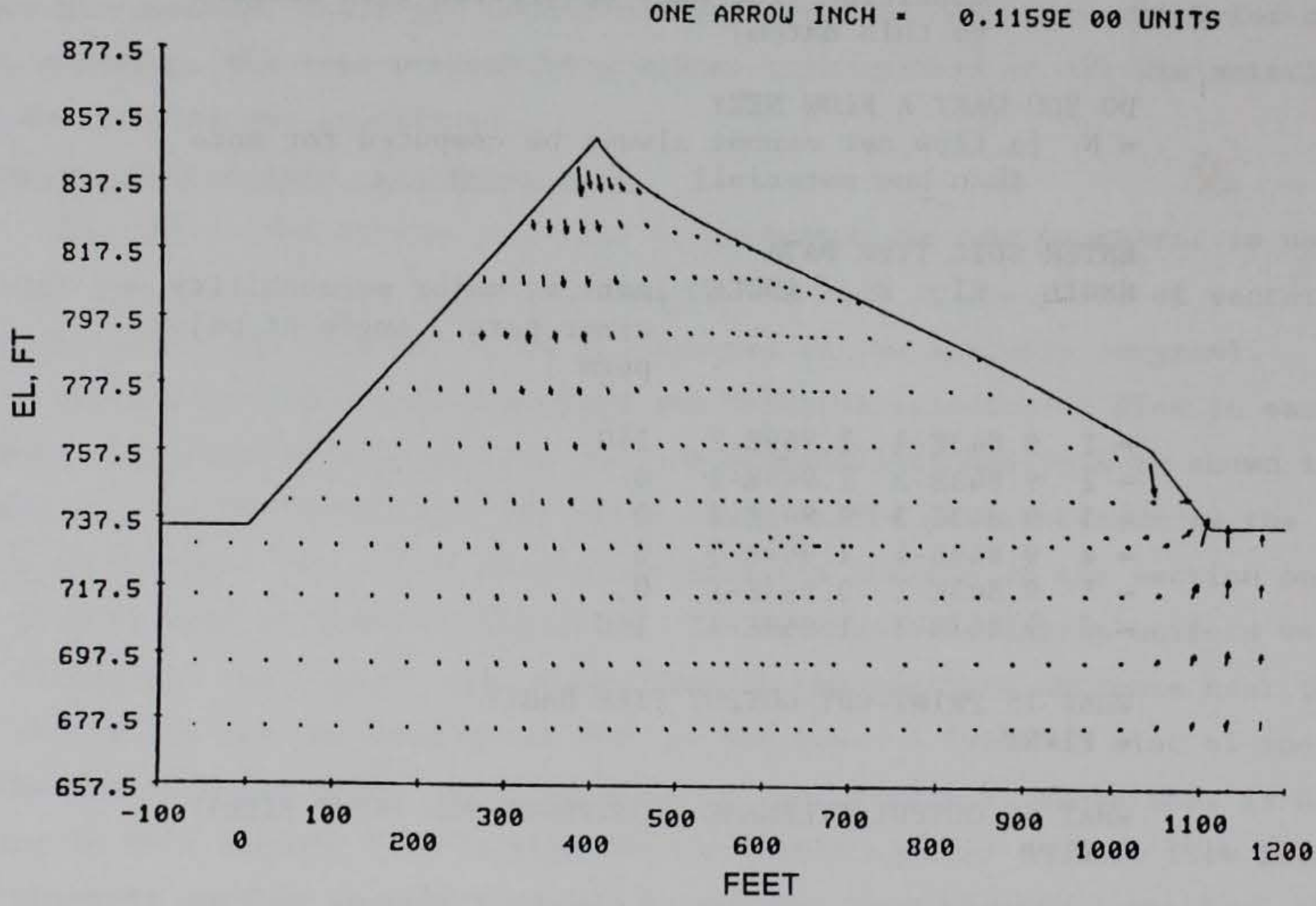



Figure 9. Enlarged plot of the top of the dam shown in Figure 8 (NTS)

velocities. What must be done is (1) change the criteria for removing skewed elements and (2) change the technique of computing discharge velocity by using a true planar triangular element instead of the collapsed four-node isoparametric element formulation. It is important to note that the quality of the head values is not affected by this process.

21. Head contours are simply the equipotential drops through the flow region, essentially, one-half of the flow net. Contours of total head for the uniform permeability analysis are shown in Figure 10. The contours occur at almost equal distances across the model.

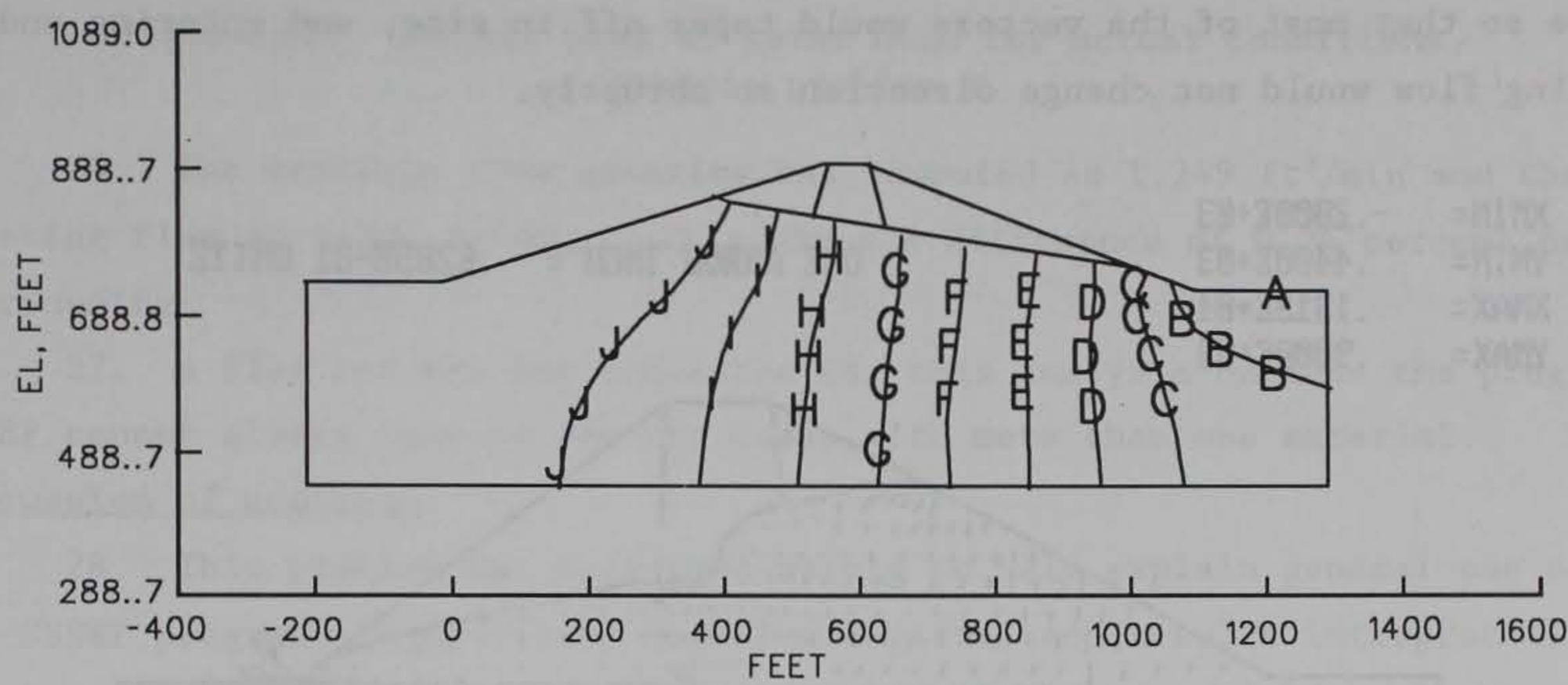



Figure 10. Contour plot of total head for homogeneous, isotropic conditions, example problem 1

22. These plots indicate that the BC have been represented correctly. The model is ready for the final analysis.

Results - nonhomogeneous, anisotropic case

23. To rerun the analysis with different permeability values the input file was edited with a word processor. The only editing required was to change material permeabilities and angles to the desired values. The seepage analysis was started, and this time the question about editing the input file was answered "No".

24. The vector plot of the final analysis with the true permeability values is shown in Figure 11. The outline of the dam and the core again have been sketched in for clarity. The core restricts flow almost completely. Most flow is through the sand blankets and the rock. The grout curtain is not very effective in altering flow; its permeability is not much different from the surrounding rock. These vectors also indicate that the model should have been extended more to the right, and possibly more to the left and deeper. The vertical vectors at the side boundaries are of the same size (same flow rate) as most of the interior vectors. The vectors at the base of the model are not much smaller than those above them. Unless these boundaries represent the true field conditions, they should have been extended to a greater distance so that most of the vectors would taper off in size, and entering and exiting flow would not change direction so abruptly.

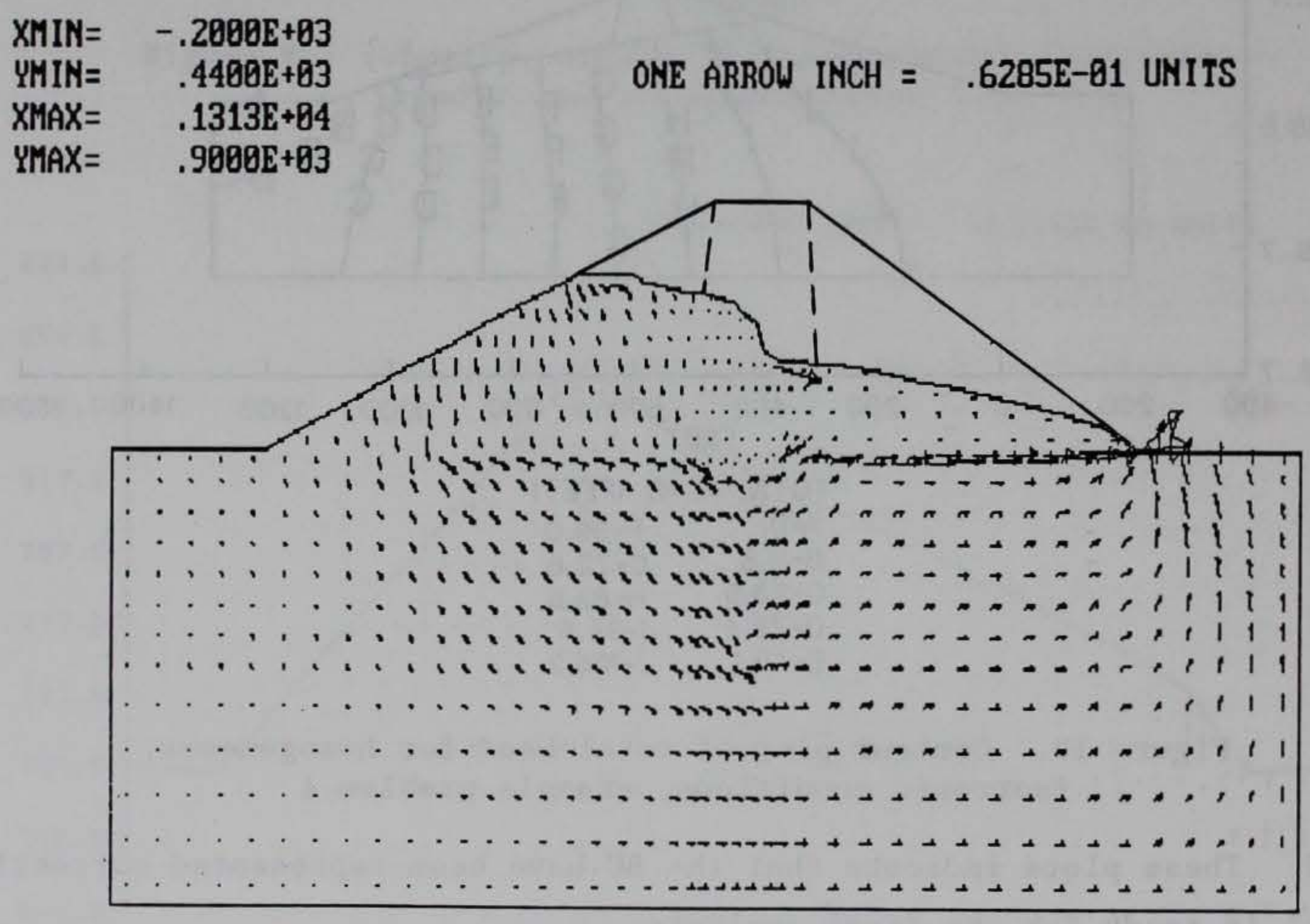



Figure 11. Velocity vectors for actual conditions, example problem 1 ("big" plot - not to scale)

25. Total head contours are shown in Figure 12. As seen from the phreatic surface and the spacing of the contours, the head drop is immediate at the core, then more uniform along the toe of the dam. The interface between the different materials, in particular the sand blanket and the rock, can be detected by the bend in each contour line.

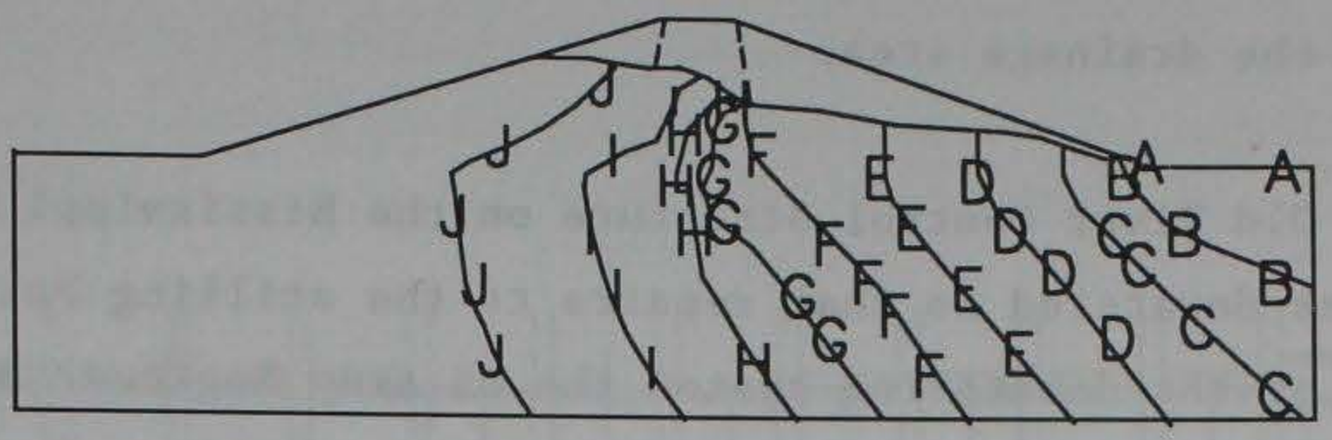



Figure 12. Contour plot of total head for actual conditions, example problem 1

26. The entering flow quantity was computed as 1.249 $ft^3$/min and the existing flow at 1.252 $ft^3$/min. This gives a difference of 0.24 percent due to rounding.

27. A flow net was not requested for this analysis because the program CSEEP cannot always compute one for cases with more than one material.

Discussion of analysis

28. This problem was performed mainly to help explain general use of the CSEEP programs, data files, modeling aspects, and results interpretation. A relatively complex geometry was modeled and aspects of the input such as the ordering parameter and additional nodes were discussed. Interpretation of the results is most readily performed by viewing plots of flow vectors and head contours using the postprocessor. Plots can help to quickly identify errors in the boundary conditions, areas of the grid that need refinement, and relative differences between different regions of the grid. For specific values, the numbers can be plotted, or the printed output can be used.

## Example Problem 2

29. This is an example of unconfined flow through an earthen cofferdam of sand on a riprap layer. Interesting aspects of the modeling include a sheetpiling and a drainage area at the toe of the embankment. In this problem, a "simplified" model is initially developed to help evaluate assumptions

and to help prepare a final model. Results are used to compute flow and exit gradients into the drainage area.

Background

30. The Old River Control Structure on the Mississippi River below Natchez, MS, was dewatered so that repairs to the stilling basin could be made. As part of the dewatering system the US Army Engineer District, New Orleans, constructed three embankment sections to form a cofferdam for the stilling basin. These embankment sections were formed by the hydraulic placement of roughly 425,000 cu yd of sand over the riprap at the downstream end of the stilling basin. The embankments were designed to have toe drains with collector pipes to intercept the underseepage which would then be pumped out.

31. The purpose of this investigation was to perform seepage analyses of the three embankment sections of the proposed cofferdam using the FE method. The specific information desired for each embankment section was: (a) the quantity of seepage needed to determine pumping requirements from a collector pipe at the toe of the embankment, and (b) the exit gradients needed to check for critical conditions or failure potential at the toe.

Site description

32. The stilling basin is divided into three bays: high north bay, high south bay, and low center bay. Each bay is separated from the others by concrete walls. An embankment is constructed downstream of the stilling basin in each bay. The embankments have different profiles and are modeled separately. The total head difference is 27 ft at the north and south bays and 34 ft at the center bay. All three cofferdam embankments have the same materials. The low center bay section was the most complex and had the greatest head difference of the three embankments, therefore it was considered the most critical section. The analysis of this section is presented in detail here, while analyses of the other sections are summarized.

33. Figure 13 shows the plan view of the site. Figure 14 is a section view of the low center bay profile. The sand, riprap, and silt permeabilities are listed in Table 1.

Modeling considerations
of low center bay section

34. It was anticipated that the majority of flow would take place through the riprap and that the base silt would have minimal flow. The phreatic surface through the sand of the embankment would be determined from the FE analysis. The sheetpiling at the end of the stilling basin was expected to

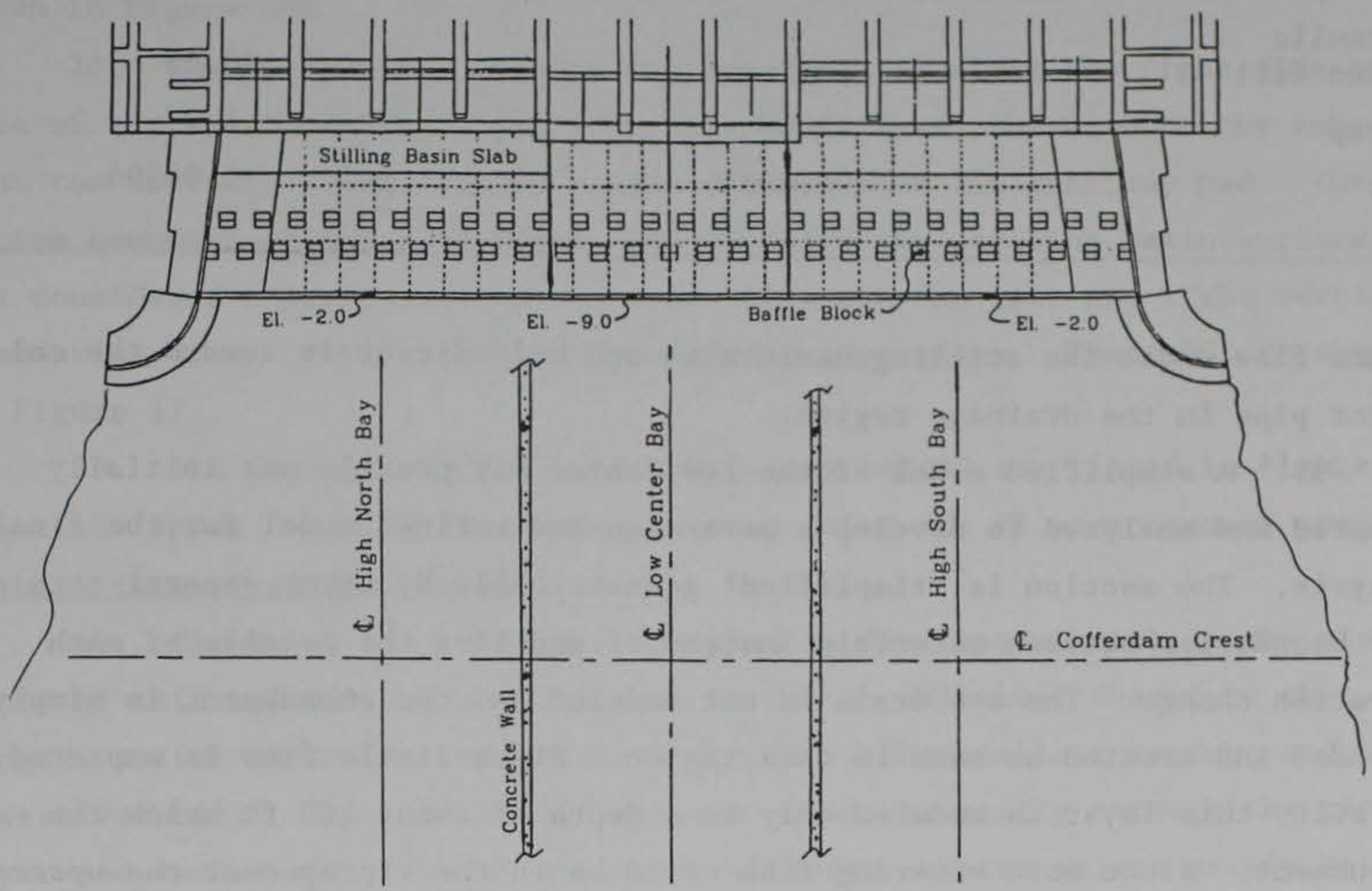



Figure 13. Plan view of stilling basin and cofferdam modeled in example problem 2

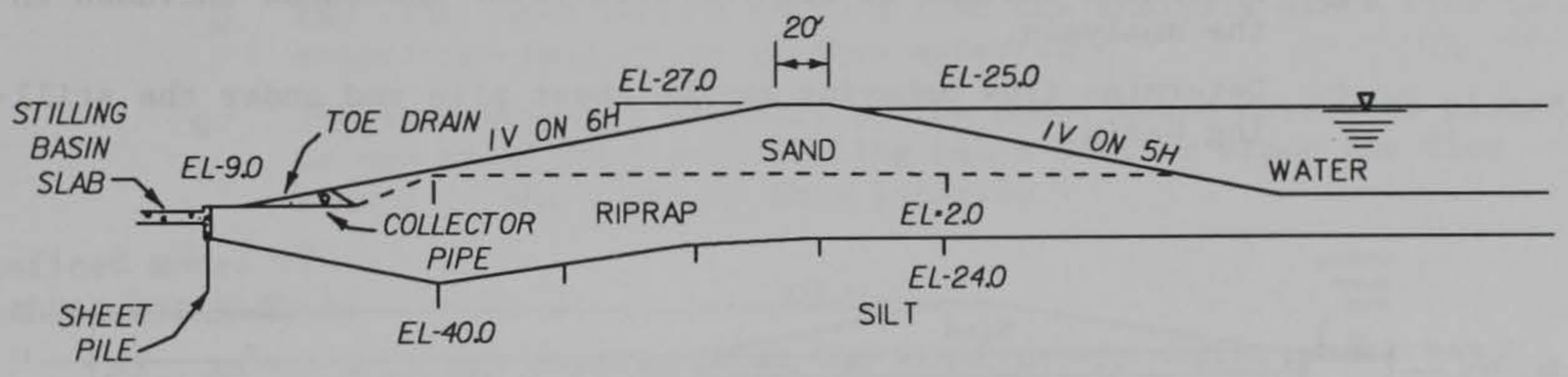



Figure 14. Section view along center line of low center bay embankment

Table 1

Material Permeabilities for Example Problem 2

| Material Type | Horizontal Permeability (feet/minute) | Vertical Permeability (feet/minute) |
|---|---|---|
| Hydraulic sand fill | 0.2 | 0.05 |
| Riprap | 1.0 | 1.0 |
| Silt | 0.00354 | 0.00394 |

reduce flow under the stilling basin slab and help direct it toward the collector pipe in the drainage region.

35. A simplified model of the low center bay profile was initially prepared and analyzed to develop a more accurate refined model for the final analysis. The section is "simplified" geometrically by using general straight line boundaries between materials instead of modeling the details of each elevation change. The toe drain is not modeled and the embankment is simply extended and treated as sand in this region. Since little flow is expected in the silt, this layer is modeled only to a depth of about 100 ft below the embankment. Since most entering flow would be in the riprap near the upstream toe, the upstream extent of the grid is only about one and one-half times the width of the embankment.

36. The simplified profile is shown in Figure 15. This model would help to:

a. Determine appropriate proportions for the FE grid.

b. Determine whether or not the silt layer should be included in the analysis.

c. Determine flow behavior at the sheet pile and under the stilling basin.

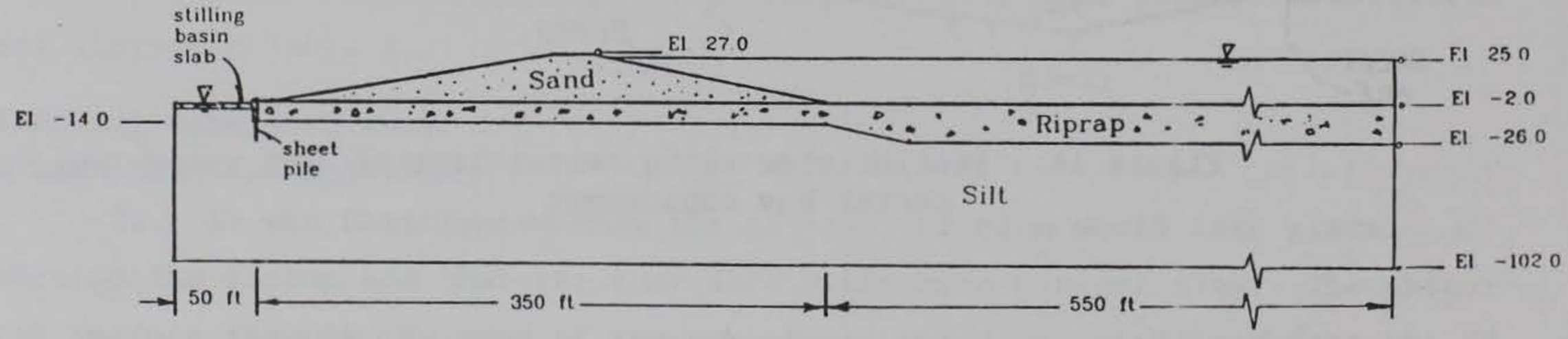



Figure 15. Simplified profile of low center bay for FE modeling

FE grid of simplified model

37. To develop an FE grid of this profile with the preprocessor the profile was divided into polygonal subregions. These subregions and additional node locations are shown in Figure 16a. The sheet pile is modeled as shown in Figure 16b.

38. The BC for this problem include the head along the right-side surface of riprap and up the right-side embankment face, the head at the embankment toe drainage area, and the confined head under the spillway pad. The bottom boundary of the silt layer, 100 ft below the stilling basin surface, was considered impervious, and the sheet pile and the left and right vertical boundaries of the model were also considered impervious. These BC are shown in Figure 17.

39. The input data files for subregions and BC are listed in Figure 18. Figure 19 shows the grid that was generated using the FE preprocessor program.

Results from simplified model

40. Figure 20 shows vectors of velocity (in feet/minute) in the elements of this model. The size of each vector is relative, therefore the longest vector indicates the greatest velocity, the smallest vector, and the lowest velocity. This shows that seepage occurs primarily through the riprap layer and secondarily through the sand cofferdam. Water exists mainly between the left toe of the cofferdam and the end of the stilling basin and sheet pile.

41. The analysis results of the simplified model show that:

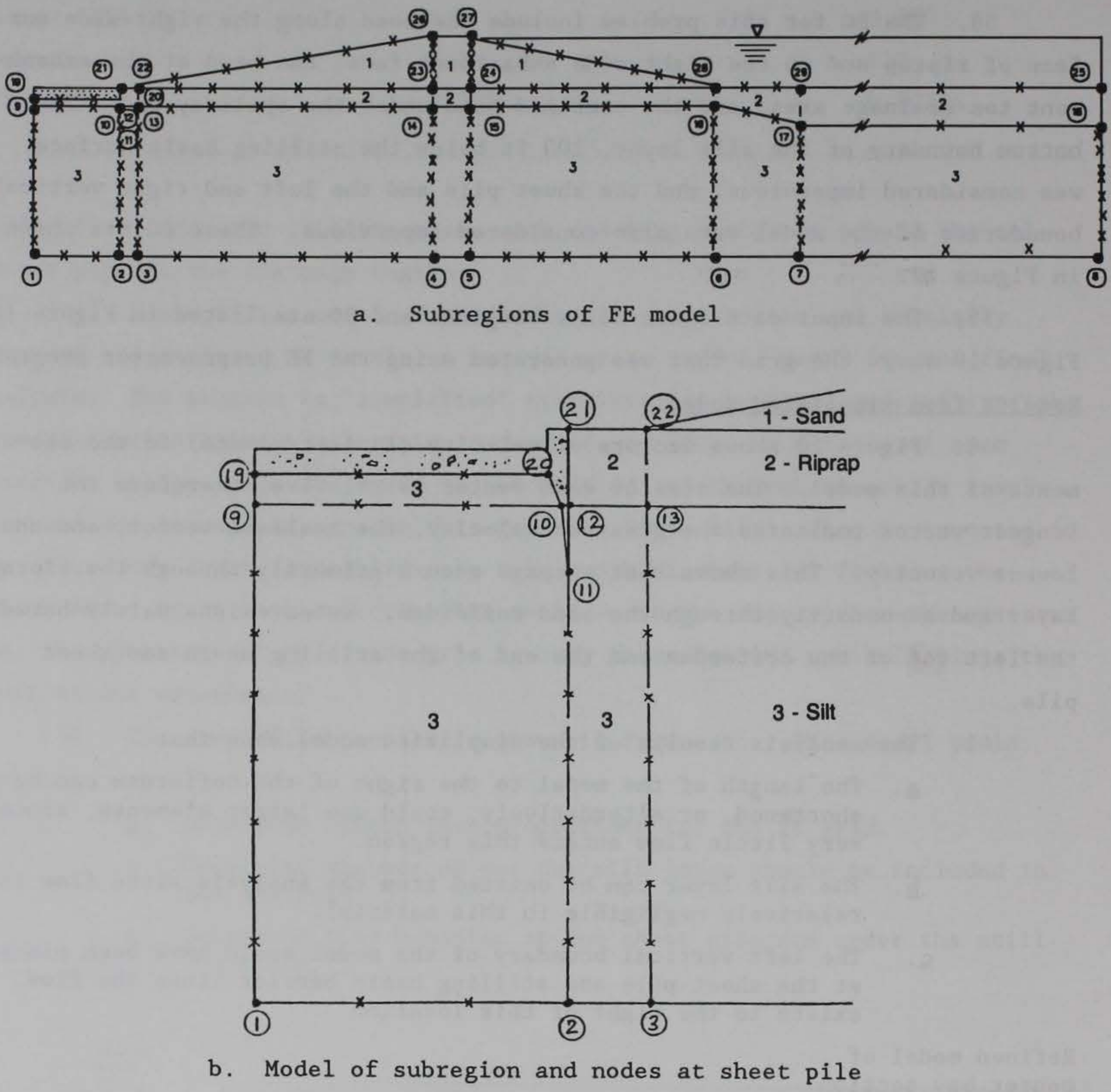
a. The length of the model to the right of the cofferdam can be shortened, or alternatively, could use larger elements, since very little flow enters this region.

b. The silt layer can be omitted from the analysis since flow is relatively negligible in this material.

c. The left vertical boundary of the model could have been placed at the sheet-pile and stilling basin barrier since the flow exists to the right of this location.

Refined model of center bay section

42. A new grid was developed for the final model of the center bay, incorporating the results listed in paragraph 41. The left-side boundary is the sheet pile, the impermeable base is the bottom of the riprap, and the right-side extension of the profile has been shortened to 125 ft past the embankment toe. The toe drain area is removed from the model, and a notch is provided at this point in the embankment. Subregions and additional nodes are




a. Subregions of FE model

b. Model of subregion and nodes at sheet pile

Figure 16. Simplified model of low center bay with partitions and nodes for FE preprocessor

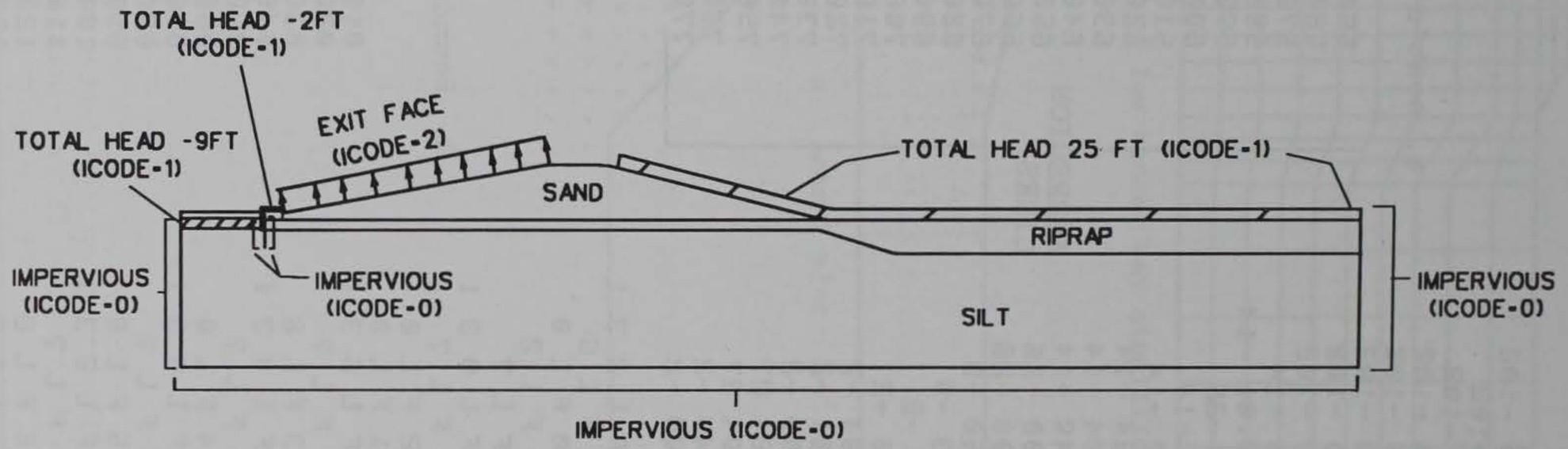



Figure 17. Boundary conditions for low center bay model

a. Input File

SUBREGION POINT COORDINATES

```
010 1 -50 -102
020 2 0 -102
030 3 10 -102
040 4 184 -102
050 5 204 -102
060 6 349 -102
070 7 400 -102
080 8 900 -102
090 9 -50 -14
110 10 -0.01 -14
120 11 0 -25
130 12 0 -14
140 13 10 -14
150 14 184 -14
160 15 204 -14
170 16 349 -14
180 17 400 -26
190 18 900 -26
200 19 -50 -9
210 20 -3 -9
220 21 0 -2
230 22 10 -2
240 23 184 -2
250 24 204 -2
260 25 900 -2
270 26 184 27
280 27 204 27
290 28 349 -2
300 29 400 -2
310 -1
```

SUBREGION LINES

```
320 1 2 F L 2 3 1
330 2 11 F L 6
340 11 10 F L 0
345 10 9 F L 2
346 9 1 F L 7
380 2 3 F L 0 3 1
390 3 13 F L 7
400 13 12 F L 0
410 12 11 F L 0
420 3 4 F L 6 3 1
430 4 14 F L 7
440 14 13 F L 6
450 4 5 F L 0 3 1
460 5 15 F L 7
470 15 14 F L 0
480 5 6 F L 6 3 1
490 6 16 F L 7
500 16 15 F L 6
510 6 7 F L 2 3 1
520 7 17 F L 7
530 17 16 F L 2
540 7 8 F L 9 3 1
```

a. cont'd

SUBREGION LINES

```
550 8 18 F L 7
560 18 17 F L 9
570 10 20 F L 0 3 1
580 20 19 F L 2
590 19 9 F L 0
600 13 22 F L 1 2 2
610 21 22 F L 0 100
620 12 21 F L 1
630 14 23 F L 1 2 2
640 23 22 F L 6
650 15 24 F L 1 2 2
660 24 23 F L 0
670 16 28 F L 1 2 2
680 28 24 F L 6 2
690 17 29 F L 1 2 2
700 29 28 F L 2
710 18 25 F L 1 2 2
720 25 29 F L 9
730 23 26 F L 6 1 1
740 22 26 F L 6 100
750 24 27 F L 6 1 2
760 27 26 F L 0
770 28 27 F L 6 1 2
```

b. Boundary Conditions File

```
010 P 19 1 1 -9
020 P 20 0 1 -9
030 P 10 1 0
040 P 11 1 0
050 P 12 1 0
060 P 21 1 1 -2
070 P 22 1 2 -2
080 P 26 0 2 27
090 P 27 0 0 0
100 A 1 1 1 25
110 P 28 1 1 25
120 P 29 1 1 25
130 P 25 0 1 25
```

Figure 18. Input data files to FE preprocessor for low center bay simplified model

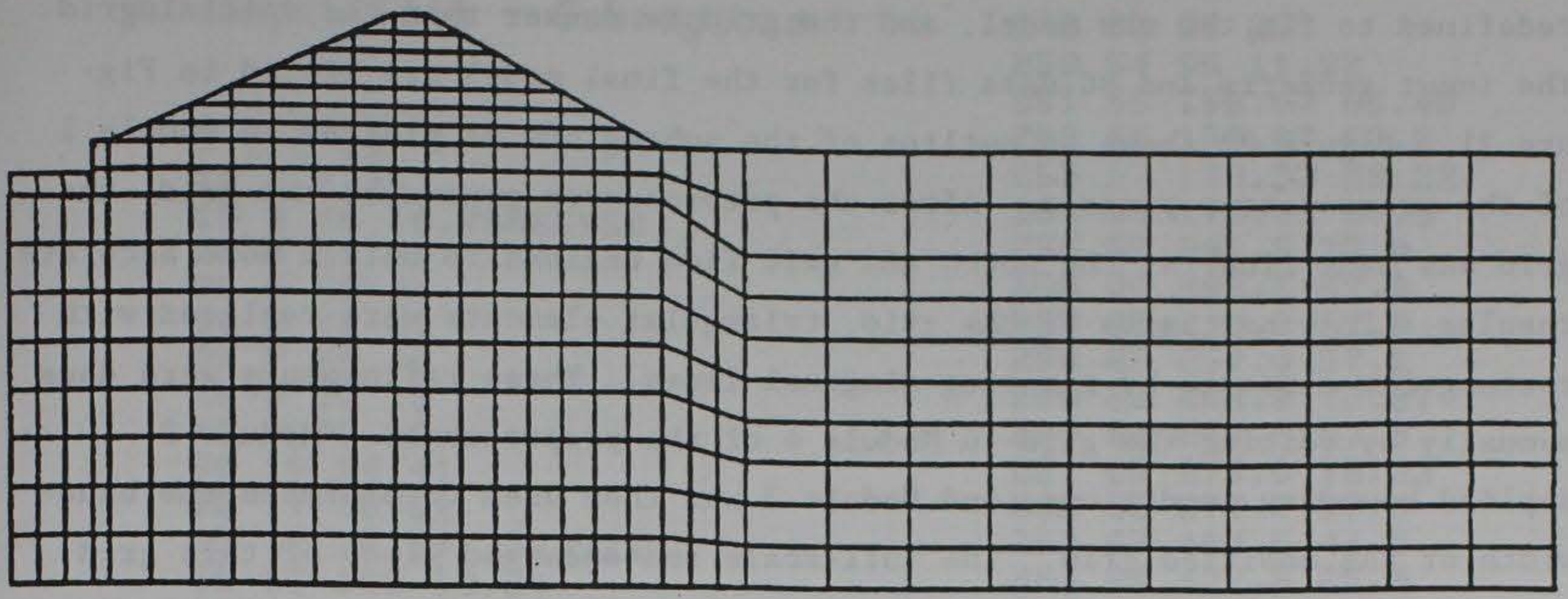
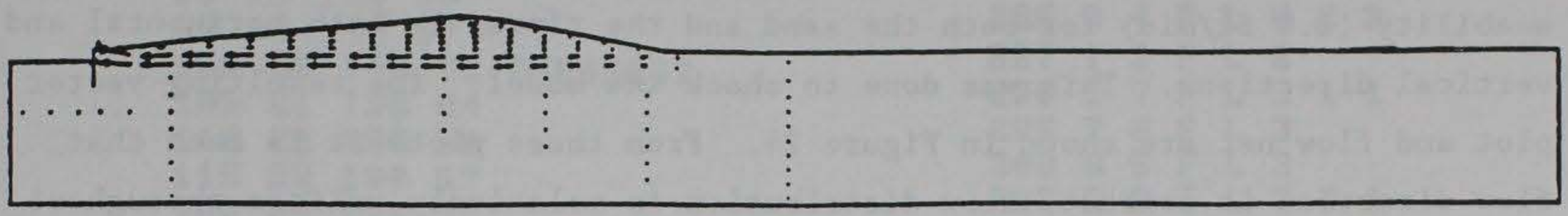
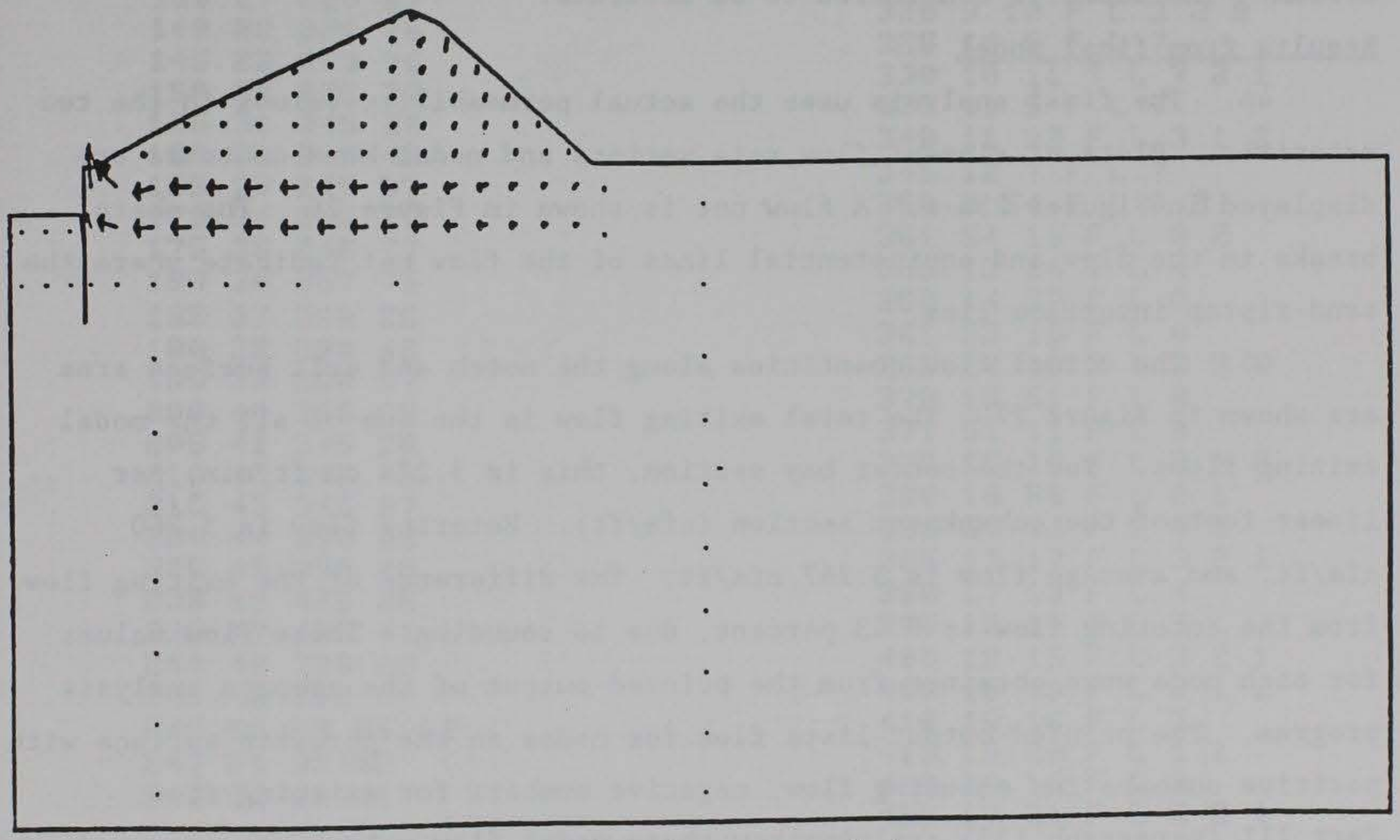


Figure 19. Grid of low center bay simplified model (NTS)



a. Actual plot



b. Big plot (not to scale)

Figure 20. Velocity vectors in simplified model with all material permeabilities at 1.0 ft/min

redefined to fit the new model, and the grid is denser than the initial grid. The input geometry and BC data files for the final model are listed in Figure 21. Figure 22 shows an outline of the subregions as plotted in Module 1 of the preprocessor program. After the preprocessor generated the grid, the grid was made finer at the notch and exit flow regions to obtain more accurate results. In other parts of the grid, triangular elements were replaced with rectangular elements by removing diagonal lines. These refinements were done manually by editing the grid in Module 4 of the preprocessor. Module 2 applied boundary conditions, and Module 3 was then used to minimize the bandwidth of the modified grid. The full-scale and enlarged plots of this grid are shown in Figure 23.

Verification of final model

43. This final model was first analyzed using only one value of permeability (1.0 ft/min) for both the sand and the riprap in both horizontal and vertical directions. This was done to check the model. The resulting vector plot and flow net are shown in Figure 24. From these plots it is seen that flow direction is correct, flow distribution is relatively uniform throughout the region, and the flow net form is correct for a homogeneous isotropic medium. The model is considered to be accurate.

Results from final model

44. The final analysis uses the actual permeability values in the two materials. Plots of element flow rate vectors and nodal head contours are displayed in Figures 25a-c. A flow net is shown in Figure 26. The sharp breaks in the flow and equipotential lines of the flow net indicate where the sand-riprap interface lies.

45. The actual flow quantities along the notch and exit surface area are shown in Figure 27. The total exiting flow is the sum of all the nodal exiting flows. For the center bay section, this is 3.274 cu ft/min, per linear foot of the embankment section (cfm/ft). Entering flow is 3.260 cfm/ft, and average flow is 3.267 cfm/ft. The difference of the exiting flow from the entering flow is 0.43 percent, due to rounding. These flow values for each node were obtained from the printed output of the seepage analysis program. The printed output lists flow for nodes on the phreatic surface with positive numbers for entering flow, negative numbers for existing flow. Part III (paragraph 139) explains how these nodal flow values are computed.

a. Input File - Subregions

```
5 1 0 29
10 2 0 41
15 3 58 16.75555556
20 4 58 29
25 5 58 41
30 6 46 47
35 7 58 49
40 8 90 10
45 9 90 29
50 10 90 41
55 11 90 52
60 12 90 54.33333333
65 13 106 13.84
70 14 106 41
75 15 106 51.36
80 16 106 57
85 17 140 18
90 18 140 50
95 19 140 57
100 20 140 62.66666667
105 21 190 24
110 22 190 50
115 23 190 57
120 24 190 71
125 25 225 25.272727273
130 26 225 47.454545455
135 27 225 57
140 28 225 75
145 29 213 75
150 30 225 77
155 31 245 26
160 32 245 46
165 33 245 57
170 34 245 75
175 35 245 77
180 36 257 75
185 37 290 26
190 38 290 48
195 39 290 57
200 40 290 68
205 41 345 26
210 42 345 48
215 43 345 57
220 44 390 26
225 45 390 48
230 46 425 26
235 47 425 41
240 48 700 26
245 49 700 41
246 50 98 55.67
247 51 98 52
248 52 98 41
249 53 98 29
250 54 98 11.92
251 55 156.67 65.45
252 56 156.67 57.0
253 57 173.33 68.22
254 58 173.33 57.0
255 59 201.5 73.0
256 60 201.5 57.0
257 61 213.0 57.0
258 62 257.0 57.0
259 63 268.0 72.67
260 64 268.0 57.0
261 65 279.0 70.33
262 66 279.0 57.0
263 67 407.5 44.5
264 68 407.5 26.0
269  -1
270 1 4 F L 8 2
275 4 5 F L 3 2
280 5 2 F L 8
285 2 1 F L 3
286 3 4 F L 8 2 3
287 1 3 F L 8
290 5 7 F L 3 1 1
295 7 6 F L 3
300 6 5 F L 3
305 3 8 F L 7 2 1
310 8 9 F L 8
315 9 4 F L 7
316 9 53 F L 0 2
320 9 10 F L 3 2 2
325 10 5 F L 7
330 10 11 T L 7 2 1
335 11 5 F L 7
340 11 12 F L 3 1 2
345 12 7 F L 7
350 8 54 F L 0 2
351 54 13 F L 0 2
355 13 14 T L 4
360 14 52 F L 0
361 52 10 F L 0
365 14 15 T L 3 2 2
370 15 51 F L 0
371 51 11 F L 0
375 15 16 F L 2 1 2
380 16 50 F L 0 1
381 50 12 F L 0 1
385 13 17 F L 3 2 1
390 17 18 F L 4
395 18 14 T L 3
400 18 15 F L 3 2 1
405 18 19 F L 2 1 2
410 19 16 F L 3
415 19 20 F L 1 1
420 20 16 F L 3
425 17 21 F L 2 2 1
```

Figure 21. Input files for final model of low center bay section (Continued)

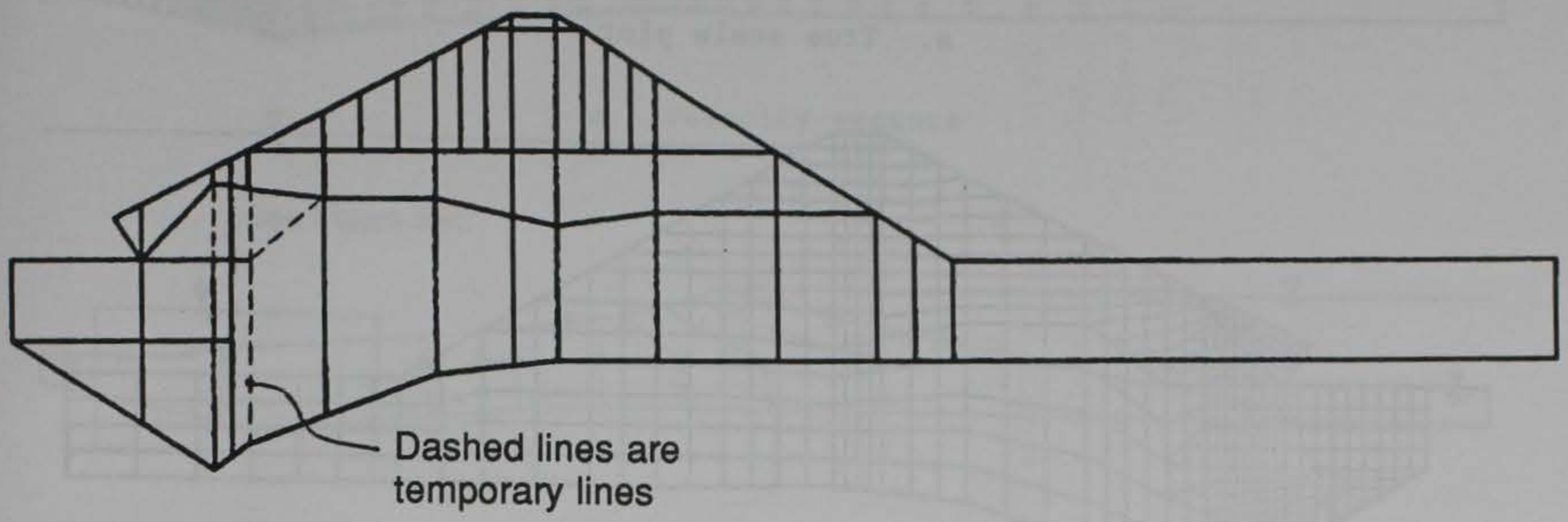
```
430 21 22 F L 4
435 22 18 F L 2
440 22 23 F L 2 1 2
445 23 58 F L 0
446 58 56 F L 0
447 56 19 F L 0
450 23 24 F L 4 1 1
455 20 55 F L 0 100
456 55 57 F L 0
457 57 24 F L 0
460 21 25 F L 2 2 1
470 25 26 F L 4
475 26 22 F L 2
480 26 27 F L 2 1 2
485 27 61 F L 0
486 61 60 F L 0
487 60 23 F L 0
490 27 28 F L 6 1
495 28 29 F L 0
500 29 59 F L 0 1
501 59 24 F L 0 1
505 28 30 F L 0 1 1
506 30 29 F L 0
510 25 31 F L 3 2 1
515 31 32 F L 4
525 32 26 F L 3
530 32 33 F L 1 1 1
535 33 27 F L 3
540 33 34 F L 6 1 1
545 34 28 F L 3
550 34 35 F L 0 1 1
555 35 30 F L 3
560 31 37 F L 3 2 1
565 37 38 F L 4
570 38 32 F L 3
575 38 39 F L 1 1 2
580 33 62 F L 0 1
581 62 64 F L 0 1
582 64 66 F L 0 1
583 66 39 F L 0 1
585 39 40 F L 3 1
590 40 65 F L 0
591 65 63 F L 0
592 63 36 F L 0
595 36 34 F L 0
600 36 35 F L 0 1 1
605 37 41 F L 3 2 1
610 41 42 F L 4
615 42 38 F L 3
620 42 43 F L 1 1 2
625 43 39 F L 3
630 43 40 F L 3 1 2
635 41 44 F L 1 2 1
640 44 45 F L 4
645 45 42 F L 1
650 45 43 F L 1 1 2
655 44 68 F L 0 2
656 68 46 F L 0 2
660 46 47 F L 3
665 47 67 F L 0
666 67 45 F L 0
670 46 48 F Q 10 2
671 520.0 26.0
675 48 49 F L 3
680 47 49 F Q 10
681  520.0 41.0
700 50 51 F L 2
705 51 52 F L 4
710 52 53 F L 2
715 53 54 F L 5
720 58 57 F L 3 1
725 56 55 F L 2 1 2
730 61 29 F L 6
735 60 59 F L 5
740 62 36 F L 6
745 64 63 F L 5
750 66 65 F L 4
760 67 68 F L 4
```

b. Boundary Condition File

```
10 P 2 1 1 41
20 P 5 1 2 41
30 P 6 1 2 47
40 P 7 1 2 49
50 P 12 1 2 52
55 P 50 1 2 55.67
60 P 16 1 2 57
70 P 20 1 2 62.66666667
75 P 55 1 2 65.45
77 P 57 1 2 68.22
80 P 24 1 2 71
85 P 59 1 2 73.
90 P 29 1 2 75
100 P 30 0 2 77
110 P 35 0 0
120 P 36 1 1 75
125 P 63 1 1 75
127 P 65 1 1 75
130 P 40 1 1 75
140 P 43 1 1 75
150 P 45 1 1 75
155 P 67 1 1 75
160 P 47 1 1 75
170 P 49 0 1 75
```

Figure 21. (Concluded)

a. True scale plot




b. Big plot (not to scale)

Figure 22. Final model of low center bay with subregions

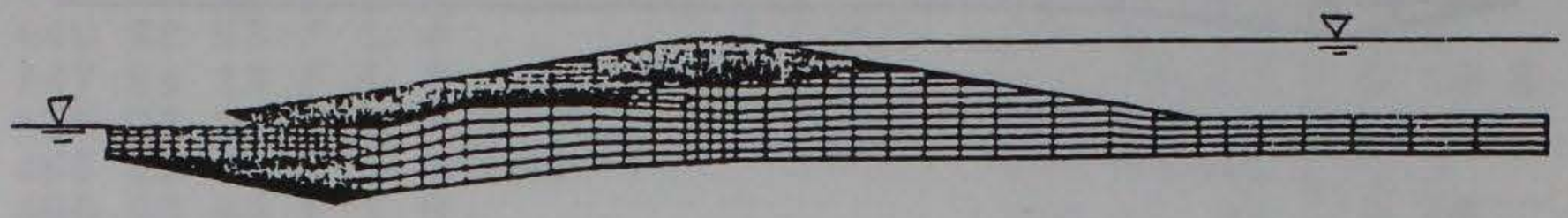
46. The exit gradients in this existing flow region were also required from the results. The exit gradient is the change in head between a surface exit node and an immediately adjacent interior node, divided by the distance between these two nodes. Exit gradients and an example calculation are shown in Figure 28. The greatest exit gradient for this center bay section is 0.68.

Discussion of center bay results

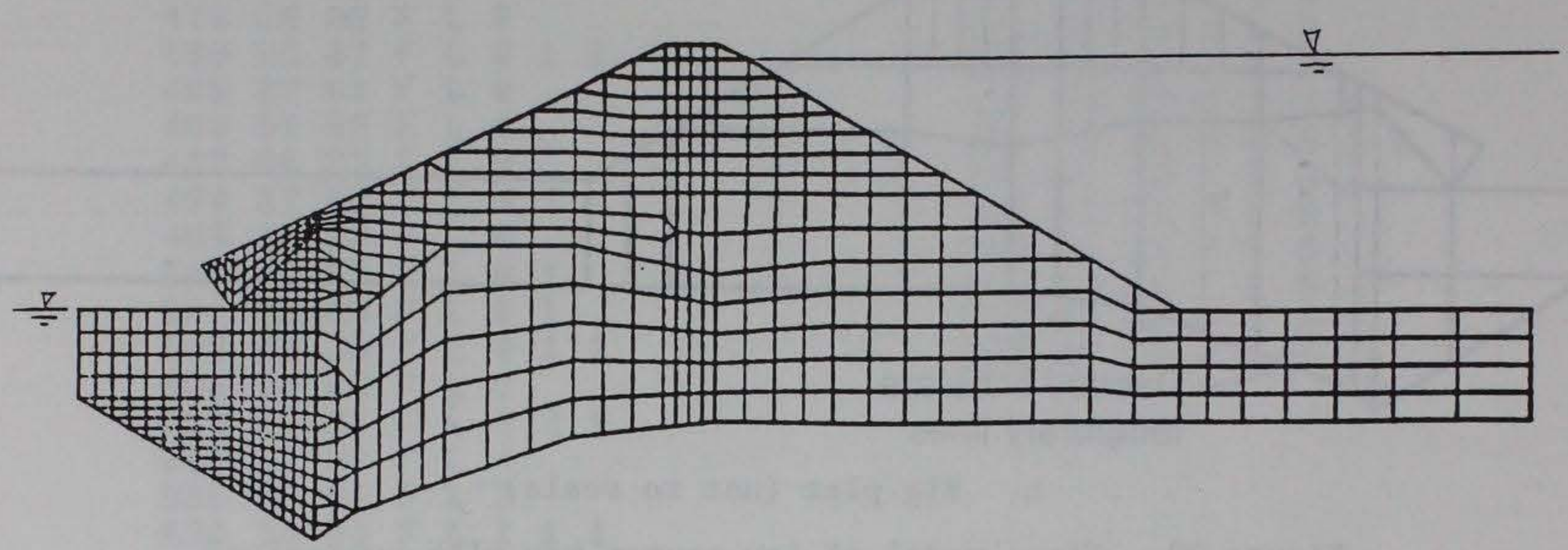
47. The analysis shows the flow is exiting as desired into the toe drain area where a collector pipe and pumps will remove the water. Exiting from the riprap is 95 percent of the flow, with the remainder coming through the sand embankment. The relatively high exit gradient in the riprap just below the sand, 0.68, may need to be decreased by use of a filter to lower the potential for sand "blowout" into the toe drain material.

FE models of south
and north bay sections

48. The south and north bay FE models were developed and analyzed without preliminary checks performed for the center bay model. Lessons learned from the simplified center bay model were applied in the development of these models.

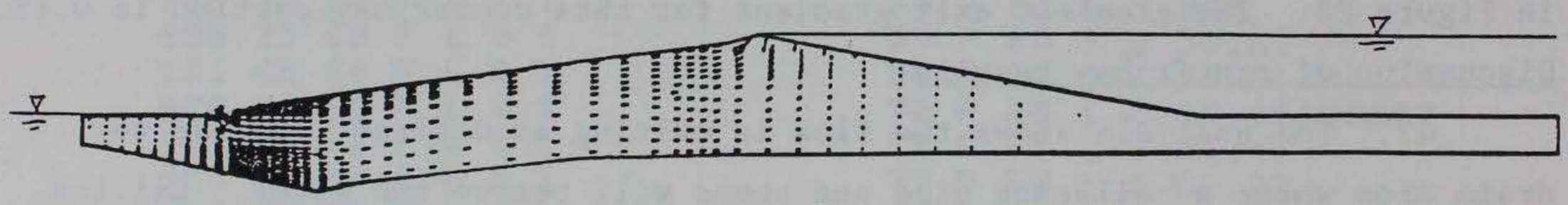


a. True scale plot

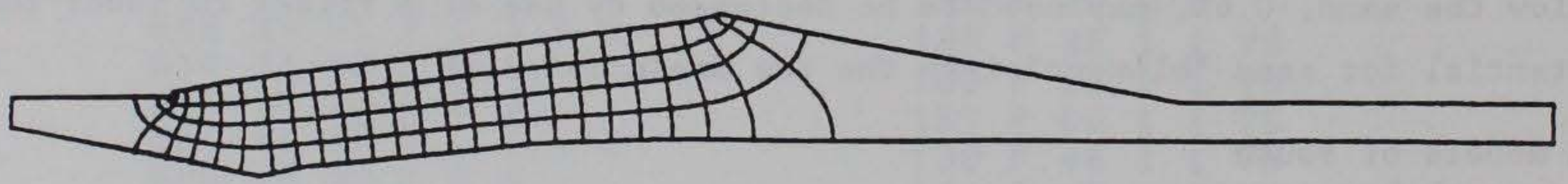


b. Big plot (not to scale

Figure 23. Generated grid of low center bay final model

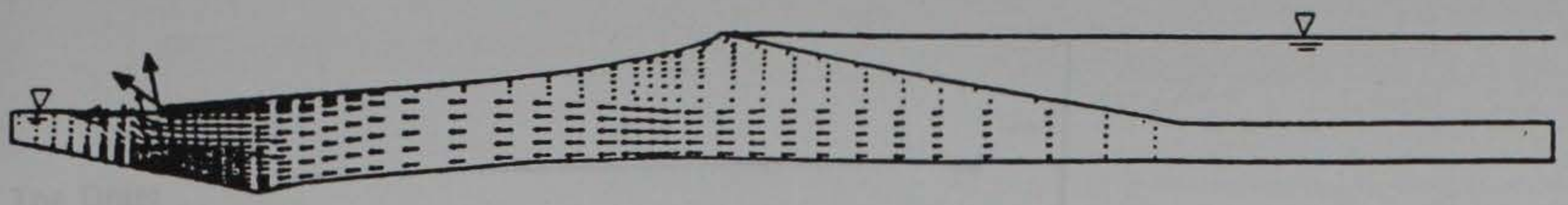


a. Velocity vectors

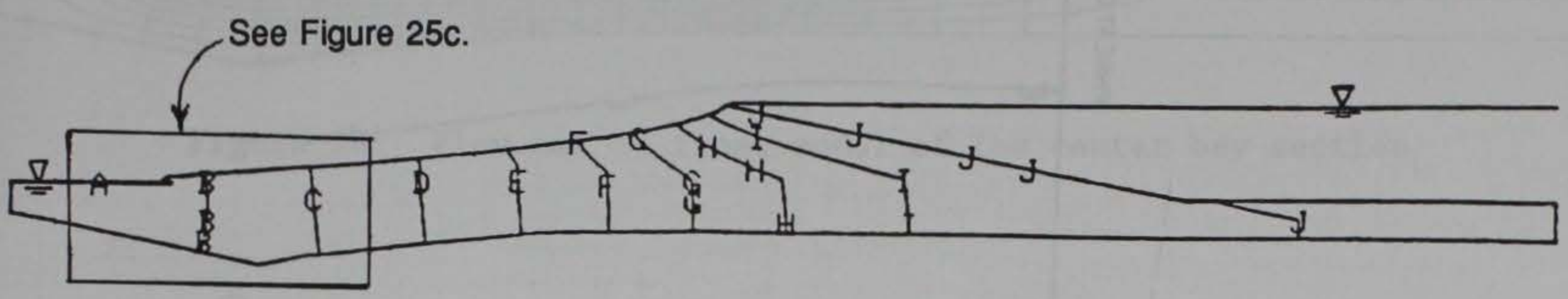


b. Flow net

Figure 24. Velocity vectors and flow net for one-permeability analysis of low center bay



a. Velocity vectors




| | | | |
|---|---|---|---|
| A = | 0.4100E 02 | F = | 0.5989E 02 |
| B = | 0.4478E 02 | G = | 0.6367E 02 |
| C = | 0.4856E 02 | H = | 0.6744E 02 |
| D = | 0.5233E 02 | I = | 0.7122E 02 |
| E = | 0.5611E 02 | J = | 0.7500E 02 |

(Feet)

b. Nodal head contours (total head)

Figure 25. Velocity vectors and total head contours for final model of low center bay with actual permeabilities used (Continued)

A- 0.4100E 02
B- 0.4200E 02
C- 0.4300E 02
D- 0.4400E 02
E- 0.4500E 02
F- 0.4600E 02 (FEET)

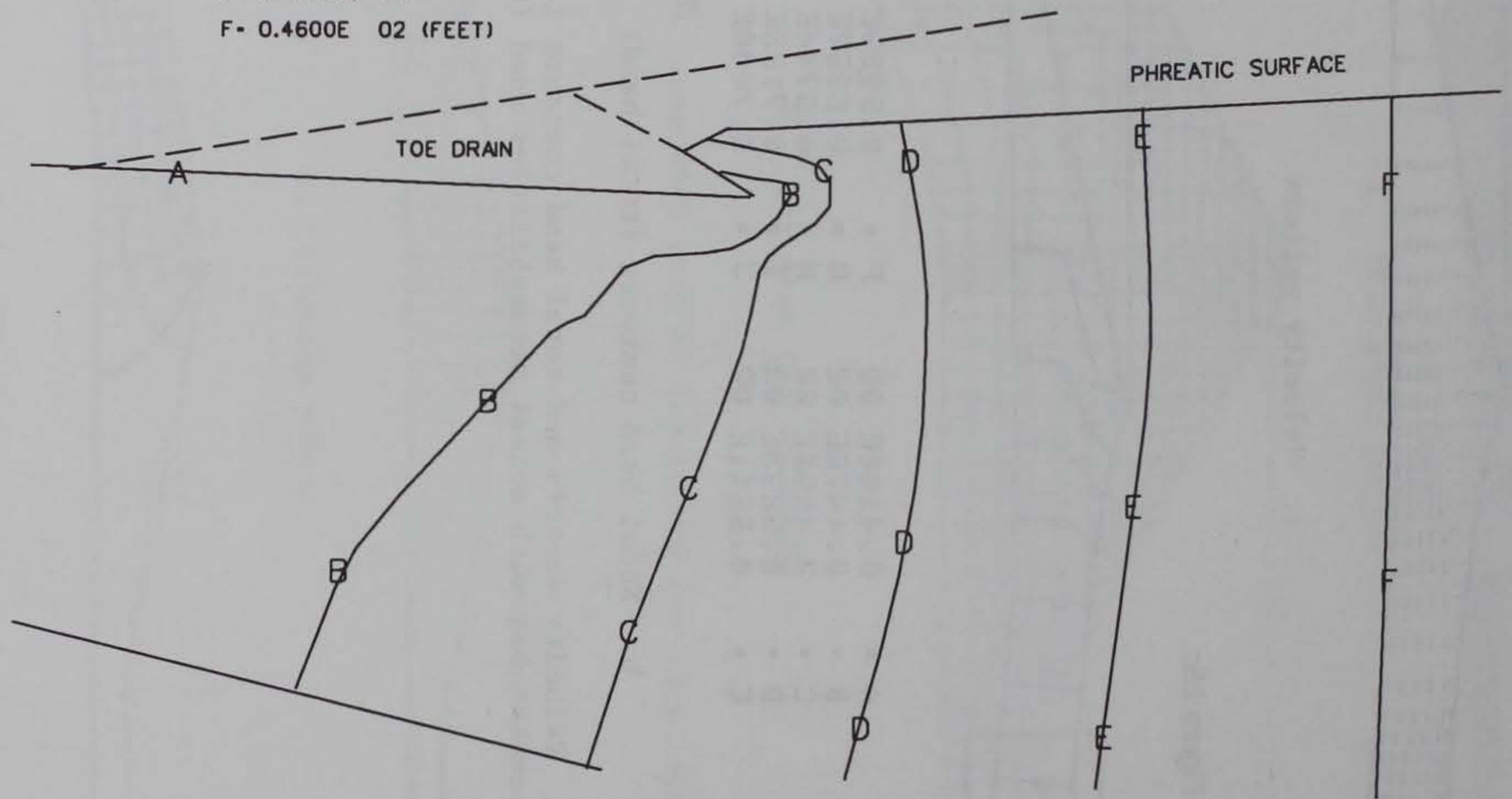



Figure 25. (Concluded)

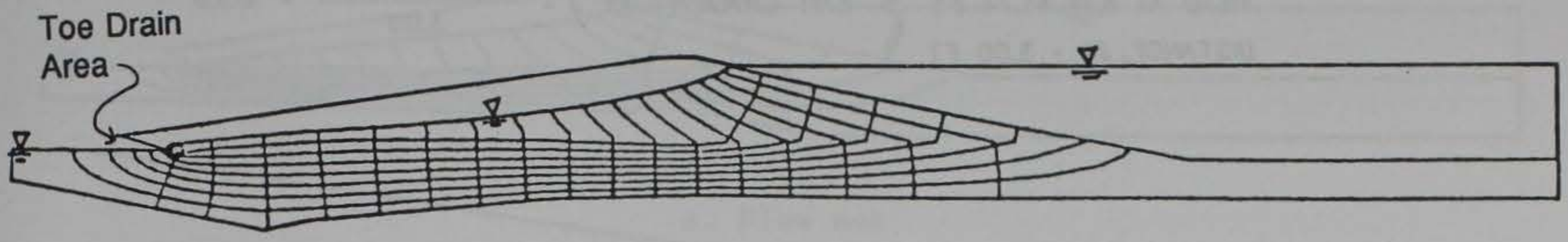



Figure 26. Flow net of final model of low center bay section

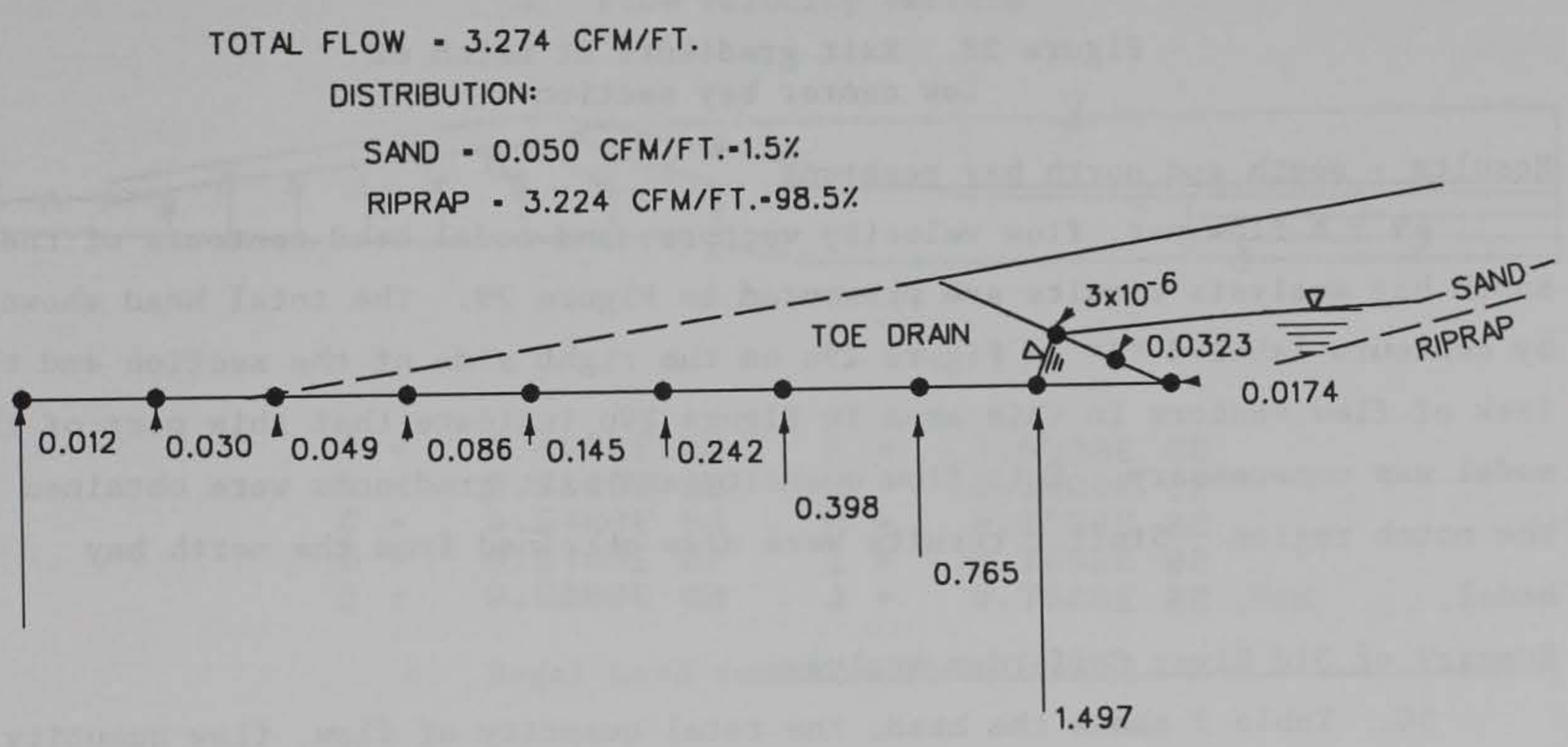



Figure 27. Exit flows at notch
of low center bay section

$$\text{GRADIENT, } i = \frac{\Delta \text{ HEAD}}{\text{DISTANCE}}$$

EXAMPLE:

HEAD AT J = 41.00 FT
HEAD AT K = 41.74 FT
DISTANCE, JK = 3.00 FT

$$\text{EXIT GRADIENT AT J} = \frac{41.74 - 41.00}{3.00} = 0.25$$

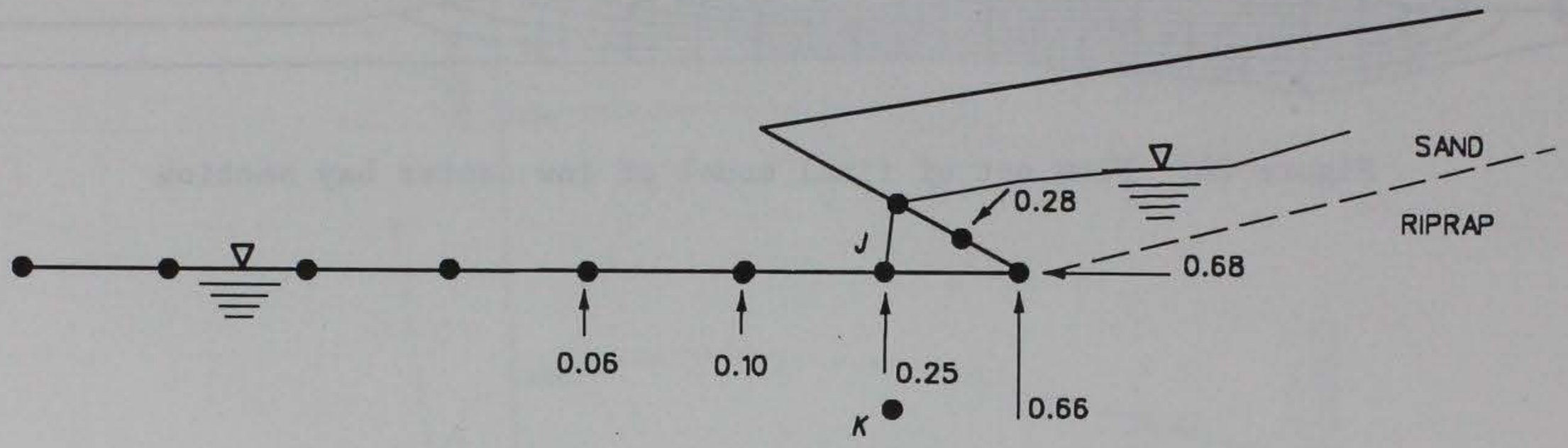



Figure 28. Exit gradients at notch of low center bay section

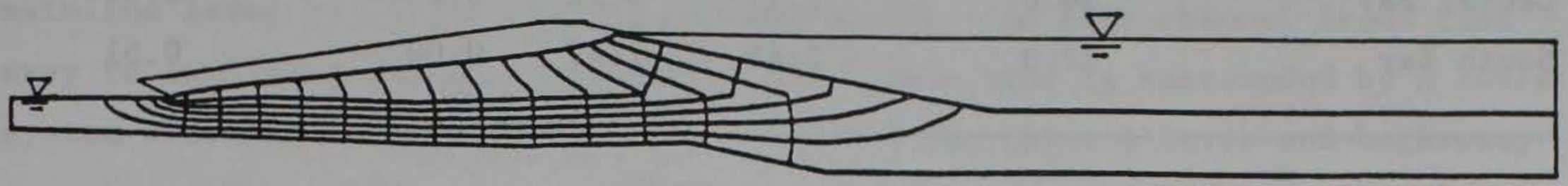
Results - south and north bay sections

49. A flow net, flow velocity vectors, and nodal head contours of the south bay analysis results are presented in Figure 29. The total head shown by contours labeled "J" in Figure 29c on the right side of the section and the lack of flow vectors in this area in Figure 29b indicate that this part of the model was unnecessary. Exit flow quantity and exit gradients were obtained in the notch region. Similar results were also obtained from the north bay model.

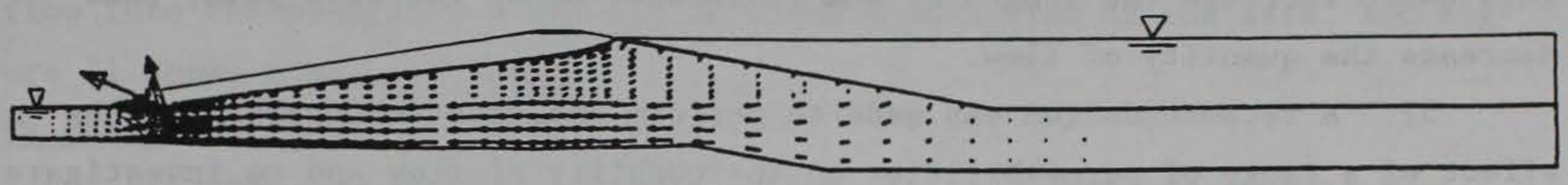
Summary of Old River Cofferdam analyses

50. Table 2 shows the head, the total quantity of flow, flow quantity through the riprap and sand embankment, and the highest exit gradient in the riprap for the three embankment sections. Exit gradients in the sand embankment are not reported because the quantity of flow coming through this material is negligible.

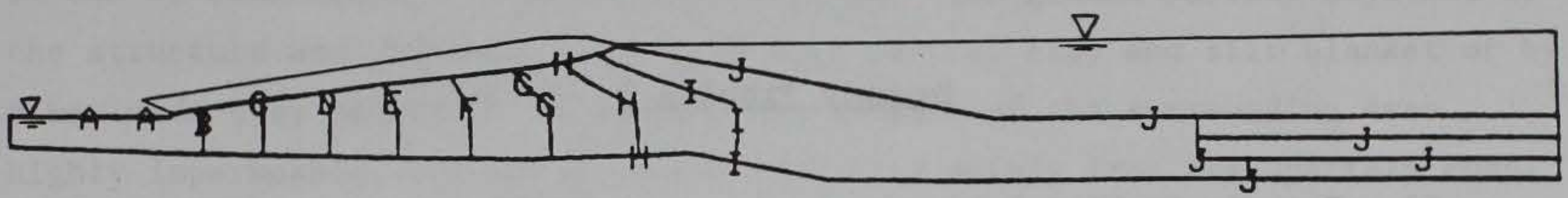
51. The US Army Engineer District, New Orleans, was considering the possibility of placing wellpoints to intercept seepage through the sand embankment to decrease the exit flow quantity and gradient. This analysis shows that the flow through the embankment is so small that wellpoints would



a. Flow net



b. Flow velocity vectors




| | | | |
|---|---|---|---|
| A = | 0.4800E 02 | F = | 0.6300E 02 |
| B = | 0.5100E 02 | G = | 0.6600E 02 |
| C = | 0.5400E 02 | H = | 0.6900E 02 |
| D = | 0.5700E 02 | I = | 0.7200E 02 |
| E = | 0.6000E 02 | J = | 0.7500E 02 (Feet) |

c. Nodal head contours (total head)

Figure 29. South Bay FE seepage analysis results

Table 2

Summary of Results from Example Problem 2

| Section | Change in Head (ft) | Flow Quantity (cfm/ft) | | | Exit Gradient |
|---|---|---|---|---|---|
| | | Total | Riprap | Sand | |
| North Bay | 27.0 | 2.74 | 2.74 | 0.00 | 0.56 |
| Center Bay | 34.0 | 3.27 | 3.22 | 0.05 | 0.68 |
| South Bay | 27.0 | 2.49 | 2.49 | 0.00 | 0.51 |

have little effect on the total quantity of flow. A more effective alternative would be to place a clay blanket on the headwater face of the embankment. This would increase the length of and resistance along the flow path, thus decrease the quantity of flow.

52. A recommendation was made to perform analyses to investigate the effect of a range of permeabilities on the quantity of flow and to investigate the effect of placement of a clay blanket on the headwater face of the sand embankment sections.

## Example Problem 3

53. Example Problem 3 is an example where CSEEP was used to assess uplift pressures on a structure using a plan view model. Certain assumptions had to be made about the site to develop a two-dimensional (2D) plan-view model. The results were used to estimate uplift due to seepage under the structure.

### Background

54. This study considers the S. A. Murray, Jr., Hydroelectric Station which is adjacent to the Mississippi River just upstream from the Old River Control Structure. The powerplant receives flow from the Mississippi River through a diversion channel and could experience differential hydraulic heads up to 26 ft for project flood conditions and 41 ft under extreme conditions. These heads cause seepage to occur under the structure and subject it to uplift pressures. Seepage control measures include concrete cutoff walls and a drainage system. This analysis was performed to determine the seepage and associated uplift pressure beneath the powerplant and other structural fea-

tures (e.g. concrete channel linings) and to study the effect of the cutoff walls on the seepage.

Site description

55. The powerplant is founded in a medium to very dense layer of fine to medium sand, approximately 100 ft deep. Below this sand layer is hard tertiary clay. A channel was cut from the Mississippi River through the mainline levee to divert flow to the powerplant. An exit channel leads flow away to auxiliary overflow channels. The entire site is surrounded by a levee system which ties into the mainline levee and the natural levee and backswamp deposits. The cutoff walls under the structure extend through the sand layer to the tertiary clay layer. Therefore, the main source for seepage under the power plant and concrete channel lining is from the upstream channel providing flow into the powerplant. Figure 30 shows a plan view of the site, and Figure 31 shows a section view.

FE Model

56. This problem is actually a 3-D case, but with two simplifying assumptions it can be solved as a 2-D problem. The first assumption is that it can be considered a confined flow problem. The ground surface adjacent to the structure and channels is covered by a natural clay and silt blanket or by a man-made clay blanket. These make the surface of the surrounding area highly impermeable, therefore, water will flow mainly from the upstream channel and the surrounding subsurface stratum under the structure to the downstream channel. The second assumption is that the seepage occurs in one uniformly thick layer having a constant permeability. These assumptions allow a 2-D plan-view model to be formed of a section taken just under the structure through the cutoff walls.

57. Figure 32 is the section model in plan view, partitioned for grid generation. Figure 33 shows the generated grid. The soil layer is considered to be homogeneous and isotropic with a permeability of 0.14 ft/min. The design permeability for the cutoff wall is $2 \times 10^{-6}$ ft/min.

Boundary conditions

58. The boundaries for the grid were chosen so that they would not unduly influence the seepage pattern around the powerplant. The BC were selected to represent a piezometric level equal to the water level of the Mississippi River. The extreme differential hydraulic head conditions, 41 ft, were applied in these analyses. The BC applied to the model are shown on the grid in Figure 33.

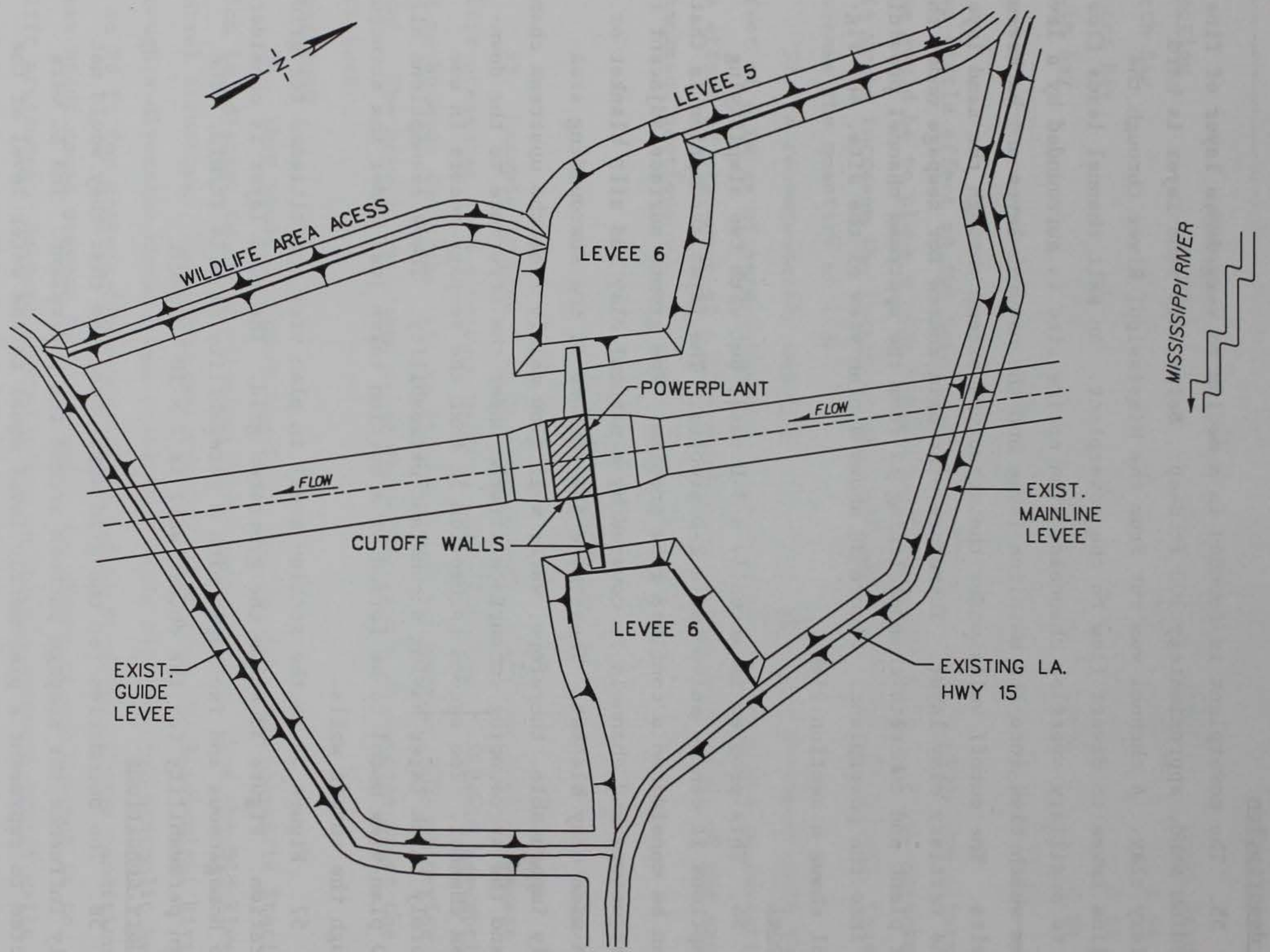



Figure 30. Plan view of site example problem 3

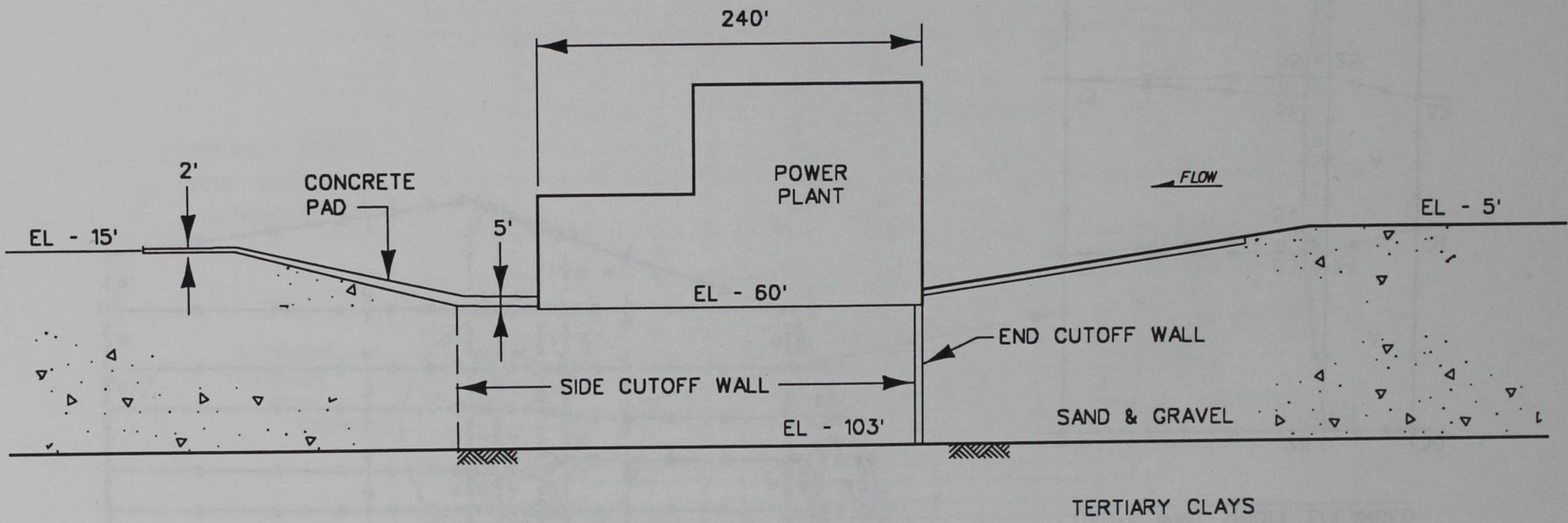



Figure 31. Section view through center line of powerplant and flow channels

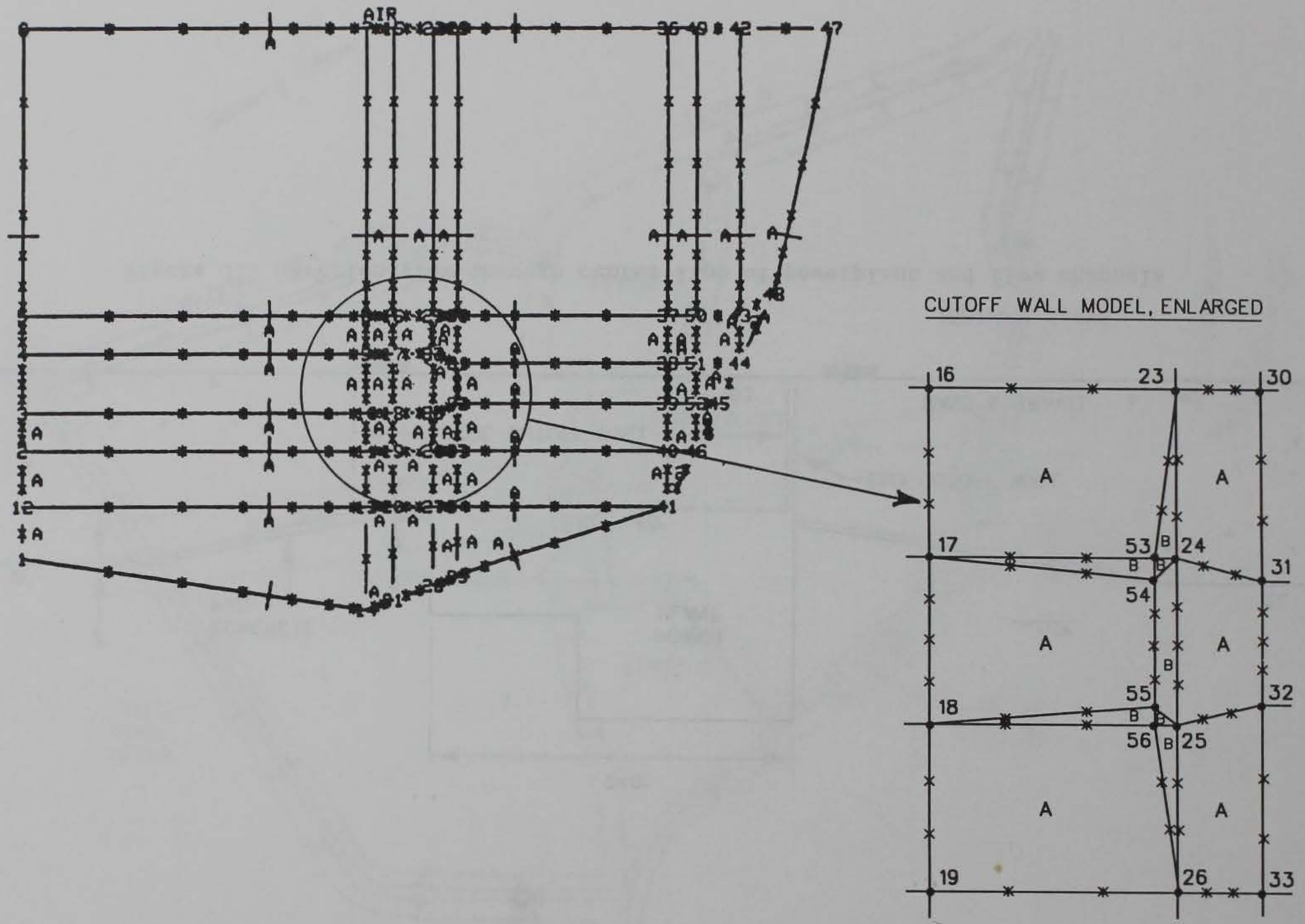



Figure 32. Subregions and nodes for plan view model

HEADWATER - 55.0'
TAILWATER - 14.0'

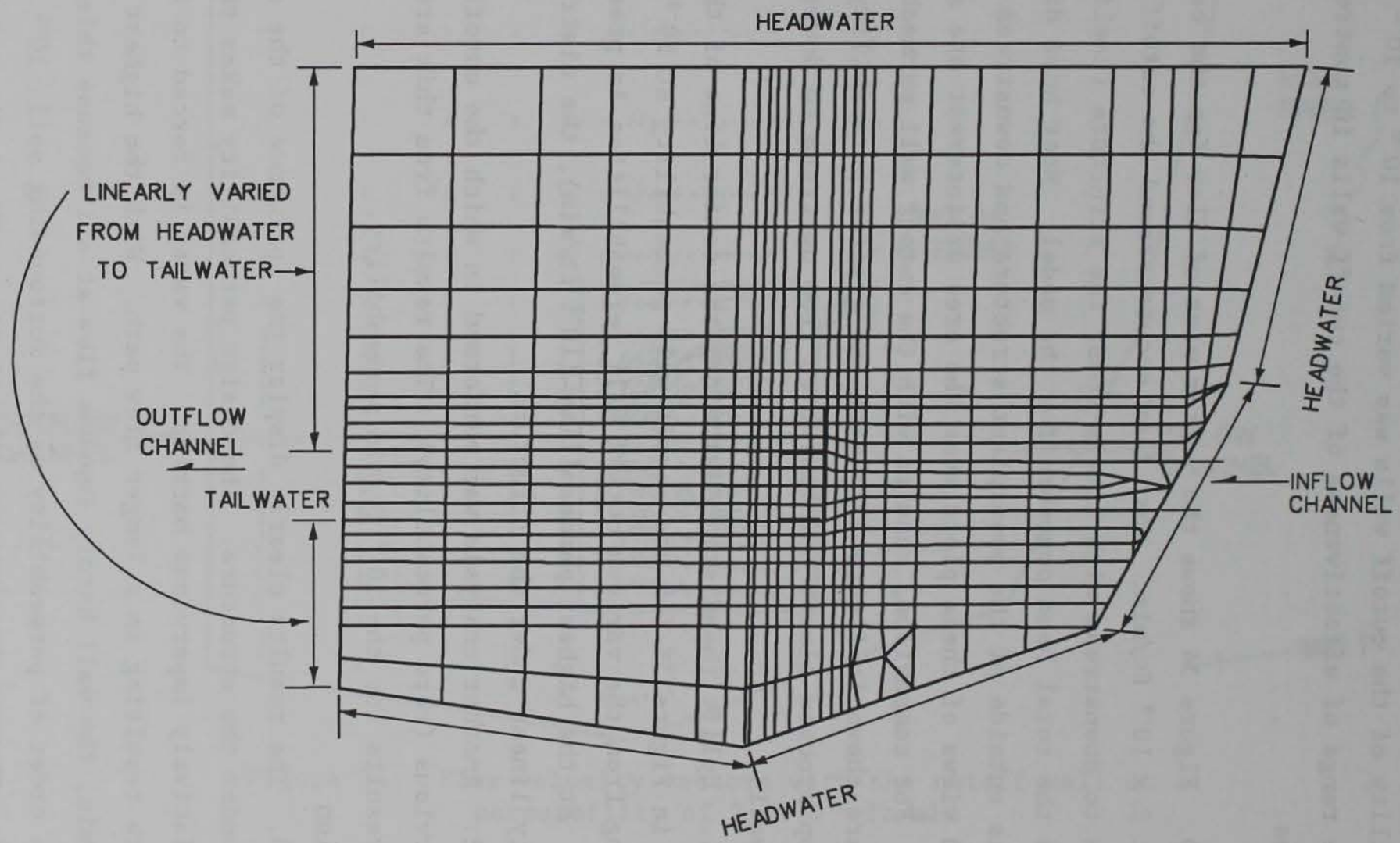



Figure 33. Grid generated for plan view model, example problem 3

Cutoff walls

59. The effect of the cutoff walls on the seepage was of particular interest with respect to the resulting uplift pressures under the powerplant and downstream channel lining. Several analyses were performed in which the permeability of the cutoff walls was varied from $10^{-6}$ to $10^{-2}$ ft/min to determine the range of effectiveness of the cutoff walls in controlling uplift pressures.

Results

60. Figure 34 shows the vector plot of flow for the case of the cutoff walls at $2 \times 10^{-6}$ ft/min. Most flow occurs around the cutoff walls from upstream to downstream with little under the structure itself. Figure 35 displays the total head contours for the model. Most head drop occurs along the walls outside of the powerplant structure and downstream channel lining. Enlarged views of these plots near the area of interest are shown in Figure 36. For comparison, results with the cutoff wall permeability at $10^{-2}$ ft/min are shown in Figure 37. With the greater permeability, the flow and head drop proceed almost uninterrupted from upstream to downstream through the cutoff wall.

61. Uplift (head at nodes) along the center line of the structure is plotted in Figure 38 for the cutoff wall permeability at $10^{-6}$ ft/min. Uplift resulting from the various cutoff wall permeabilities is presented in Figure 39. At the highest permeability ($10^{-2}$ ft/min), the distribution of head is nearly linear under the structure.

62. Another analysis was performed in which the cutoff wall was modeled as impervious (zero permeability). The results from this are almost identical to the results for the $10^{-6}$ ft/min permeability.

Discussion

63. The results clearly display the influence of the cutoff wall on the uplift under the structure. The design permeability makes the cutoff wall act as a relatively impervious barrier. The water is forced to flow around the structure resulting in a longer flow path. With the highest permeability, $10^{-2}$ ft/min, the wall hardly impedes flow at all because this value is near the same order of permeability as the surrounding soil, $10^{-1}$ ft/min.

64. The results were used by the Lower Mississippi Valley Division of the USACE in evaluating the powerplant design with respect to the levee flood control system.

XMIN= 0.
YMIN= 0.
XMAX= 0.591SE 04
YMAX= 0.4377E 04

ONE ARROW INCH = 0.2446E-01 UNITS

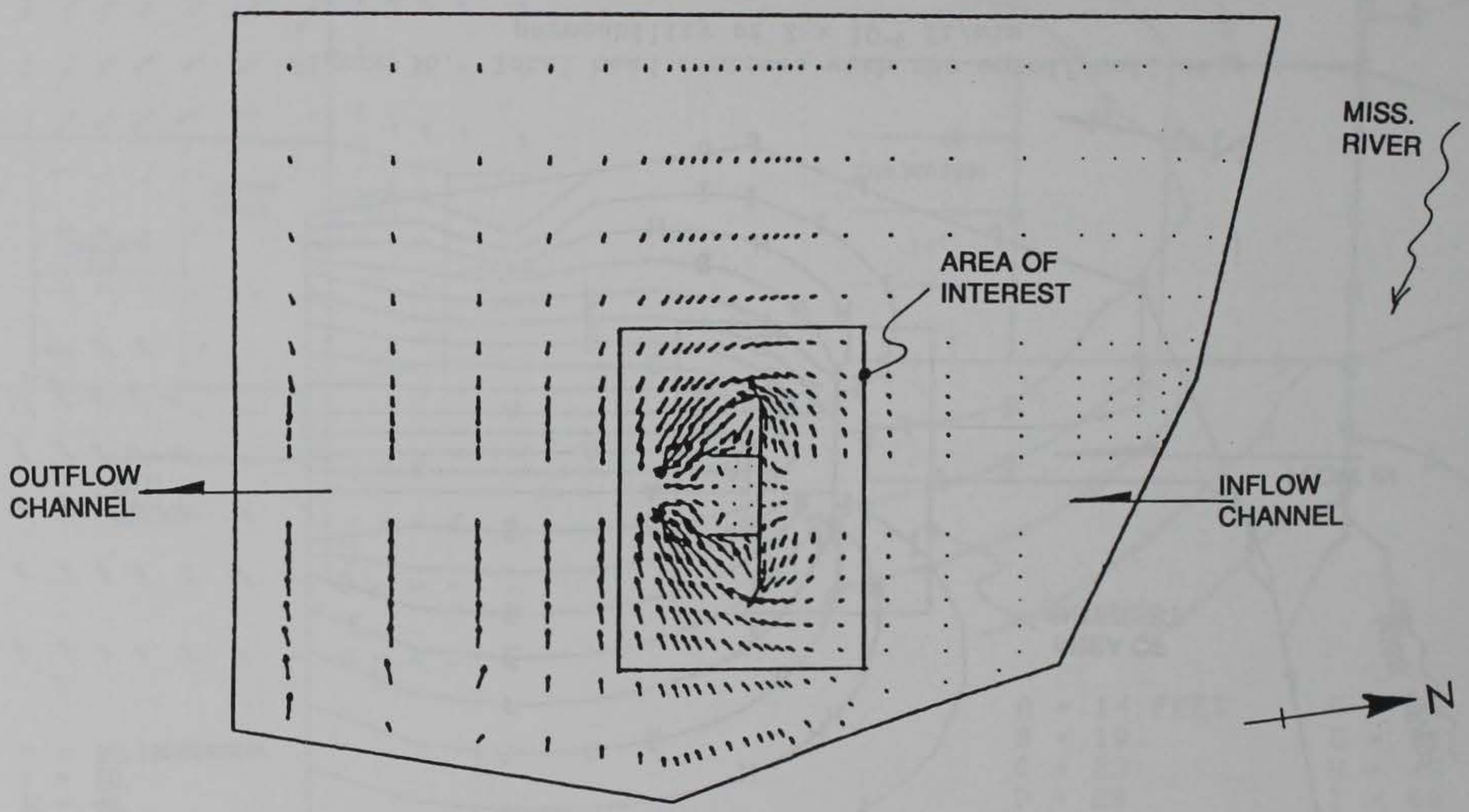



Figure 34. Flow velocity vectors with the cutoff wall at a permeability of $2 \times 10^{-6}$ ft/min

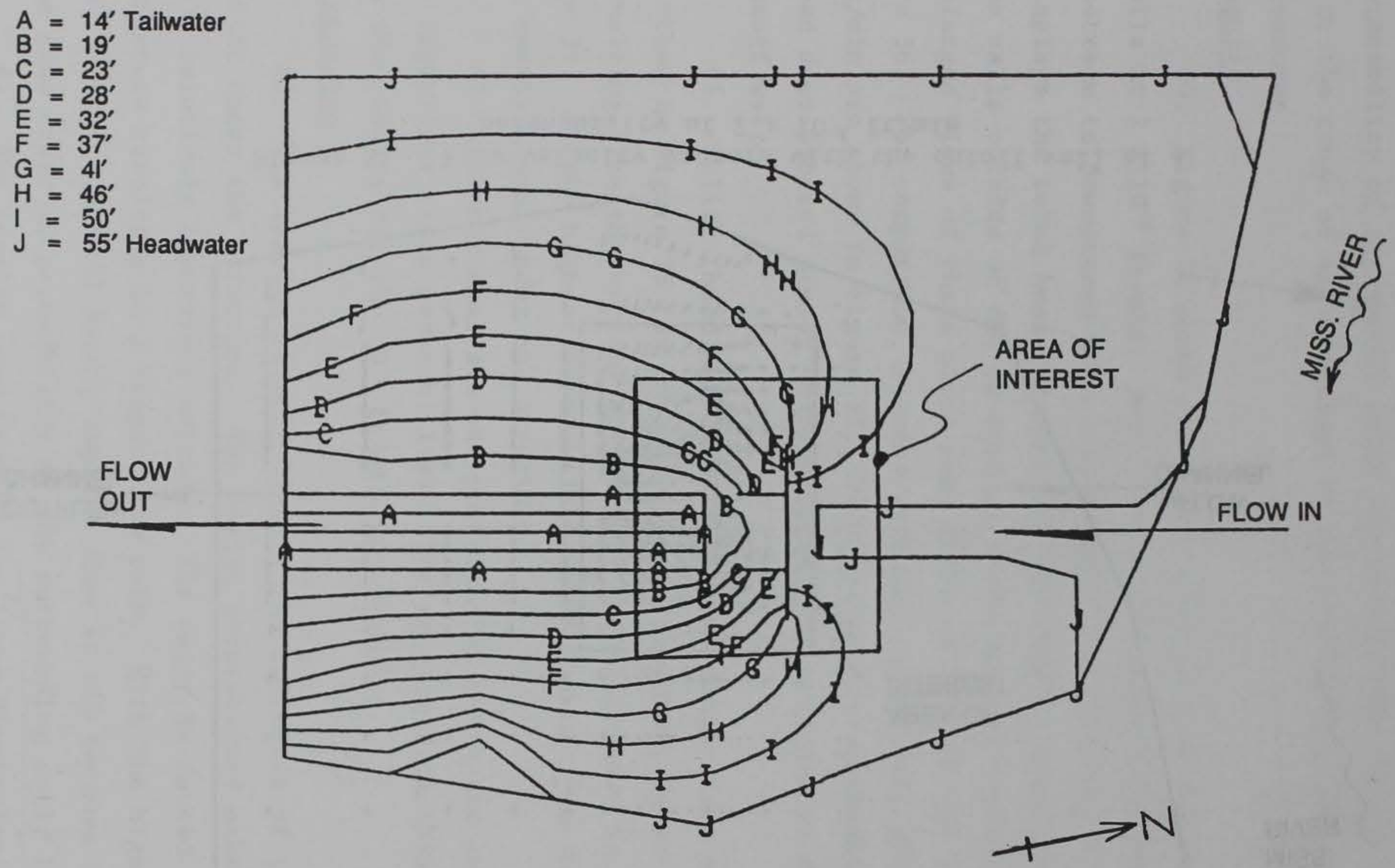
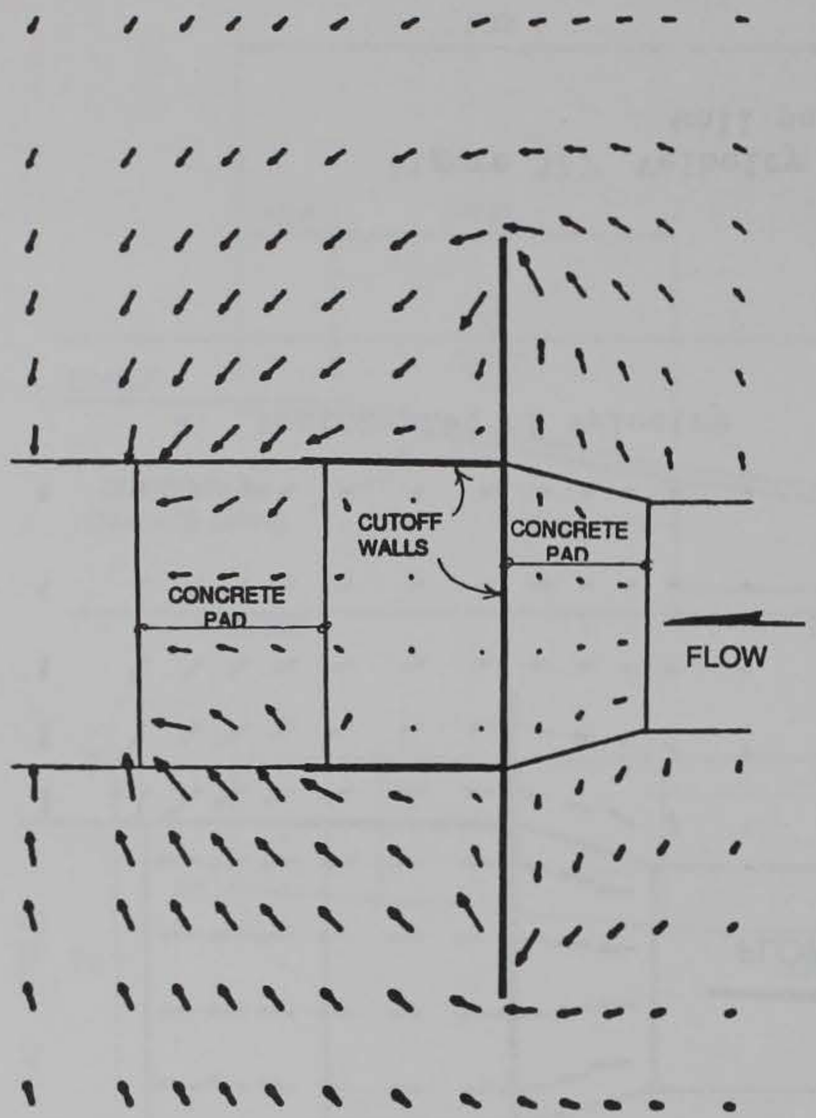
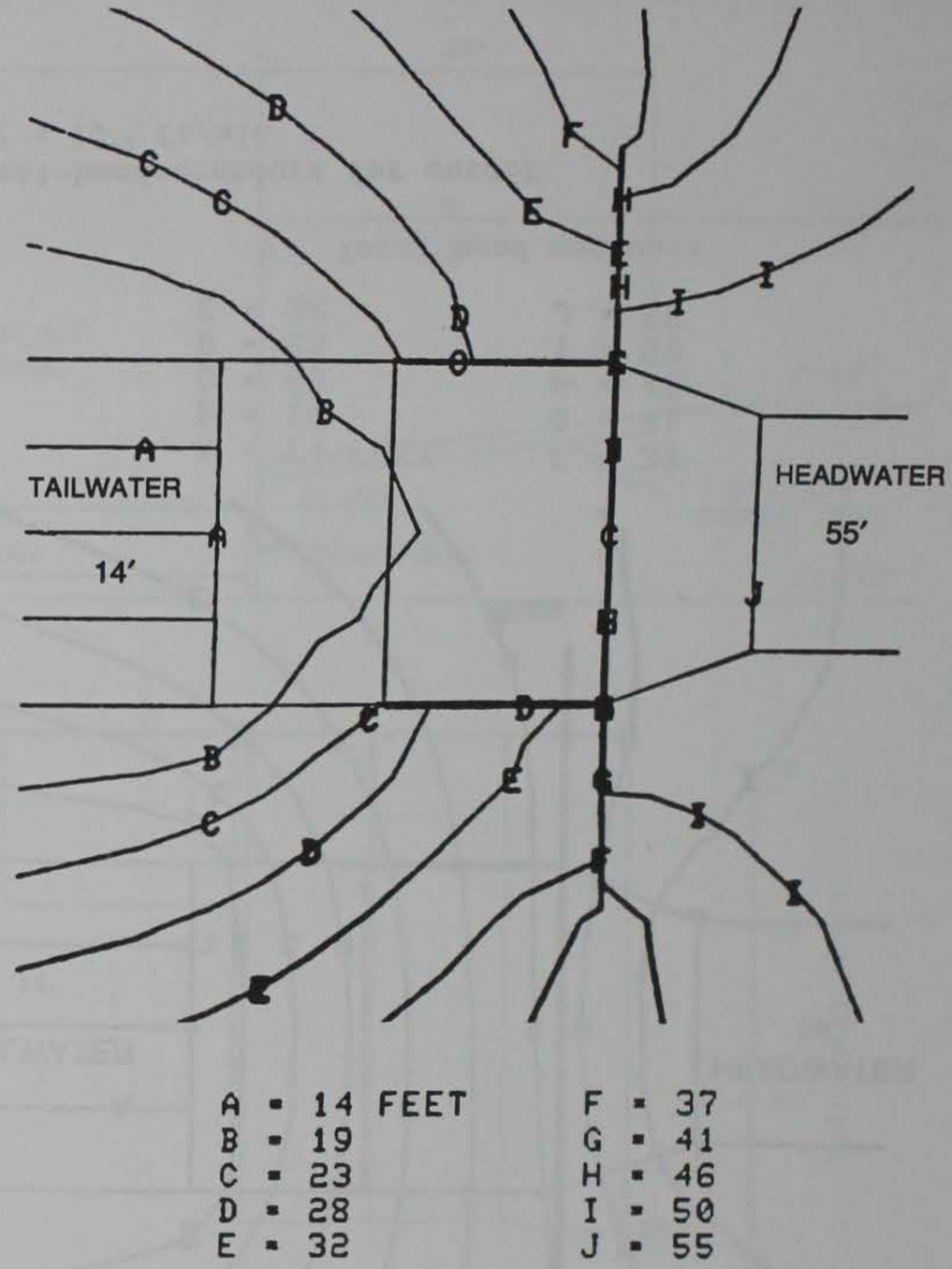



Figure 35. Total head contours with the cutoff wall at a permeability of $2 \times 10^{-6}$ ft/min

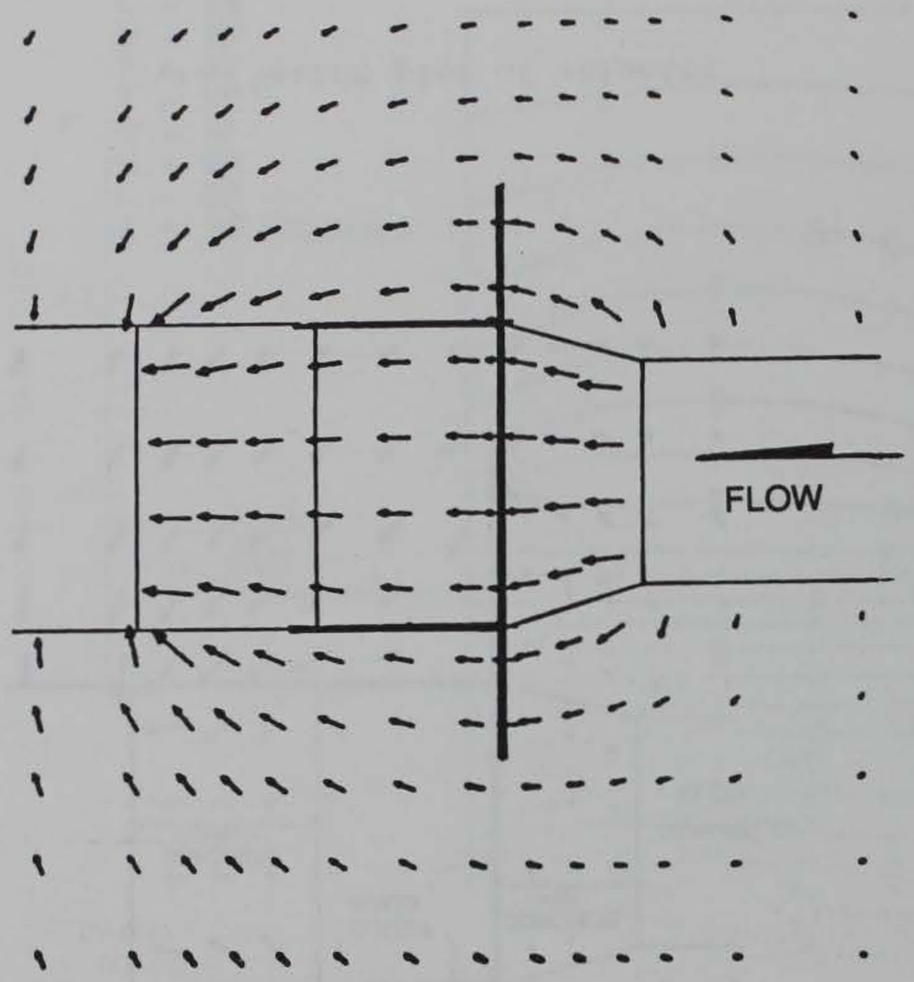



a. Vector plot of velocity

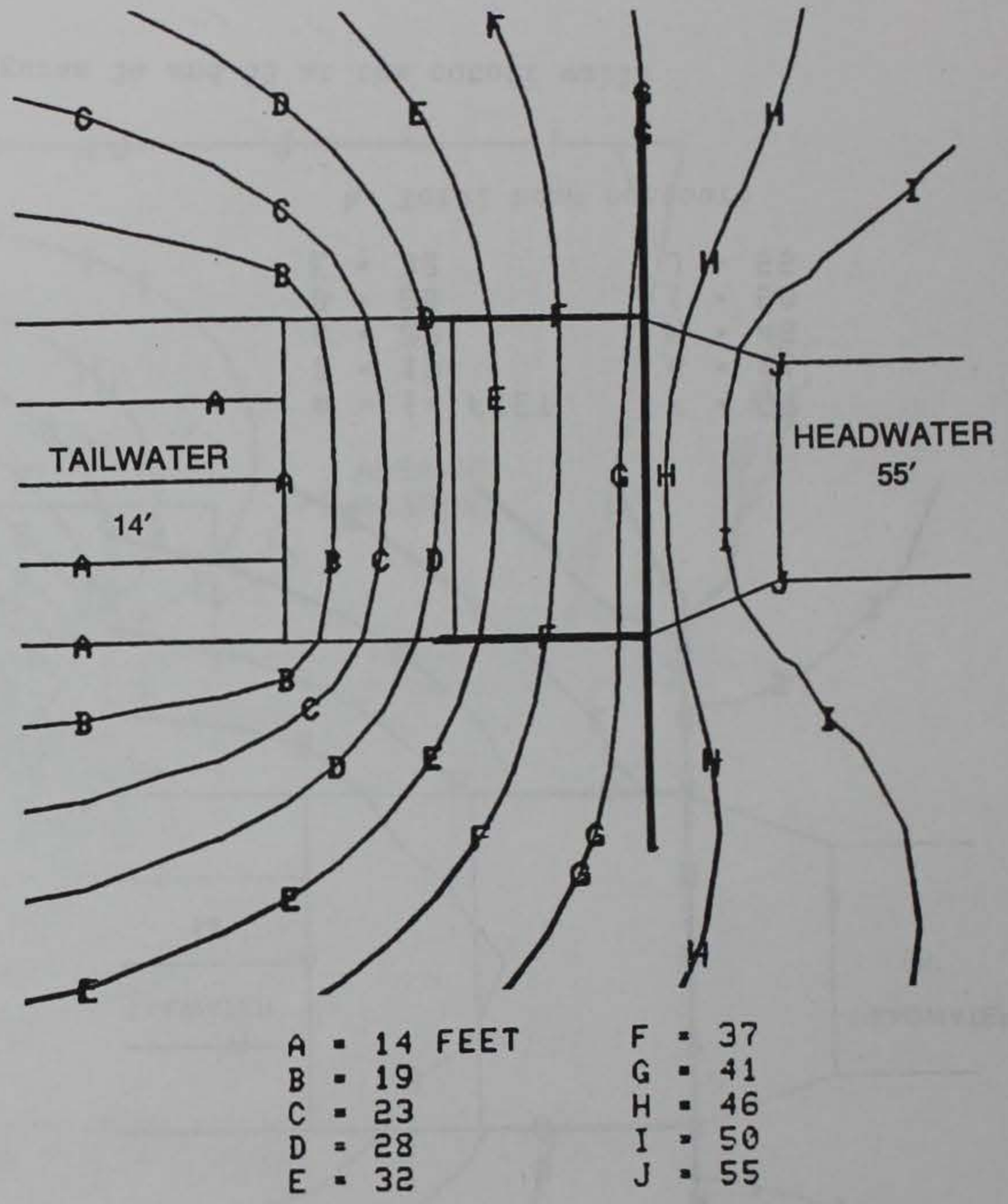



b. Total head contours

Figure 36. Enlarged plots of Figures 34 and 35 at the cutoff walls




a. Vector plot of velocity




b. Total head contours

Figure 37. Velocity vectors and total head contours for cutoff wall permeability of $2 \times 10^{-2}$ ft/min

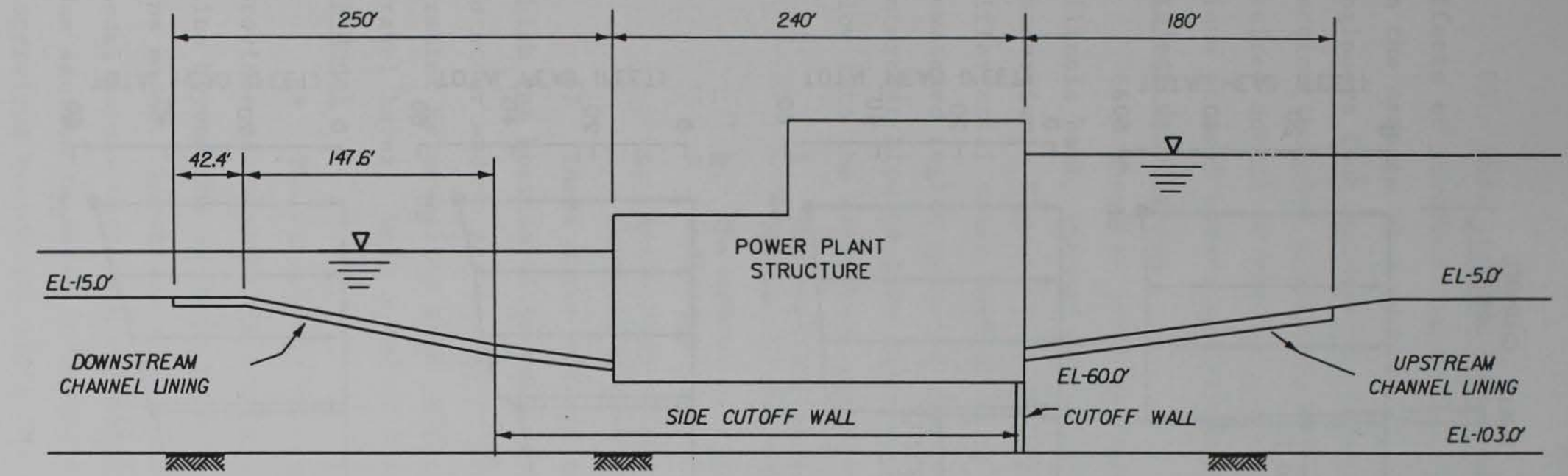



Figure 38. Uplift at center line of powerplant with cutoff wall permeability of $2 \times 10^{-6}$ ft/min

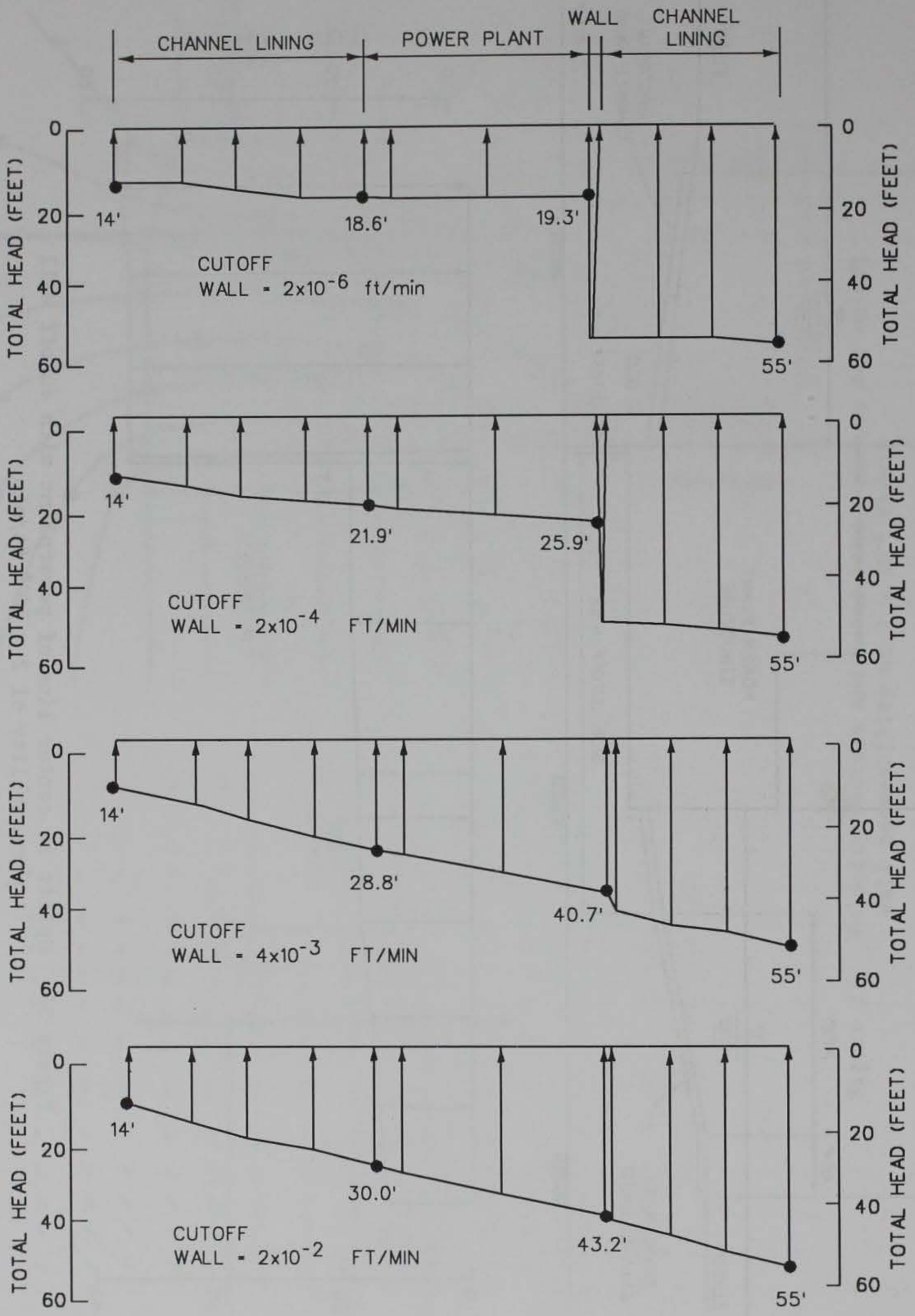



Figure 39. Uplift at center line of powerplant and channel linings for a range of cutoff wall permeabilities

## Example Problem 4

65. This example is one of a series of analyses investigating the effects of riverbed scour, soil anisotropy, and the presence of a gravel bed on the seepage at a section of the first stage cofferdam for the Corps of Engineers Lock and Dam No. 26 (Replacement) (Melvin Price Lock & Dam). The section includes a cellular cofferdam and wellpoints to intercept flow. Desired output is how the quantity of flow is influenced by different conditions of soil strata and permeabilities.

### Project description

66. The area to be modeled is a cross section extending from the Illinois bank, through the cellular cofferdam structure, to the dewatered excavation. Figure 40 shows this section. Seepage occurs due to a differential total head of 90 ft between the river surface elevation and the dewatered region enclosed by the cofferdam. Wellpoints inside the excavation intercept flow to keep the area dewatered. For this problem, the quantity of flow into the excavation depends in part on:

a. The possibility of a gravel layer existing just under the cofferdam and extending landward

b. The extent of a scoured region in the river bed outside of the cofferdam

c. Anisotropy of the soils represented by different horizontal and vertical permeability values.

67. These three factors were investigated by performing 16 analyses in which the horizontal-to-vertical permeability ratio was varied for cases of: no scour and no gravel layer; no scour with gravel layer (gravel at 50 percent greater permeability than sand); scour and no gravel layer; and, scour and gravel layer. Only a few of the cases are presented in this report.

### FE Model

68. The FE grid of the section is shown in Figure 41. A slurry trench provides an impermeable boundary at the left end of the model. A vertical line beyond the Illinois bank is treated as impermeable at the right end of the model. Locations of wellpoints are indicated in Figure 41. These are nodal points where the wellpoints are located. A close-up view of the cofferdam section is shown in Figure 42. The sheet piles of the cofferdam provide impervious boundaries along the extent to which they are driven into the soil. The gravel and scour layer profiles are modeled and material properties for them modeled in the boundary conditions file by specifying a head at nodes in

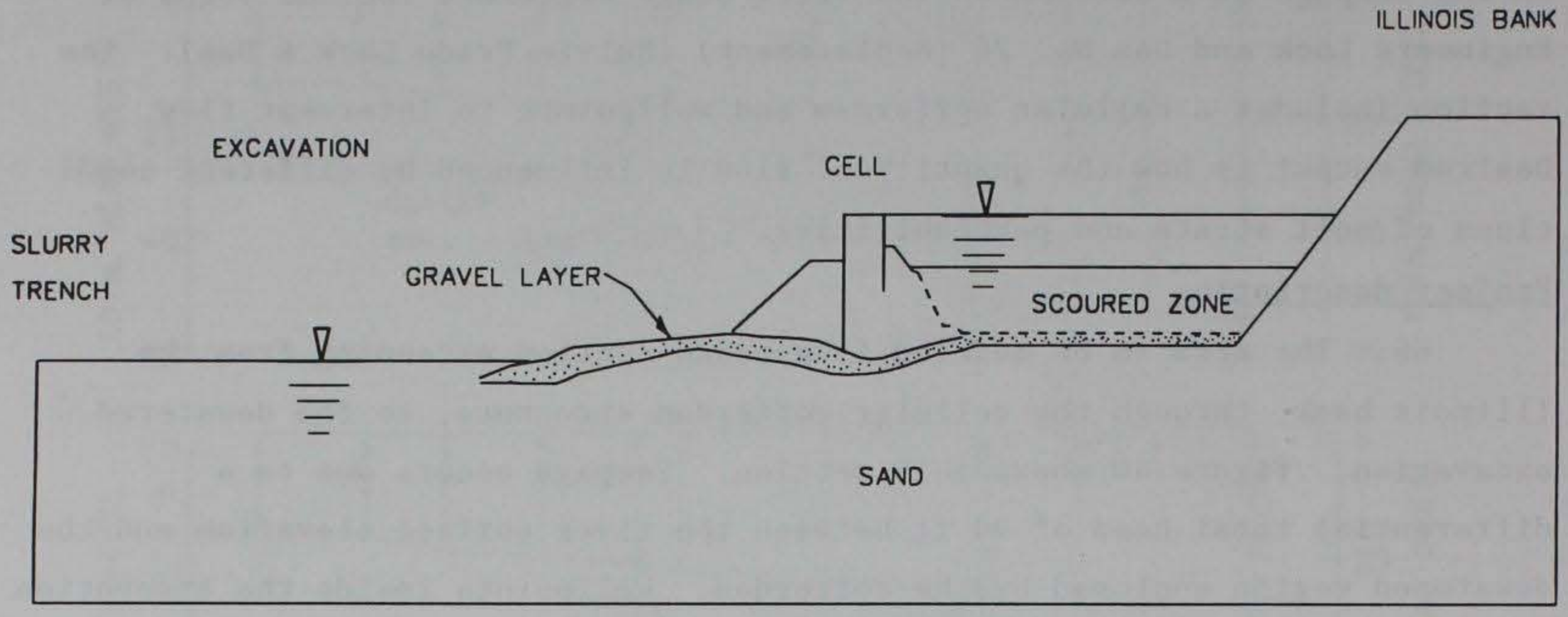



Figure 40. Section of cofferdam, river, and riverbank for example problem 4

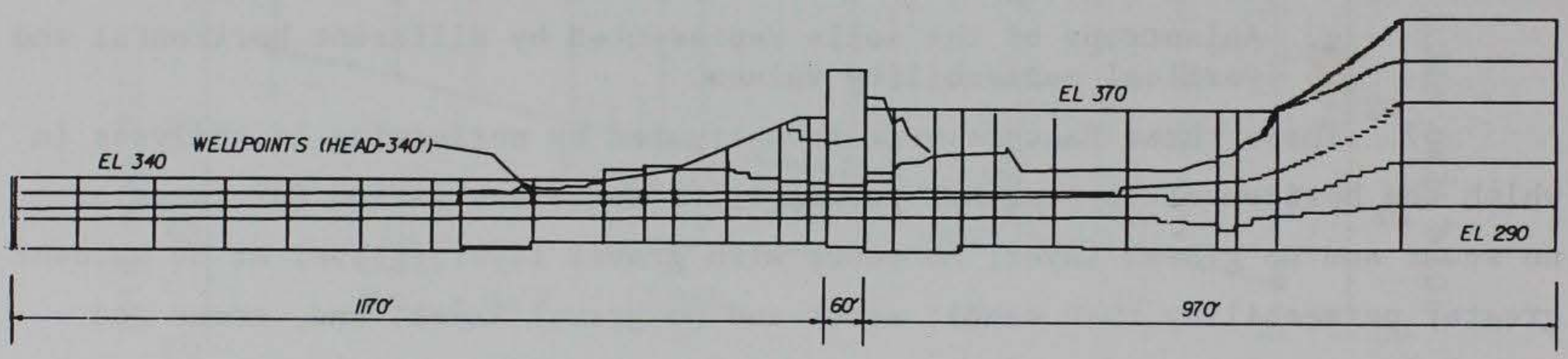



Figure 41. Grid of the section for example problem 4

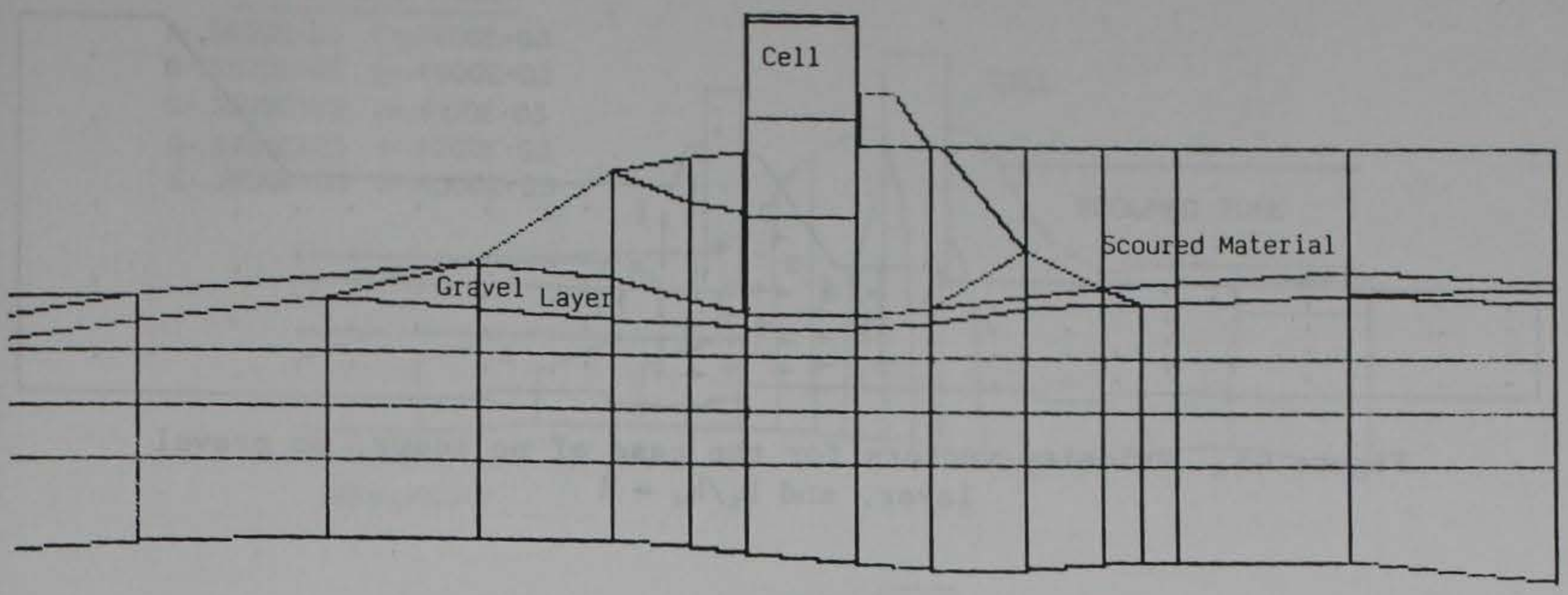



Figure 42. Enlarged plot of the grid at the cofferdam cell

the are provided in those analyses where they are considered. For those cases not modeling gravel and/or scour, the elements are given the properties of the surrounding sand.

Analysis results

69. The simplest case is with no scour and no gravel layer modeled and with the horizontal-to-vertical permeability ratio of the sand equal to one. The vector plot of flow for this case is shown in Figure 43. The majority of flow occurs in the immediate vicinity of the cofferdam and very little flow is experienced in the left and right extensions of the grid. This shows that the model was extended to an appropriate distance away from the main flow region so that the boundaries do not highly influence the flow behavior in the region of concern. Head contours in the cofferdam area are presented in Figure 44. The excavation-side head of 340 ft is maintained by the wellpoints as indicated by the contours labeled "A" occurring within the model. The head drop is almost uniform across the region under the cofferdam. This is because the flow medium is a homogeneous, isotropic material. These results for this simple case show that the model and analysis represent the problem well.

70. As an example of some of the studies performed, a set of head contour plots is shown in Figure 45 for the extreme case when both a scoured region and gravel layer are present. Each plot represents an analysis of this condition with a different horizontal-to-vertical permeability ratio for the sand. As the permeability ratio is increased, more head loss occurs between the river bottom and the cofferdam.

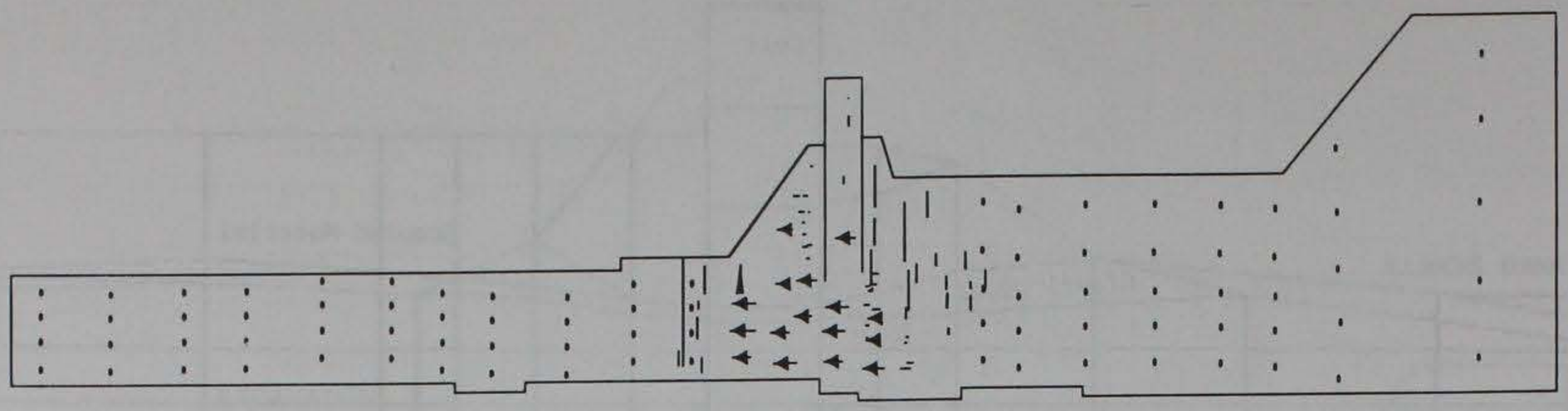


Figure 43. Velocity vectors for the case of no scour, no gravel layer, and $k_h/k_v = 1$

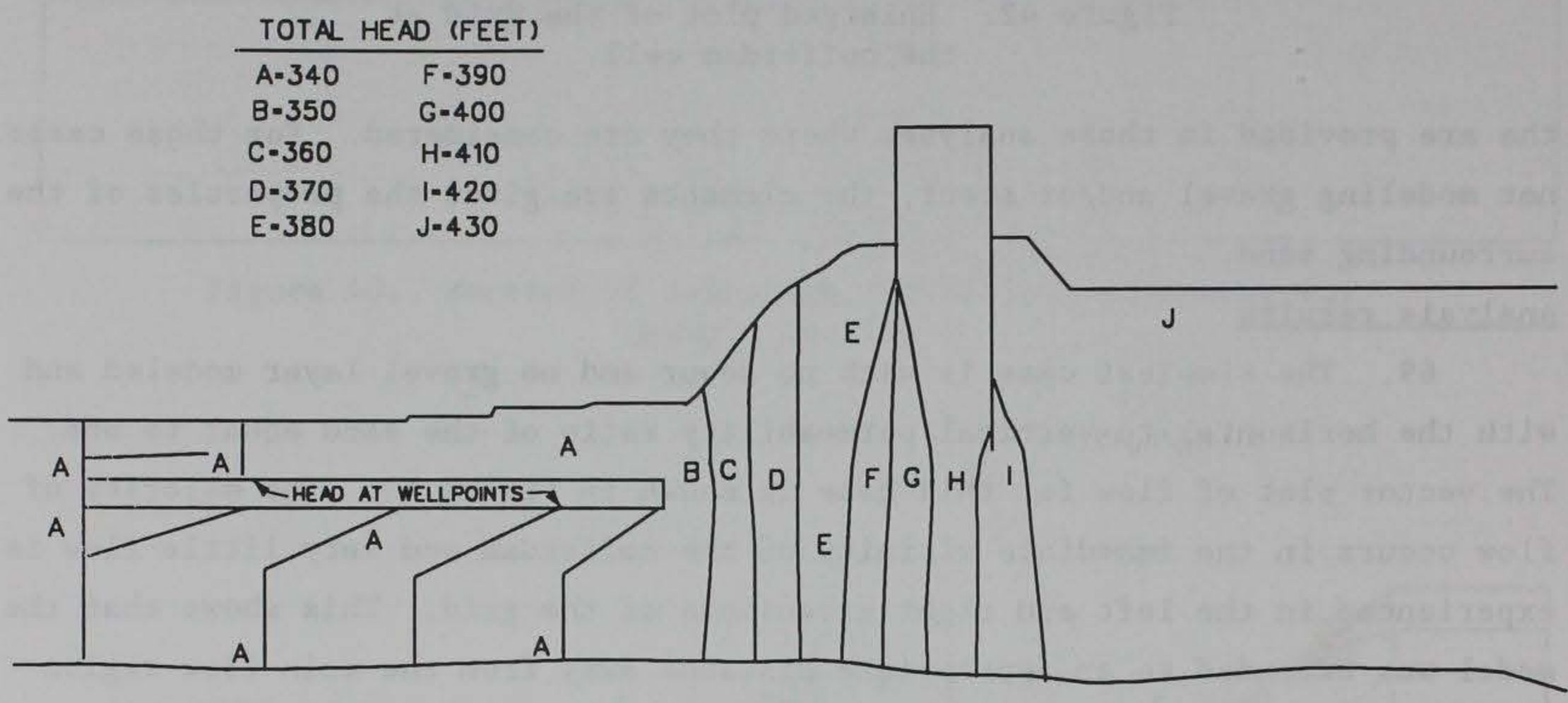



Figure 44. Total head contours for the case of no scour, no gravel layer, and $k_h/k_v = 1$

Summary of results

71. A concise, useful summary of the flow quantities from all the analyses performed in this study is presented in Figure 46 as plots of flow-versus-permeability ratio. One can see immediately that the greatest flow quantity with any of the permeability ratios is caused by the extreme condition in which both the scour and a gravel layer exist (top curve plotted), and that for any of the four conditions modeled, the greatest flow occurs when the horizontal-to-vertical permeability ratio of the sand is one. For permeability ratios greater than about 7, the flow quantity is nearly constant in each case. It is also noted that the permeability ratio affects the flow much more than the presence of a gravel layer or scoured region.

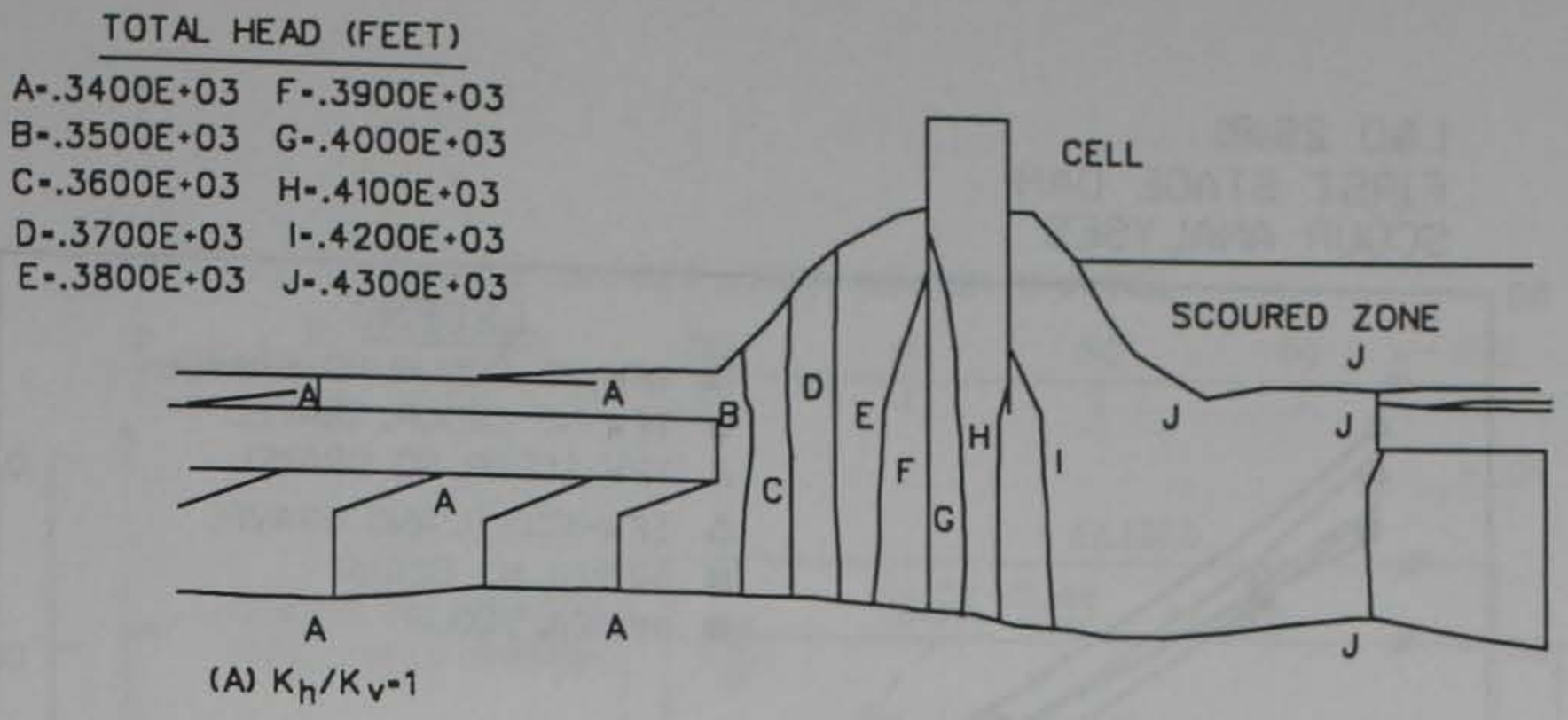



Figure 45. Total head contour plots through cofferdam with gravel layer and scoured region for a range of permeabilities

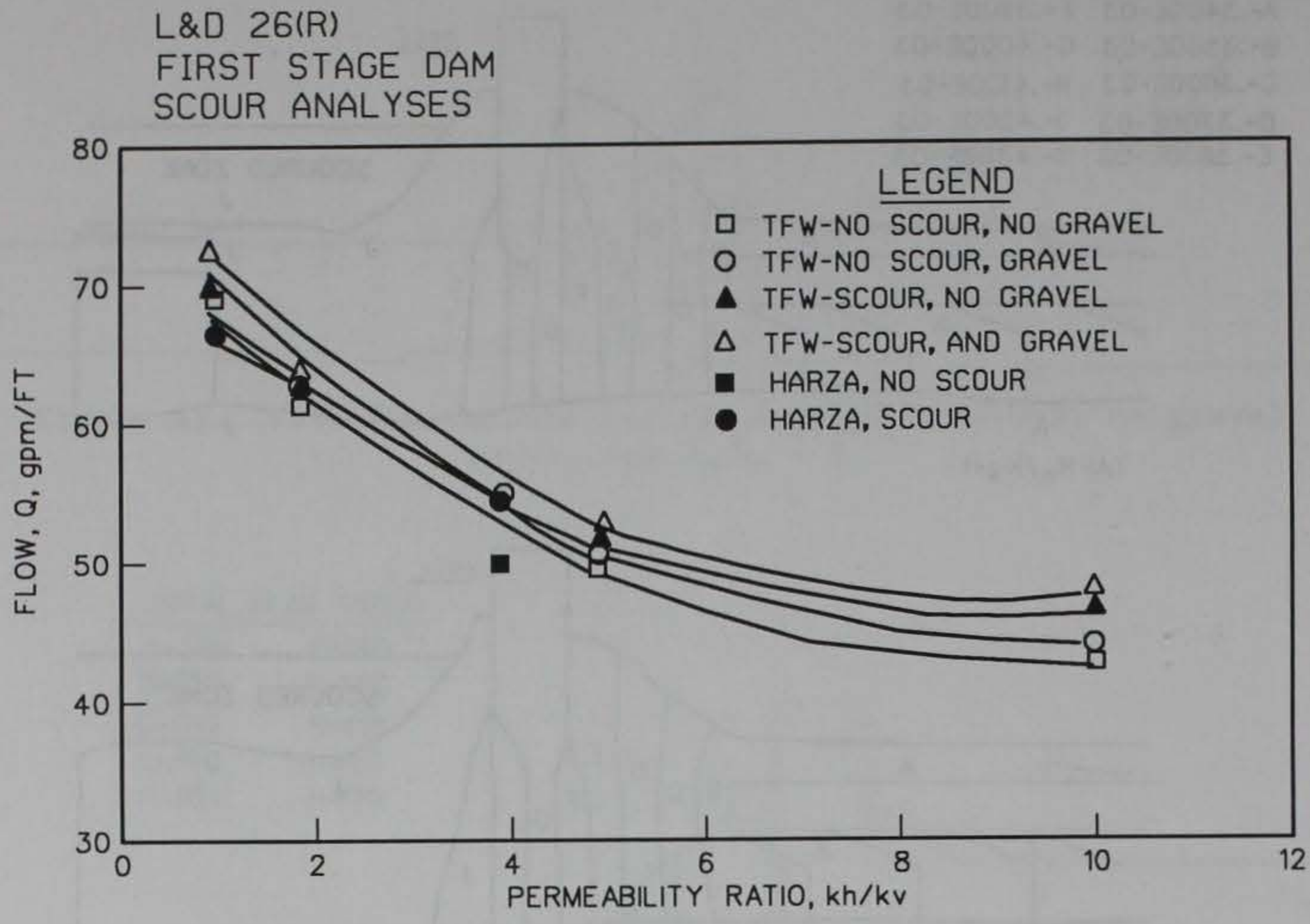



Figure 46. Summary of parametric study results for example problem 4

72. This series of analyses and the form of the results plotted in Figure 46 shows how one model can be used to perform a parametric study of the variables that may affect a case. If used in the planning stages of a project, a plot such as the one in Figure 46 could be used as a design curve possibly for planning a dewatering system.

## Example Problem 5

73. The seepage analysis in this example is used to determine the quantity of flow into the drainage region under a U-Frame channel base so that the drainage system can be designed.

U-Frame channel model

74. The design of a drainage system under a U-Frame channel requires knowledge of the quantity of flow into the region so that the drainage blanket and/or filter type and thickness and the size of collector pipes can all be designed. CSEEP is used to compute this flow for the U-Frame section shown in Figure 47. Only one-half of the section is modeled because it is symmetrical about the vertical center line of the channel.

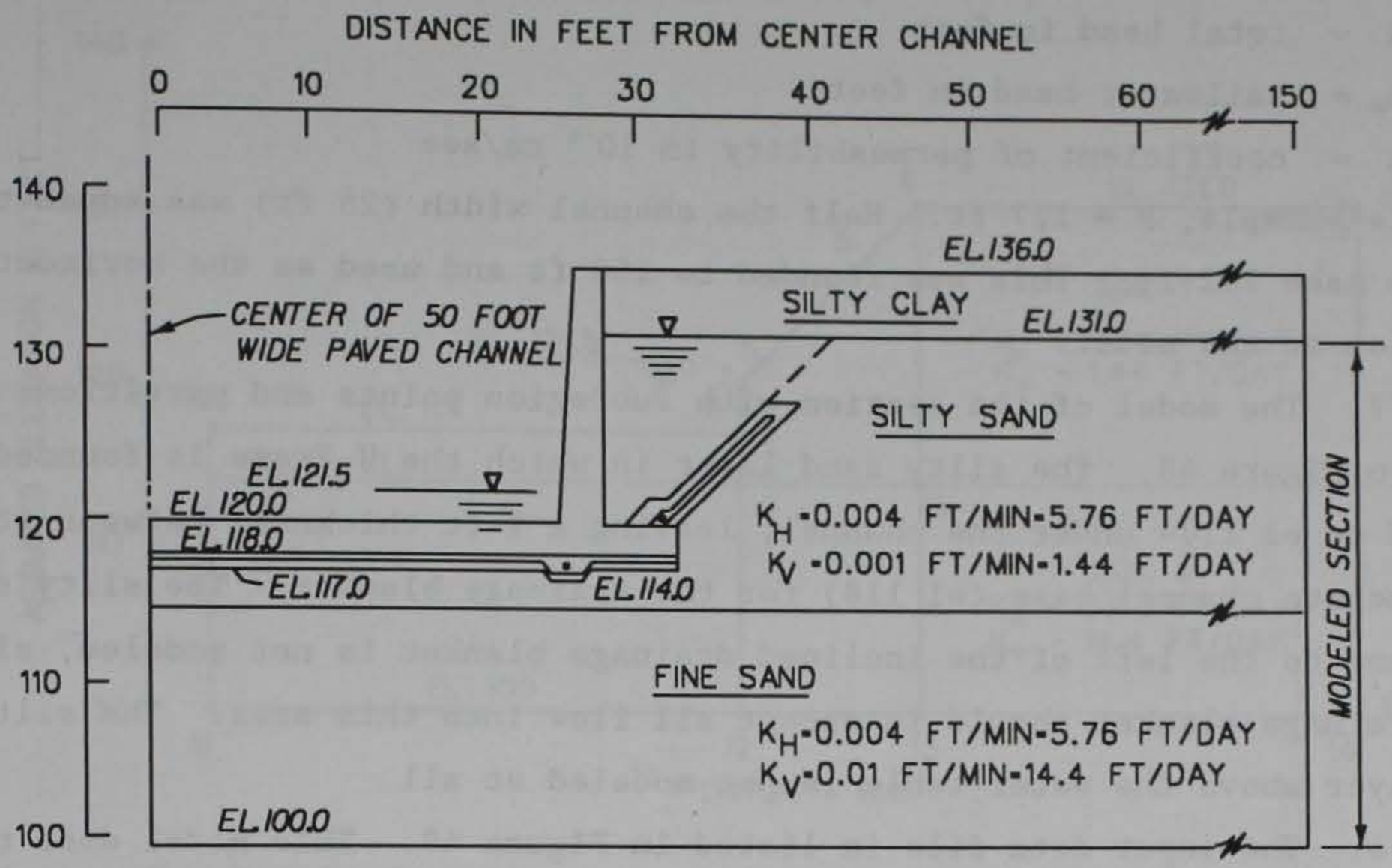



Figure 47. Half-section of U-frame channel for example problem 5

75. The critical head condition will be analyzed. This condition is a differential head of 9.5 ft between the groundwater elevation outside the channel and the uplift head under the channel. The bottom layer of fine sand will conduct much of the flow since it permeability is 10 times that of the silty sand above. An inclined drainage blanket intercepts flow that approaches the side wall of the channel and a horizontal one handles the flow under the floor of the channel. Both drainage blankets will direct the flow to collector pipes.

76. The distance from the center of the U-Frame to the source of steady state seepage was taken as the radius of influence, R, for the silty sand layer. The radius of influence is defined from TM 5-818-5 (Headquarters, Department of the Army, 1971) as "the radius of a circle beyond which pumping of a dewatering system (in this case, flow into the drainage blanket due to a head differential) has no significant effect on the original groundwater level or piezometric surface." The radius of influence is calculated as:

$$R = C(H-h_w)\ (k)^{1/2}$$

where:

C = coefficient depending on type of flow from source (3 for artesian and gravity flow)

H = total head in feet

$h_w$ = tailwater head in feet

k = coefficient of permeability in $10^{-4}$ cm/sec

For this example, R = 127 ft. Half the channel width (25 ft) was added to this to make 152 ft. This was rounded to 150 ft and used as the horizontal dimension of the model.

77. The model of the section with subregion points and partitions is shown in Figure 48. The silty sand layer in which the U-Frame is founded is modeled to el 117* under the channel, leaving a 1-ft thickness between it and the concrete channel base (el 118) for the drainage blanket. The silty sand above and to the left of the inclined drainage blanket is not modeled, since this drainage blanket should intercept all flow into this area. The silty clay layer above the water table is not modeled at all.

78. The input data file is listed in Figure 49. This model does not fully partition the region around the inclined drainage blanket into three- and four-sided polygons. This causes a "spider-web" grid to be generated. Figure 50 displays the generated grid.

Boundary conditions

79. The BC file for this problem is listed in Figure 49. Since the right-side boundary of the model is considered to be the extent of the radius of influence - where the original groundwater level is not affected by the seepage flow into the drainage system - it is given a BC of full groundwater head along the side (points 1, 2, and 3 in the BC file).

80. The left-side boundary of the model is the center line of the section. This is assigned the condition of impermeability. Most of the flow will travel up into the drainage area here, and this condition is mirrored for the left half of the U-frame section. This allows for maximum flow to occur and the drainage system can be designed to handle this. The top boundary of the model has tailwater conditions under the channel base along the area where the drainage blanket will be placed (points 7 through 10), an exit flow

---

* All elevations (el) sited herein are in feet referred to National Geodetic Vertical Datum (NGVD) of 1929.

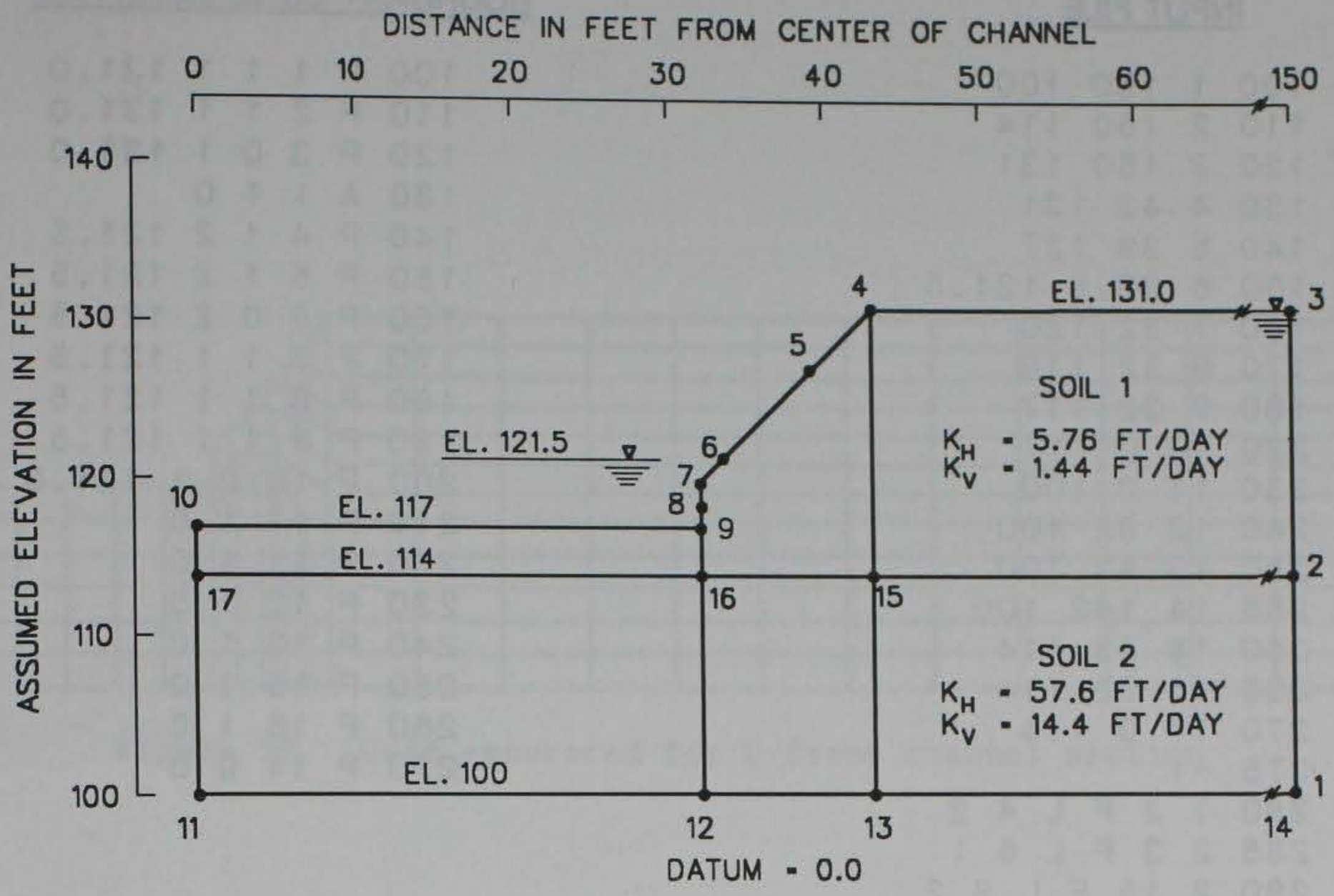



Figure 48. Model of problem 5 section with subregion points and lines

surface along the inclined drainage blanket (points 4 through 6), and an impermeable surface between point 4 and point 3 since flow will not exit here.

Analysis results

81. The flow net from the analysis is shown in Figure 51. Two different material permeabilities are the cause of the two different shapes in the flow net (curvilinear squares and rectangles). The phreatic surface starts at the headwater at the upper right corner of the model and flows to the tailwater at the right corner of the U-Frame base below the inclined blanket. Flow lines connect headwater to tailwater as shown and equipotential head drop is relatively uniform across the region.

82. The plot of flow vectors is presented in Figure 52. This plot and the flow net clearly show the flow in greater quantity through the lower, fine sand layer. The quantity of flow along the drainage areas is listed in Figure 53. The flow sum is 6.0 $ft^3$/day along the inclined side drainage blanket, and 43.6 $ft^3$/day along the base. These values represent flow per linear foot of the channel and were obtained from the printed output of CSEEP which lists entrance and exit flow for nodes on the phreatic surface.

83. With this information the drainage system was designed to have a center pipe and an end pipe under the base and one pipe on the side of the

**INPUT FILE**

```
100  1  150  100
110  2  150  114
120  3  150  131
130  4  43  131
140  5  39  127
150  6  33.5  121.5
160  7  32  120
170  8  32  118
180  9  32  117
220  10  0  117
230  11  0  100
240  12  32  100
250  13  43  100
255  14  142  100
260  15  43  114
265  16  32  114
270  17  0  114
275  -1
280  1  2  F  L  4  2
285  2  3  F  L  6  1
290  2  15  F  L  8  2
295  3  4  F  L  8  1
300  4  5  F  L  1  1
310  5  6  F  L  2  1
320  6  7  F  L  0  1
330  7  8  F  L  0  1
335  8  9  F  L  0  1
340  11  17  F  L  4  100
350  17  10  F  L  0  100
360  10  9  F  L  6  100
370  11  12  F  L  6  2
375  12  16  F  L  4  2
380  12  13  F  L  4  2
390  13  15  F  L  4  2
400  13  14  F  L  7  2
410  14  1  F  L  0  2
420  15  4  F  L  6  1
450  15  16  F  L  4  2
455  16  17  F  L  6  2
460  16  9  F  L  0  1
```

**BOUNDARY CONDITIONS FILE**

```
100  P  1  1  1  131.0
110  P  2  1  1  131.0
120  P  3  0  1  131.0
130  A  1  1  0
140  P  4  1  2  121.5
150  P  5  1  2  121.5
160  P  6  0  2  121.5
170  P  7  1  1  121.5
180  P  8  1  1  121.5
190  P  9  1  1  121.5
200  P  10  0  1  121.5
210  P  17  1  0
220  P  11  1  0
230  P  12  1  0
240  P  13  1  0
250  P  15  1  0
260  P  16  1  0
270  P  14  0  0
```

Figure 49. Input files to the preprocessor for example problem 5

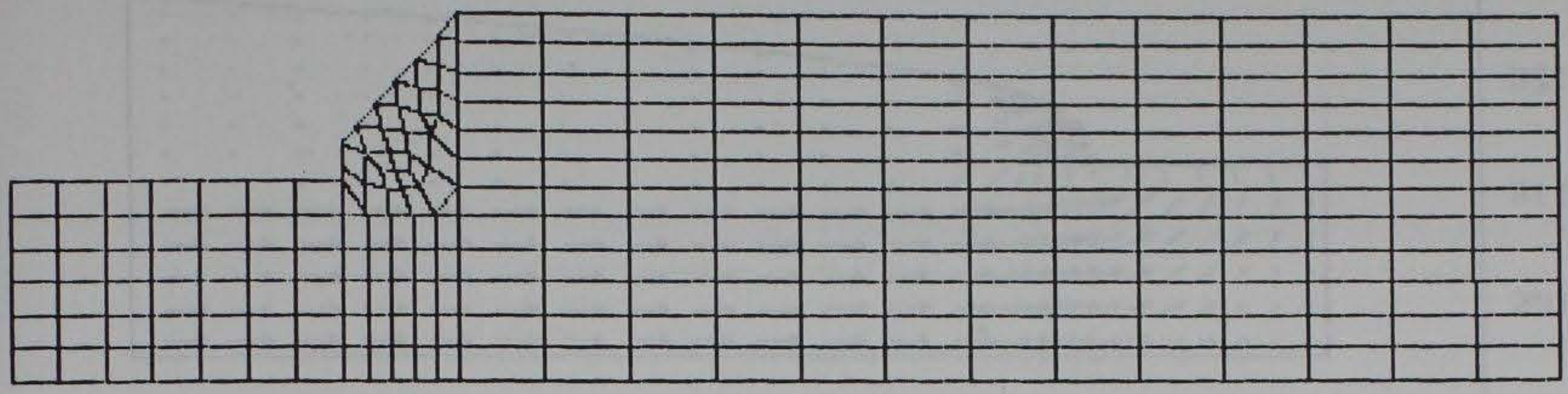


Figure 50. Grid generated for U-frame channel section

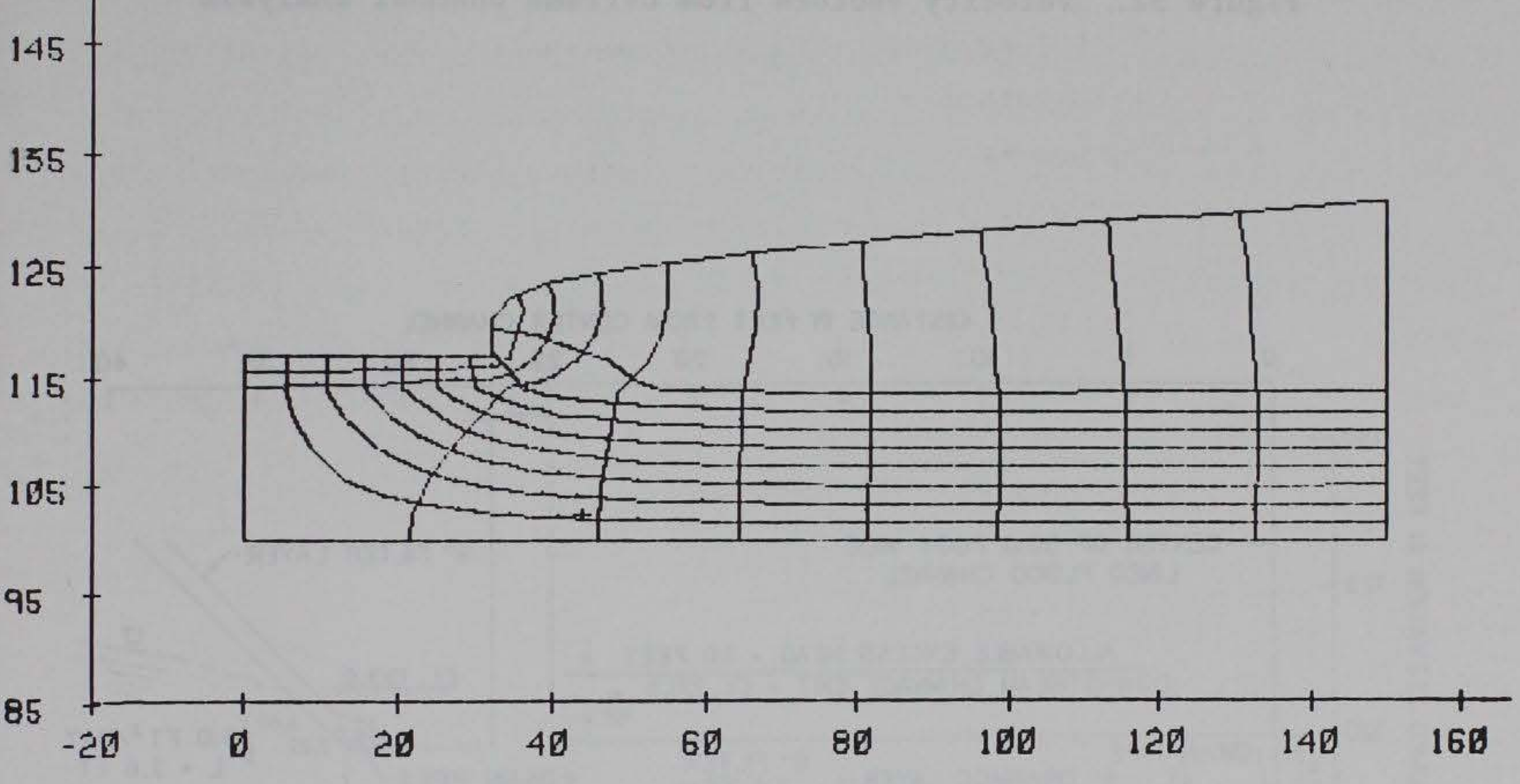



Figure 51. Flow net from U-frame channel analysis

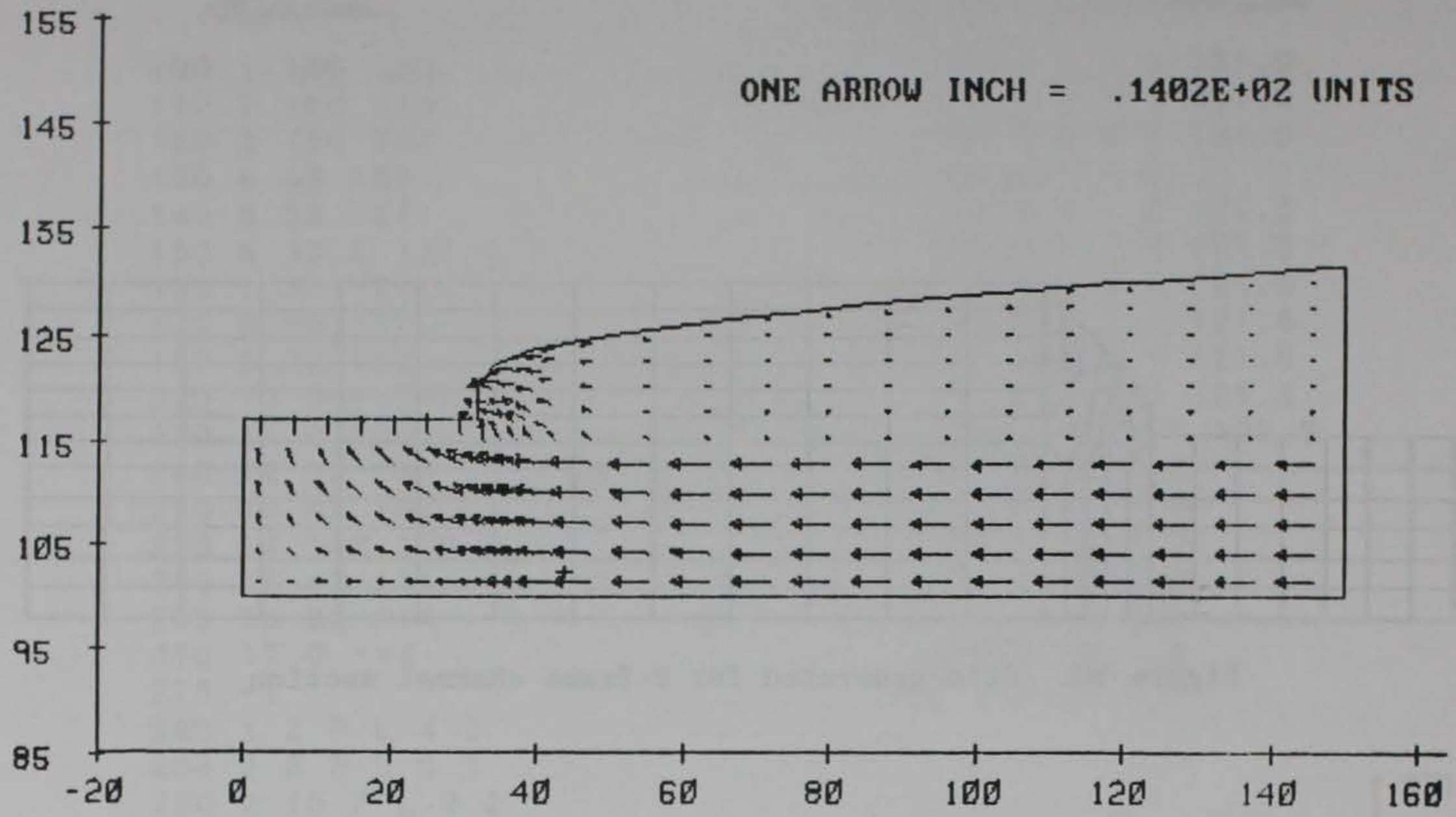



Figure 52. Velocity vectors from U-frame channel analysis

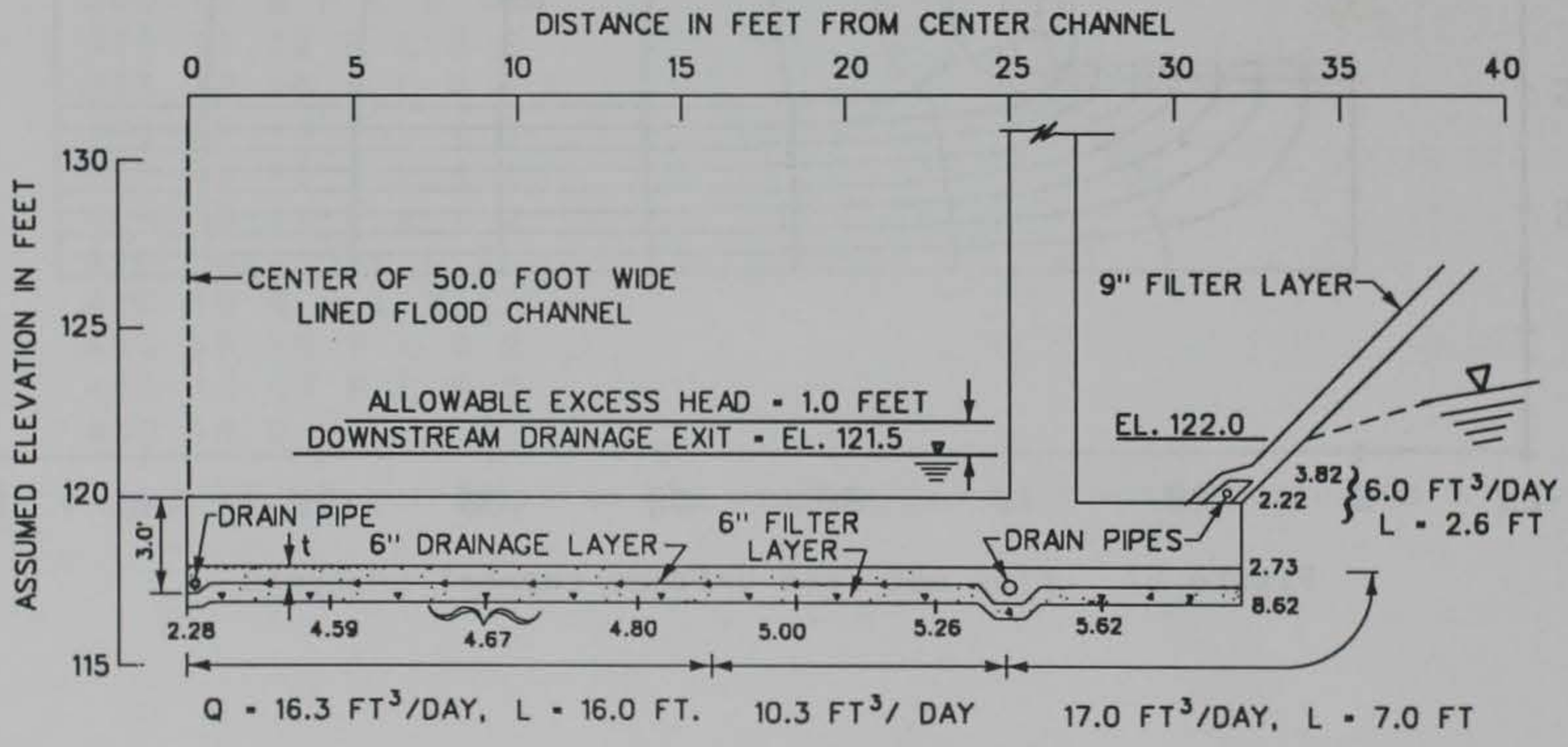



Figure 53. Flow values under channel bottom taken from printed seepage analysis output

channel. Flow to these pipes is conducted by a 6-in. drainage layer and a 6-in. filter layer. As shown in Figure 53, the drainage system is partitioned into anticipated flow quantities entering each of the three pipes. Design of the drainage system was based on criteria presented in USAE Engineer Manuals 1110-2-1901 and 1110-2-2502 (Headquarters, Department of the Army, 1986 and 1989, respectively).

## PART III: ASPECTS OF PROGRAM USE

84. This part addresses areas of potential difficulty in using the seepage program and modeling a problem. The problems discussed are ones experienced by past users of the program.

| Program Capacity | |
|---|---|
| Item | Maximum |
| Nodes | 1,000 |
| Elements | 950 |
| Materials | 12 |
| File-names | 8 characters<br>(or 5 plus 3-character extension) |

### Organizing Data Files

85. There are many different input and output files used with the seepage package. In the preprocessor program (X8200) there are four input files and one output file; in the seepage analysis program (X8202) there is one input file and two output files; and in the postprocessor program (X8201) there is one input file. Confusion arises not only in keeping track of all these file names, but also in understanding the input-output sequence between each program in the package. The flow chart shown in Figure 54 can be helpful in keeping track of the six different files used in an analysis. Fill in the chart as you go through your problem. It is helpful to develop a naming convention which can be applied each time the seepage package is used. An example of this, below, shows acronyms for the type of file used as part of the filename.

| File Type | Name | | |
|---|---|---|---|
| Input | *name*IN | or | *name*.IN |
| Restart | *name*RE | or | *name*.RES |
| Boundary Condition | *name*BC | or | *name*.BC |
| Output | *name*OT | or | *name*.OUT |
| Printout | *name*PT | or | *name*.PRT |
| Postprocessor | *name*PP | or | *name*.PP |

The purpose of each file is briefly summarized in the following paragraphs.

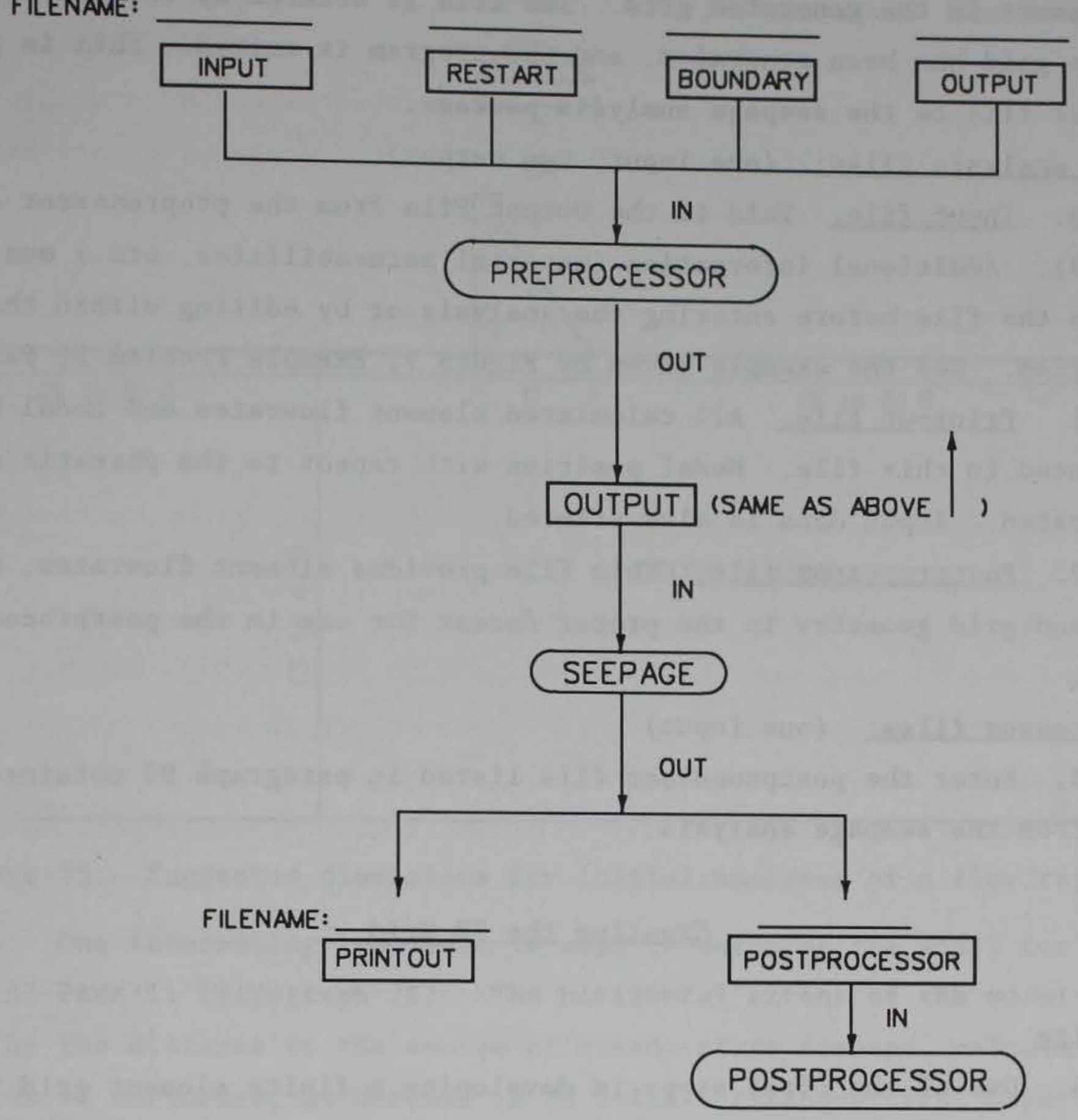



Figure 54. Flow chart describing data files used in the seepage programs

Preprocessor files: (three input, one output)

86. Input geometry file. This file defines basic geometric regions of the grid (points and line segments), tells the preprocessor how many extra nodes to generate, and defines regions of different material types.

87. Restart file. The preprocessor writes this file when Module 1 is exited or if the SAV command is used when editing in Module 1. If the program is exited and started again, the restart file can be used instead of the input file to enter the most recent data.

88. Boundary conditions file. This file defines seepage boundary conditions to be applied to the generated grid.

89. Output file. This file contains the coordinates and boundary conditions for each node, and the surrounding nodes and material type number of

each element in the generated grid. The file is written by the preprocessor when the grid has been generated, and the program is exited. This is part of the input file to the seepage analysis package.

Seepage analysis files: (one input, two output)

90. Input file. This is the Output File from the preprocessor (paragraph 89). Additional information (material permeabilities, etc.) must be added to the file before entering the analysis or by editing within the analysis program. See the example given by Figure 7, Example Problem 1, Part II.

91. Printout file. All calculated element flowrates and nodal heads are printed in this file. Nodal position with repect to the phreatic surface is indicated. Input data is also printed.

92. Postprocessor file. This file provides element flowrates, nodal heads, and grid geometry in the proper format for use in the postprocessor program.

Postprocessor files: (one input)

93. Enter the postprocessor file listed in paragraph 92 obtained as output from the seepage analysis.

## Creating the FE Grid

### Model size

94. One of the first steps in developing a finite element grid is to determine the extent or dimensions of the model. For some problems this is relatively easy, such as when natural boundaries dictate modeling conditions. However, for many cases there is some amount of difficulty in selecting how long, wide, and deep, the region should be. There are no set rules for determining the extent of the model since each case is different; however, a general recommendation can be made for a starting point: use the width of the structure, levee, dam, or whatever item is of major concern through, around, or under which seepage occurs, and extend the model five to six times this width to either side of it, and three to four times this width below it, or to an impermeable barrier - whichever comes first. Figure 55 shows an application of this technique. This should provide enough space to the model to keep the BC from affecting the flow in the area of concern. If this area is too large, (see Example Program 2, Part II, paragragh 41), it can be reduced in subsequent grid refinements or the elements toward the outside boundaries can be made very large so that less computer storage is required.

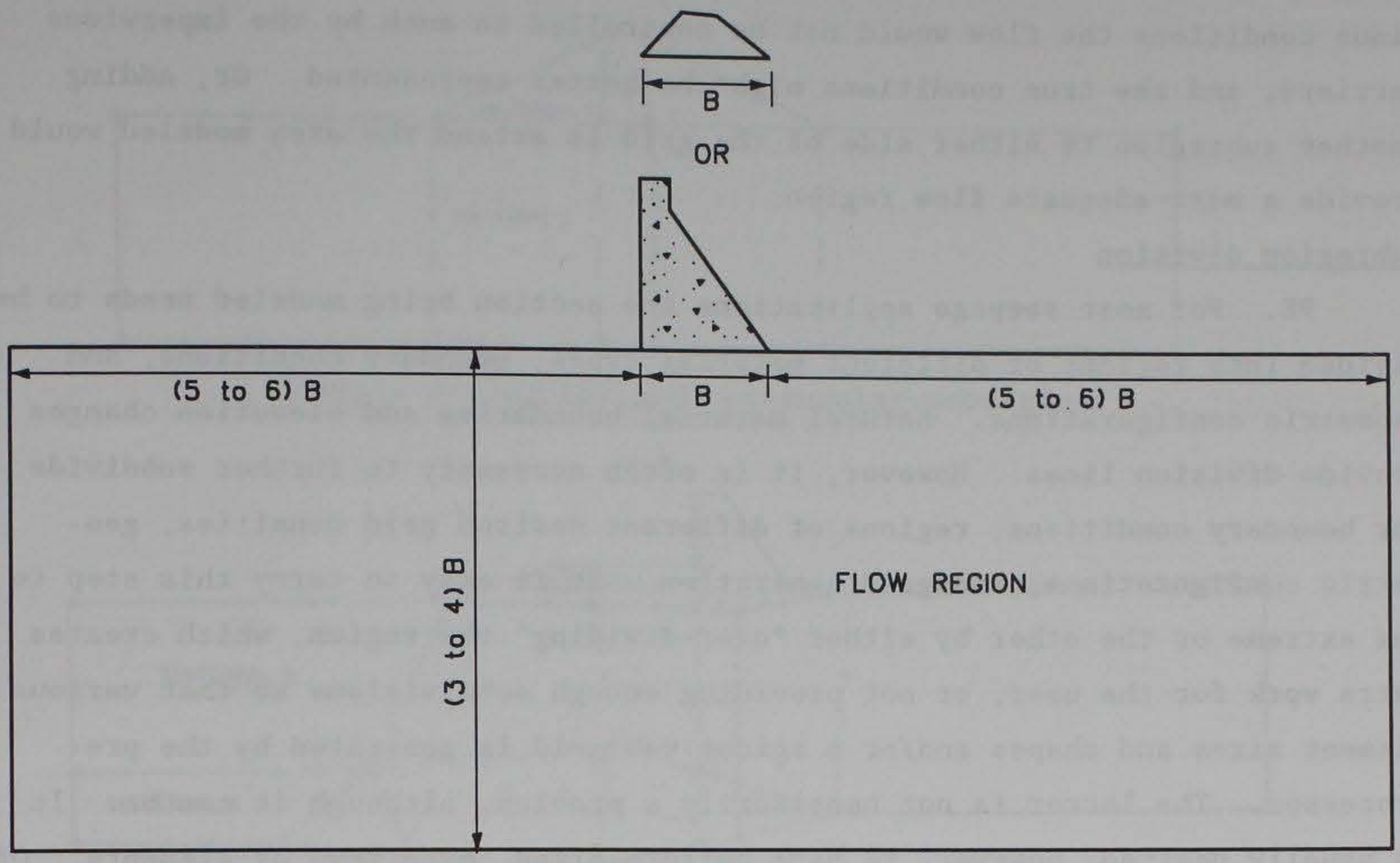



Figure 55. Suggested dimensions for initial analyses of a flow region

95. One interesting technique is used in defining the model for Example Problem 5, Part II (paragraph 76). The horizontal extent of the model is determined by the distance to the source of steady-state seepage, calculated by the radius of influence, as defined in TM 5-818-5 (Headquarters, Department of the Army, 1971). This, or a similar technique, may be applicable to one's particular problem.

96. It is advisable, particularly with complex problems or with inexperience in these type of analyses, to form a trial model with the expectation that it will be refined or modified to some extent after initial analyses have been performed. In Example Problem 2, Part II, the size of the final grid is reduced after initial analyses showed that the region was more than large enough to model the flow. This was determined by viewing the vector plot of the flow shown in Figure 20.

97. An example of a model which should probably be larger is the model in Example Problem 1 (Figure 2). If, in reality the conditions at the location of the side boundaries are not impervious but continue indefinitely in either direction, then this model is not a good representation of the section. This problem is revealed by the vector plots (Figure 11) and discussed in

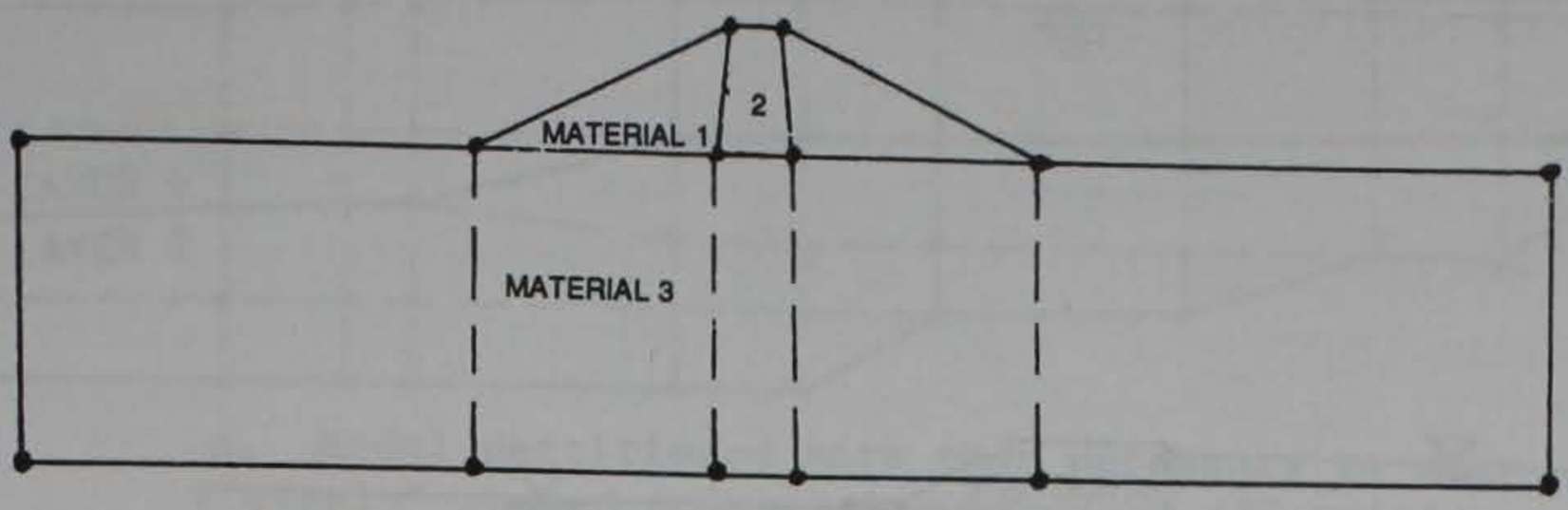
paragraph 24 . By specifying head along the side boundaries instead of impervious conditions the flow would not be controlled so much by the impervious barriers, and the true conditions might be better represented. Or, adding another subregion to either side of the grid to extend the area modeled would provide a more adequate flow region.

Subregion division

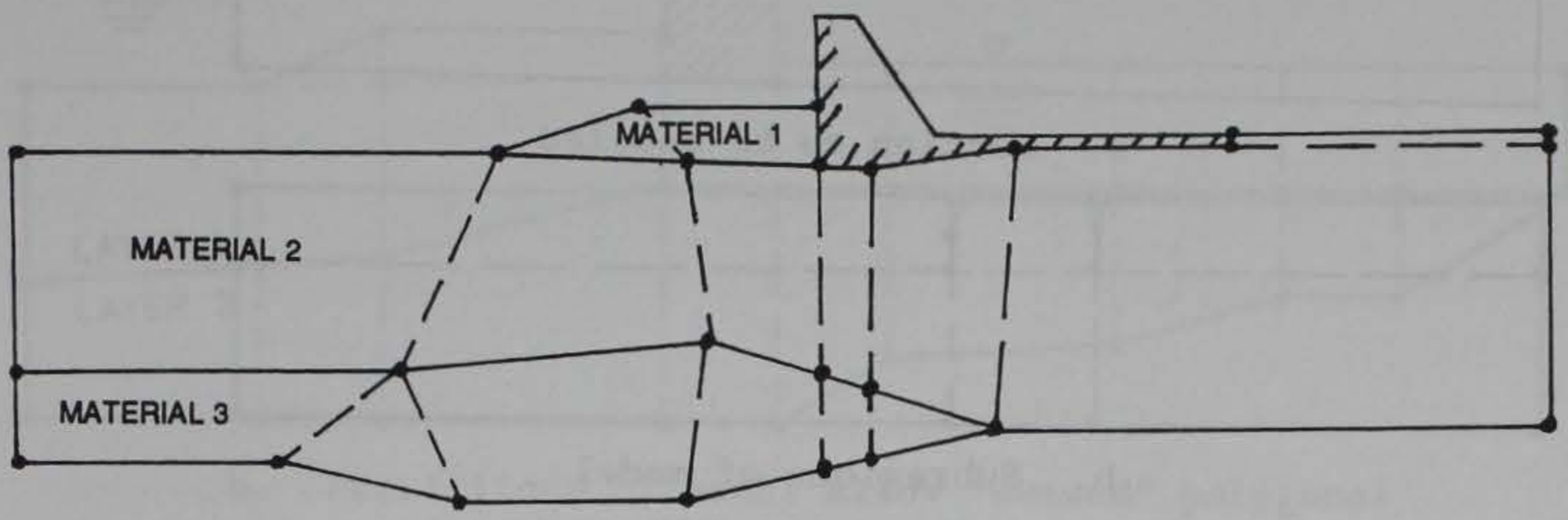
98. For most seepage applications the section being modeled needs to be divided into regions of different material types, boundary conditions, and geometric configurations. Natural material boundaries and elevation changes provide division lines. However, it is often necessary to further subdivide for boundary conditions, regions of different desired grid densities, geometric configurations, and grid generation. It is easy to carry this step to one extreme or the other by either "over-dividing" the region, which creates extra work for the user, or not providing enough subdivisions so that various element sizes and shapes and/or a spider-web grid is generated by the preprocessor. The latter is not necessarily a problem, although it can be. It is usually desired, however, to have uniform-sized, even rows of elements. Of the two, the former, over-dividing the section, is the more frequent problem.

99. It is not always necessary to create a detailed, exact grid. The model should be a good geometric representation of the problem, but since the solution is a close approximation and not exact, it may be inappropriate to spend excess time and computer memory on intricate, dense grids. A sufficient solution may often be obtained from simple models. The most effective forms of the subregion (for ease of grid development) in most seepage applications are triangular and rectangular, or three- and four-sided regions. Embankments, dams, levees, and similar formations can easily be divided into triangular and rectangular regions as shown in Figure 56. Five-sided rectangular subregions can be used effectively if the number of nodes on opposite sides is equal or if a "spider-web" grid (from uneven number of nodes) is not undesirable, such as that used in Example Problem 5, Figure 50. Figure 57 shows an evenly gridded five-sided subregion.

100. An example of over-dividing the model as discussed is shown in Figure 58a. In this case, the entire input file is nearly complete as written by hand. The capabilities of the preprocessor are hardly used. A more efficient division of subregions for this problem is shown in Figure 58b.




a. Simple triangular and rectangular subregions

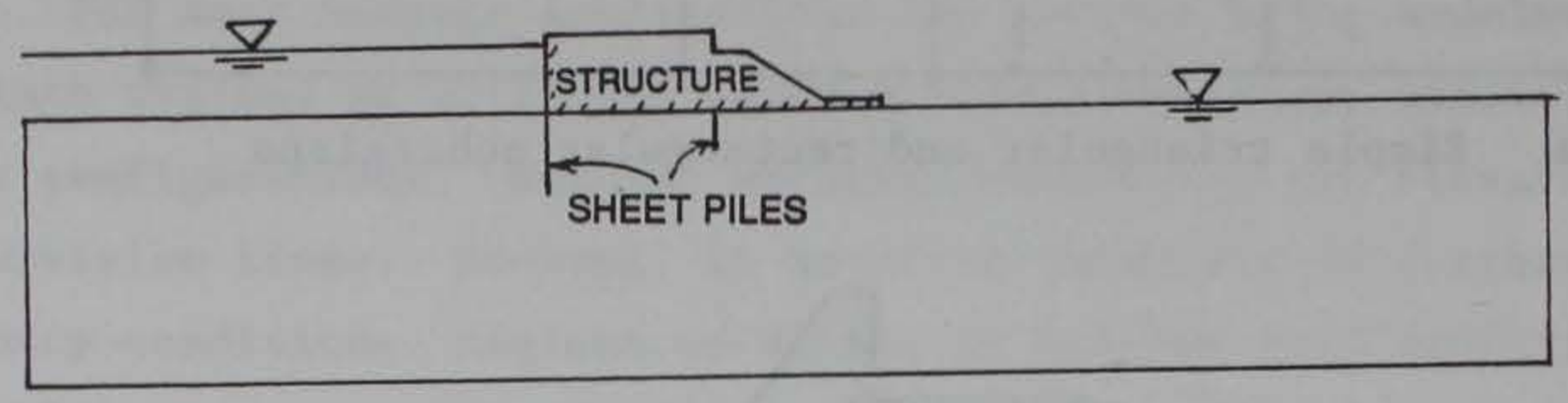



b. "Uneven" subregion polygons

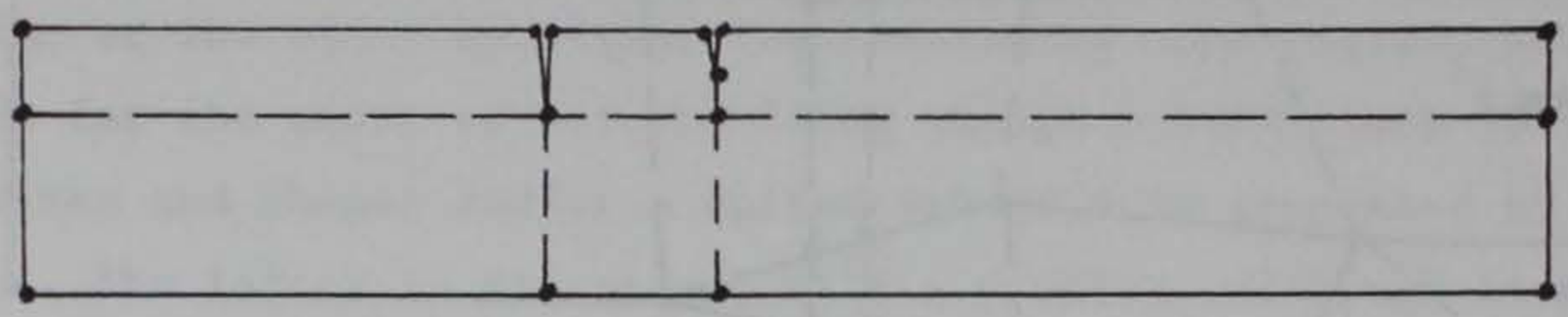
Figure 56. Examples of subregion shapes

Element size

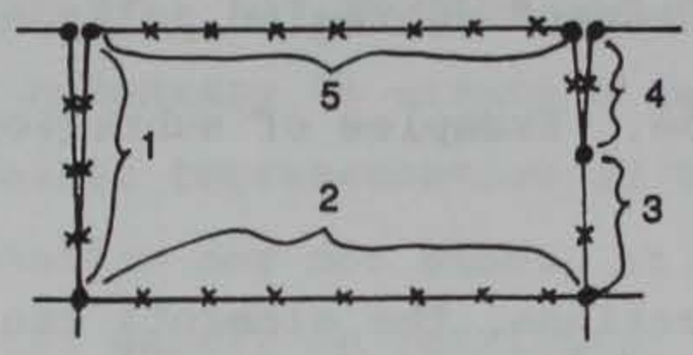
101. For many applications, the elements can be enlarged toward the bottom and outside boundaries of the grid. The grid should be denser around the areas of most concern, where most flow or highest gradients are expected to occur. Small elements can be used throughout the entire grid if one has the resources (computer memory, time, and funds) to accomodate this. The size of the individual elements in a "dense" region of the grid is again relative to the particular problem. It may take two or three modeling attempts before appropriate configurations are discovered. For instance, the section shown in Figure 59a can be modeled by the simple subregions and node placement shown in Figure 59b; however the resulting uniform grid, Figure 59c, may not provide results that are as accurate as desired. Figure 59d shows subregions added to refine the grid in the main flow region, and Figure 59e shows this grid. Possibly a better model is that shown in Figure 59f in which the nodes extending away from center and downward are spaced quadratically so that the elements immediately adjacent to the dense region are similar in size to the



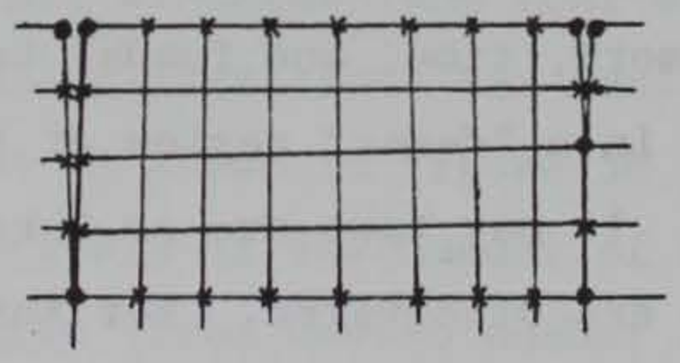

a. Section to be modeled



b. Subregions of model

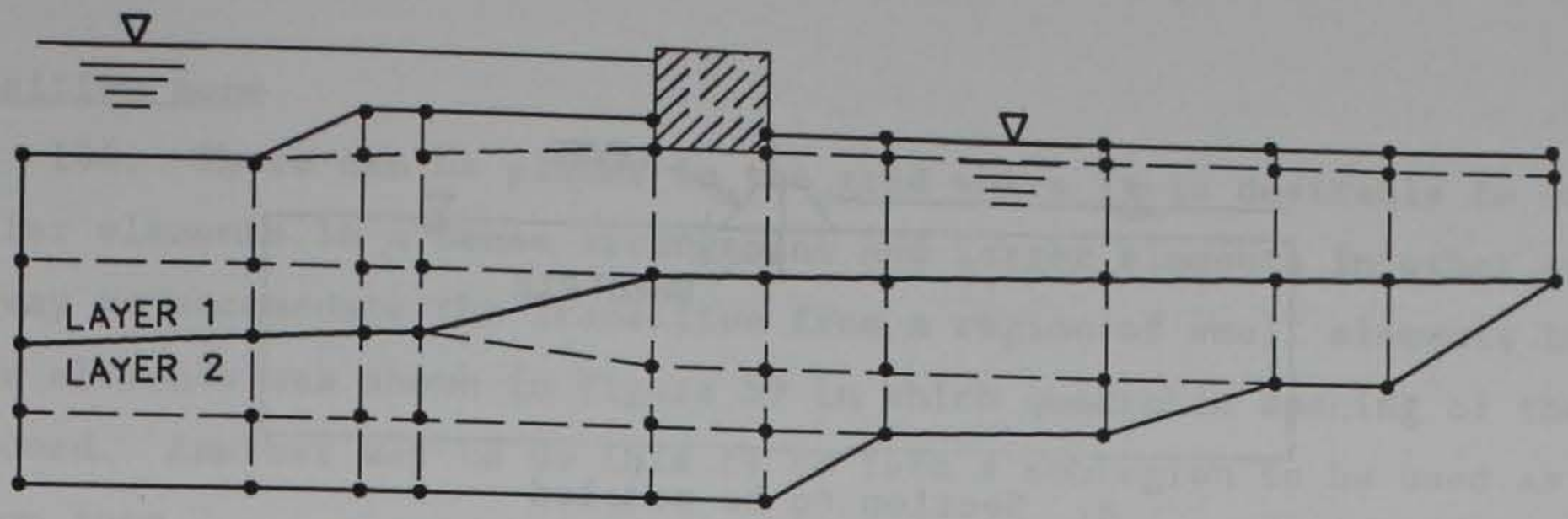



c. Close-up of 5-sided subregion between sheet piles

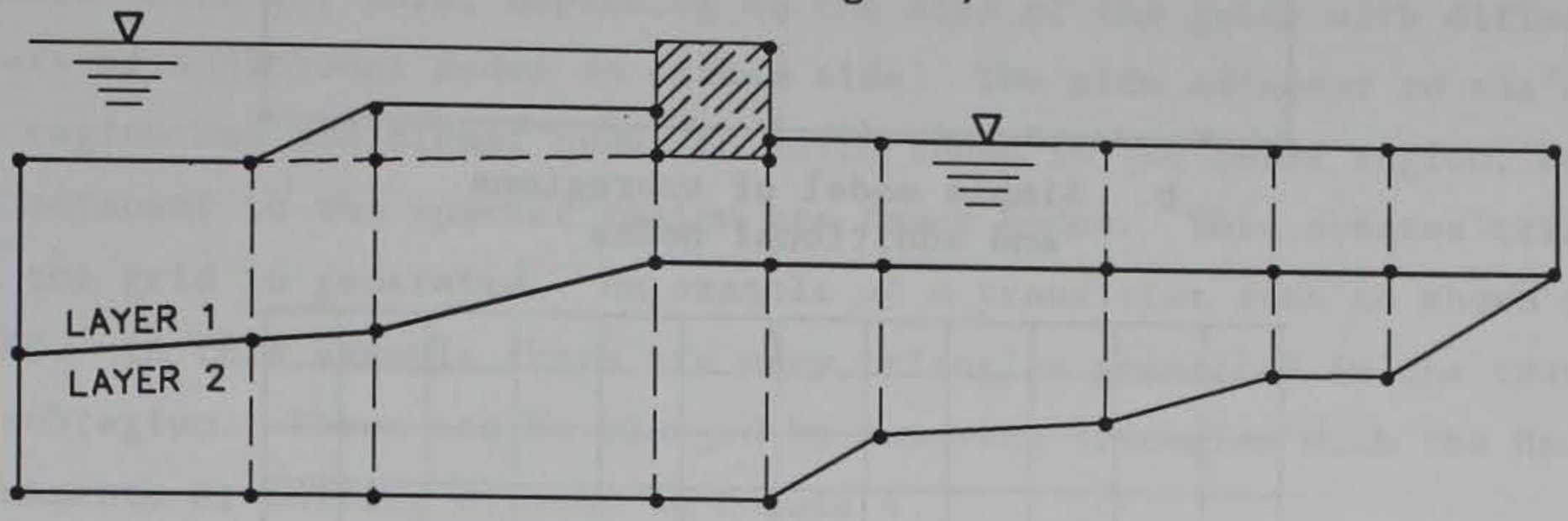


d. Grid of 5-sided sub-region with equal number of nodes on opposite sides

Figure 57. Evenly gridded 5-sided subregion




a. Model partitioned more than necessary to make "evenly" shaped polygonal subregions (55 points, 43 subregions)



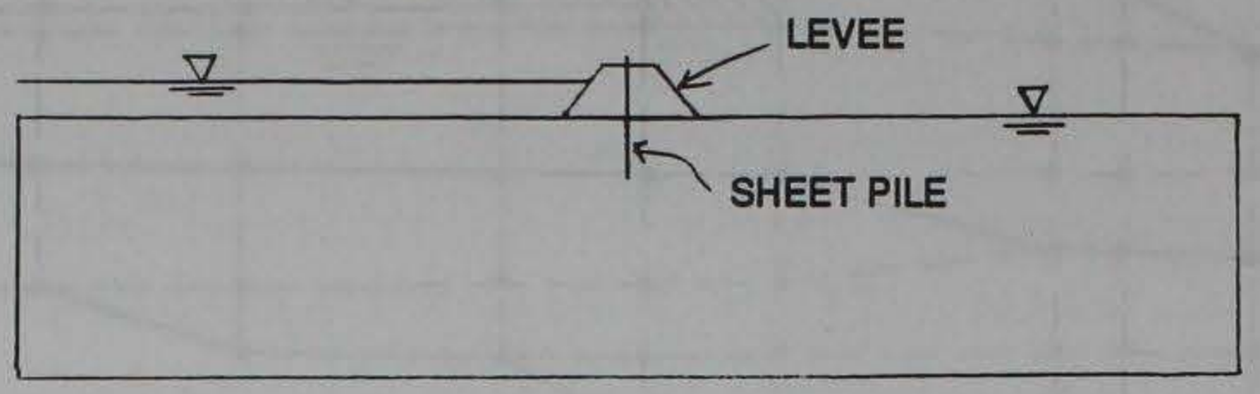

b. Partitiions of model allow "skewed" polygonal subregions (32 points, 21 subregions)

Figure 58. Example of over-divided region

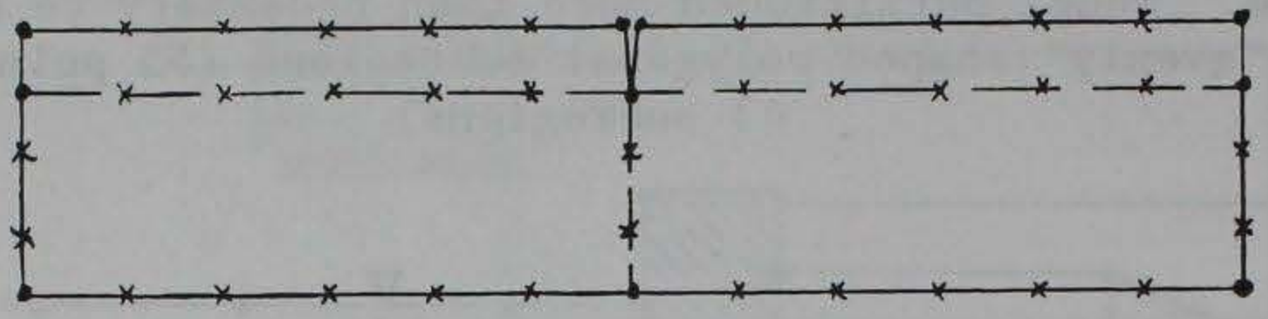
denser elements, and gradually get larger toward the sides and bottom. This also produces fewer elements and nodes than the grid in Figure 59e.

102. The exact size of the elements in one's particular problem cannot be computed by set rules. One's experience in finite element analysis is the best teacher. Some experienced analysts develop their own grids and use the node generating features of the FE-Seepage program (X8202) directly, without going through the preprocessor (X8200). All the example data files shown in Part II used the preprocessor.

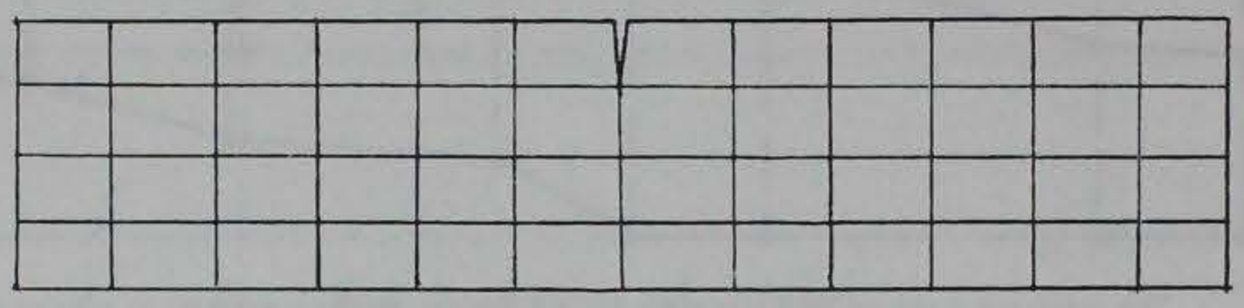
103. A good way to determine if a grid is fine enough is to prepare a simple model (one material, rough outline of the region, etc.) and compare results from its analysis with results from similar problems, rough hand calculations, or other methods of analysis to verify the model. Then perform another FE analysis of the same problem using a finer grid. If the results are alike or agree to some acceptable tolerance, then the less dense grid may be more appropriate because it uses less computer memory. If, however, the results differ significantly or unacceptably, then the denser grid or even a more refined one is required.



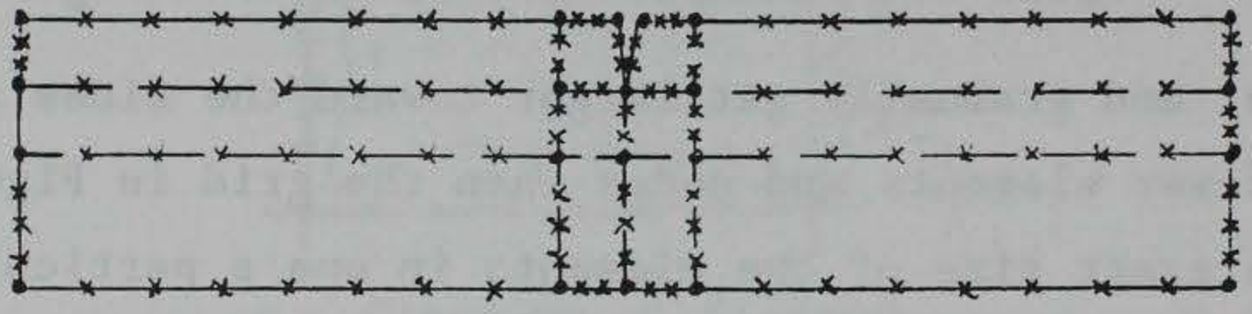

a. Section to be modeled



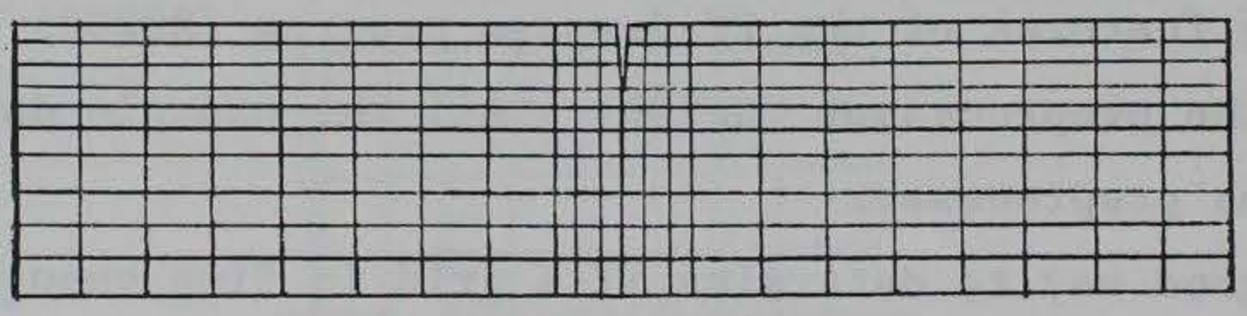
b. Simple model of subregions and additional nodes



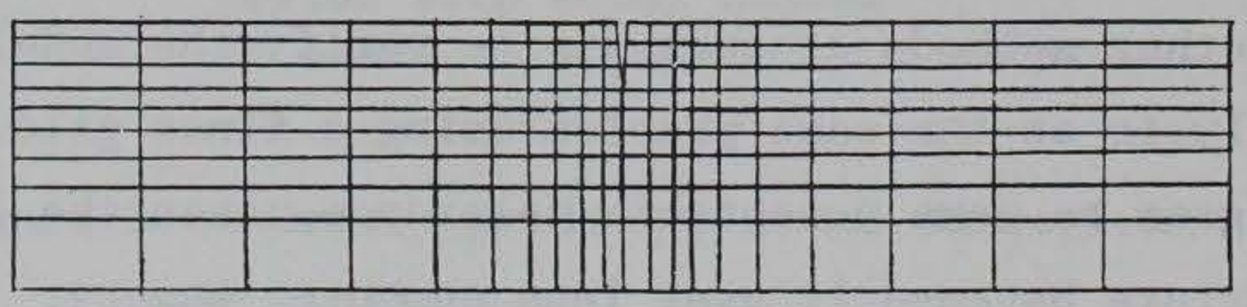
c. Grid generated from simple model



d. Denser model of subregions and additional nodes



e. Grid generated from denser model



f. Use of quadratic nodal spacing to make a more efficient grid, fewer elements and modes than in (e)

Figure 59. Various grid densities and configurations

Transition zone

104. There can be places in the grid where it is desirable to have smaller elements in a dense arrangement and larger elements in other areas. One way to accomodate the transition from a region of small elements to one of large elements was shown in Figure 59 in which quadratic spacing of the nodes was used. Another way to do this is to form a subregion to be used as a transition zone.

105. The transition zone should be a narrow subregion about one or two elements thick (or more, depending on the size of the grid) with different numbers of additional nodes on either side. The side adjacent to the denser grid region has additional nodes to match those in the dense region, but the side adjacent to the sparcer region has fewer nodes. This creates triangles when the grid is generated. An example of a transition zone is shown in Figure 60. In this example there are many triangles generated in the transitional subregion. These can be changed by removing triangles with the Module 3 refinements or editing by hand in Module 4.

106. Two-step transition zones can also be used if necessary in large grids. A transition zone can be formed between areas of dense and medium size elements, and another between the medium and large size elements. This would be useful for areas where it is necessary to go from many elements to few elements, such as from 10 to 3.

107. It is recommended that the transition technique be used when geometric configuration or other details make it difficult to use the quadratic spacing or other means of creating regions of different element sizes. Sharply skewed triangles or polygons can affect the behavior characteristics of the element and alter the calculations. Also, the grid may not be as aesthetically desirable with a transition zone as it is with smooth, quadratic element spacing.

Temporary or fixed points and lines

108. The subregion points and lines are designated as either temporary or fixed in the input data file. 'Fixed' means the point or line cannot be moved from the given coordinates during grid smoothing. This designation should be used for definite boundary lines, borders, and any locations that should remain in the position given. 'Temporary' means the points or lines can be slightly altered in the process of smoothing the grid (grid refinements, Module 3) if necessary to make the grid less complex or have fewer elements (Figures 32 and 33 in the Preprocessor report, MP K-77-5 (Tracy

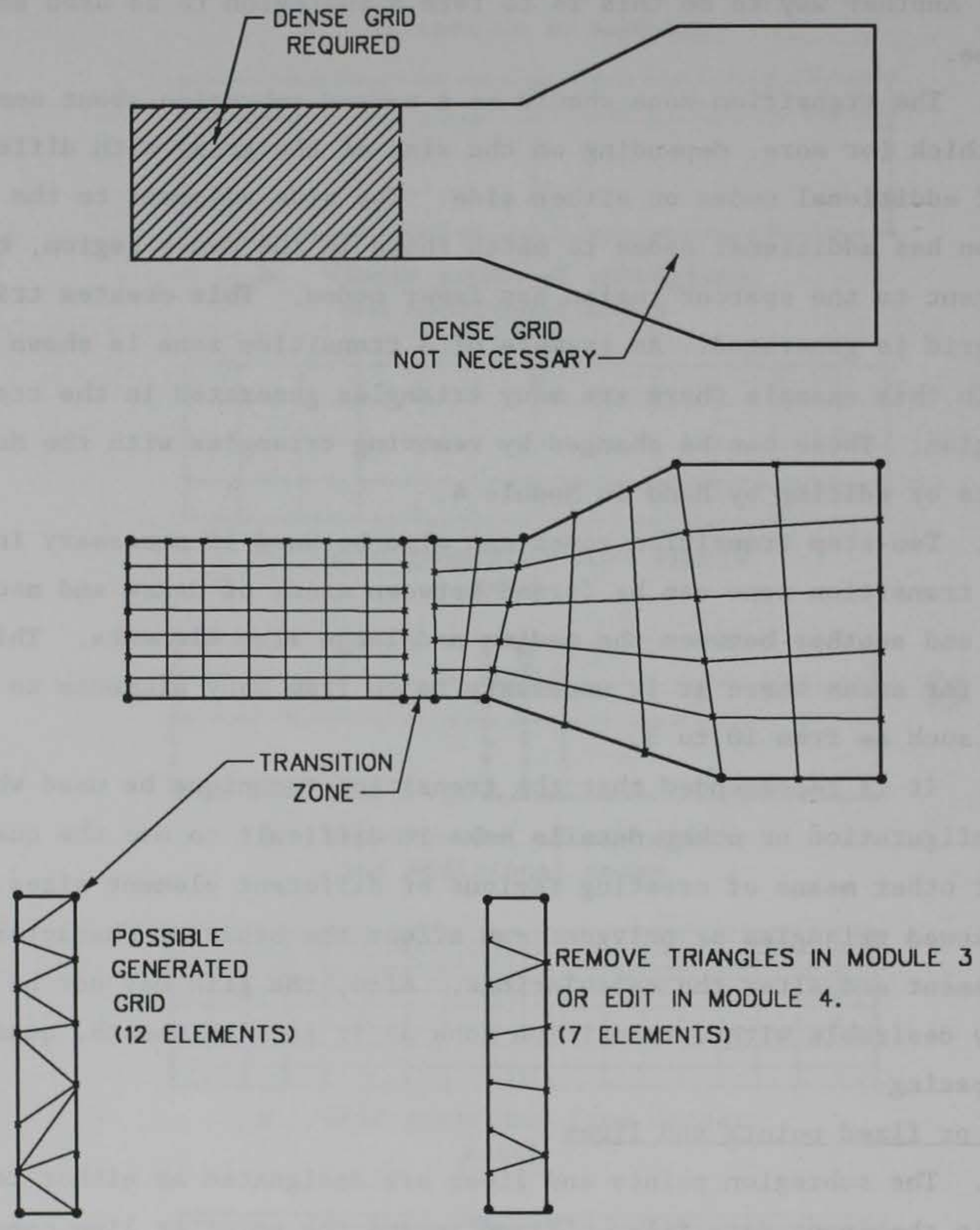



Figure 60. Example of transition zone

1977b)). Points and line segments designated as temporary should be only those not associated with a material boundary or set location within the grid. It is not mandatory to use temporary points and lines. It is also not necessary to apply the first two refinements of Module 3; one can assign all parts of the grid the 'fixed' condition and not apply the smoothing and triangle removal of the preprocessor, only the bandwidth minimizer. However, any grid which uses complex subregions that result in an unstructured triangular mesh should be smoothed.

Material type

109. For each subregion, the material type number should be provided once with one of the line segments defining that subregion. It should not be listed for every line segment.

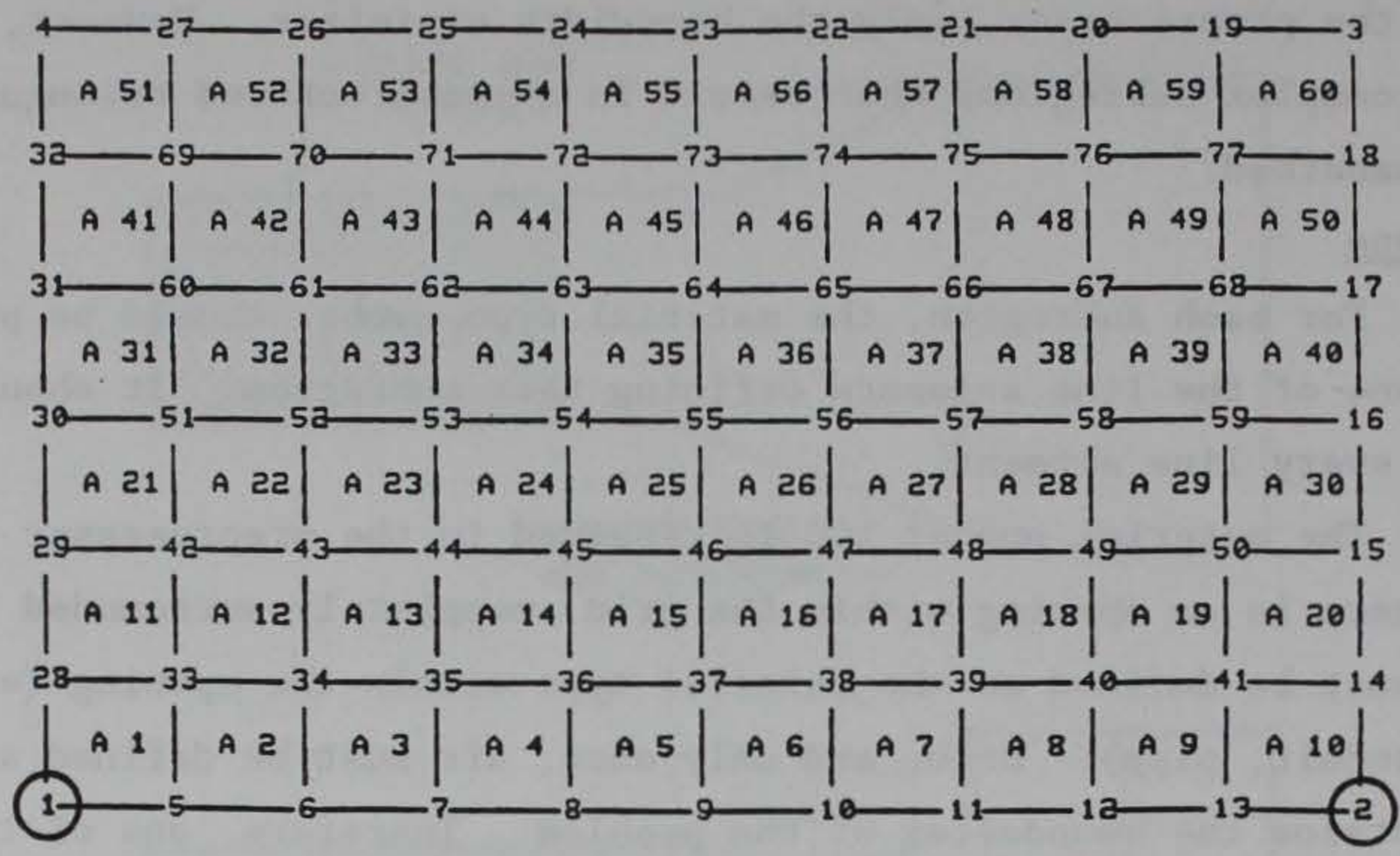
110. The material number 100 is reserved in the preprocessor for air. Whenever there is an opening within the grid, completely surrounded by the grid, air must be defined as the material type within the opening (e.g. a gallery, conduit, pipe). Once, and only once, air must be defined as the material outside the boundaries of the problem. Therefore, one of the external boundary subregion lines must be typed in the data file so that when rotated counterclockwise about the first point defining the line, the material to the left of the line is air and is given the number 100 on that subregion data line.

Ordering parameter

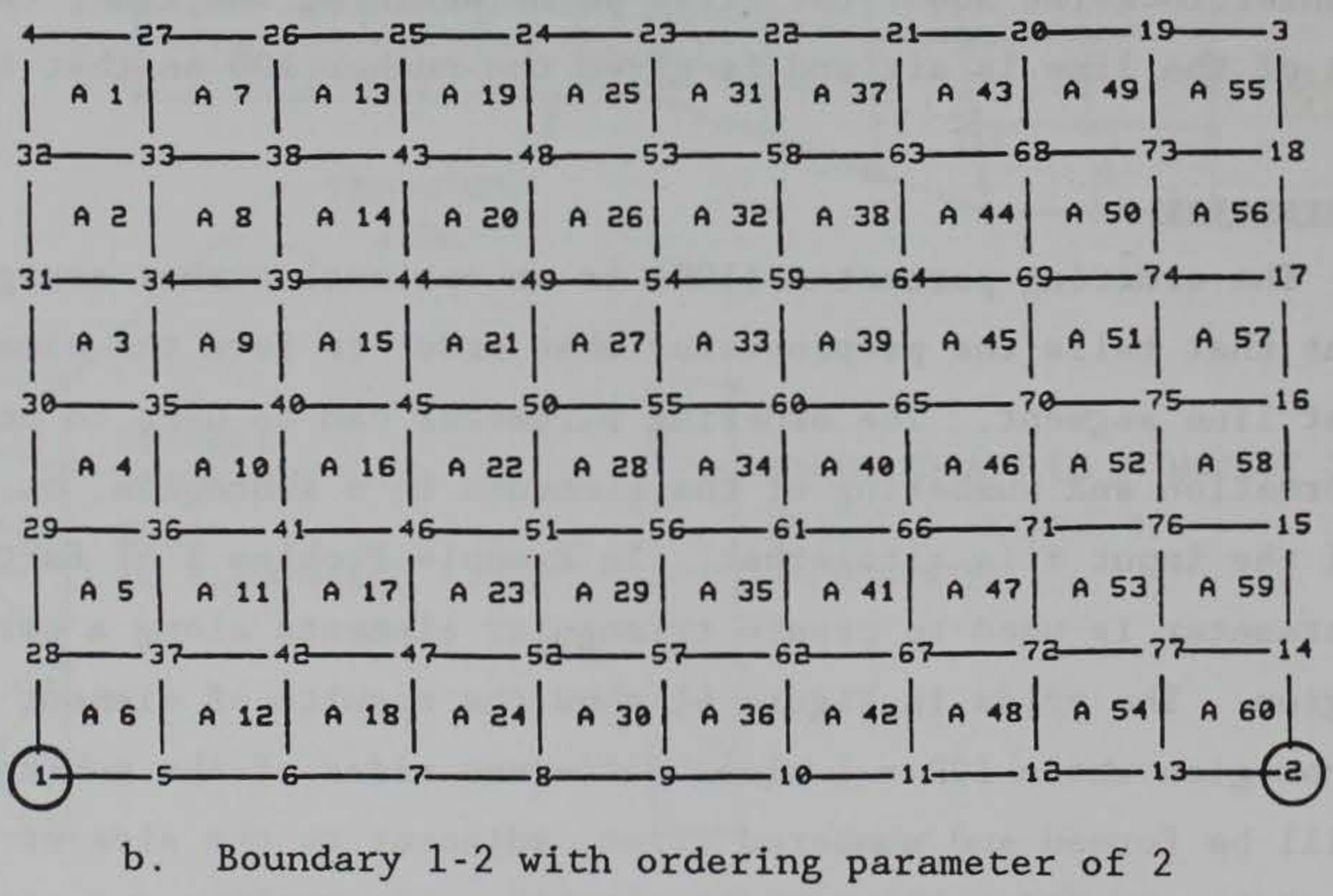
111. The ordering parameter (IOR) is an optional number assigned to a line segment that tells the preprocessor what order to form the elements adjacent to that line segment. The ordering parameter can be used to control the order of formation and numbering of the elements in a subregion, or it can be left out of the input file altogether. In Example Problem 1 of Part II, the ordering parameter is used to create triangular elements along a certain side of a subregion. The grids in Figure 61 show the results of element formation within a subregion where IOR = 1 along different sides of the subregion. Elements will be formed and numbered first, adjacent to the side of the subregion with IOR = 1. If not entered for a line segment, the default for IOR is 1.

Use of modules in the preprocessor

112. Creating the FE model is the purpose of the preprocessor program in CSEEP. The four modules of the preprocessor each have a function in this. The modules do not have to be used in numerical order of '1', '2', '3', '4',

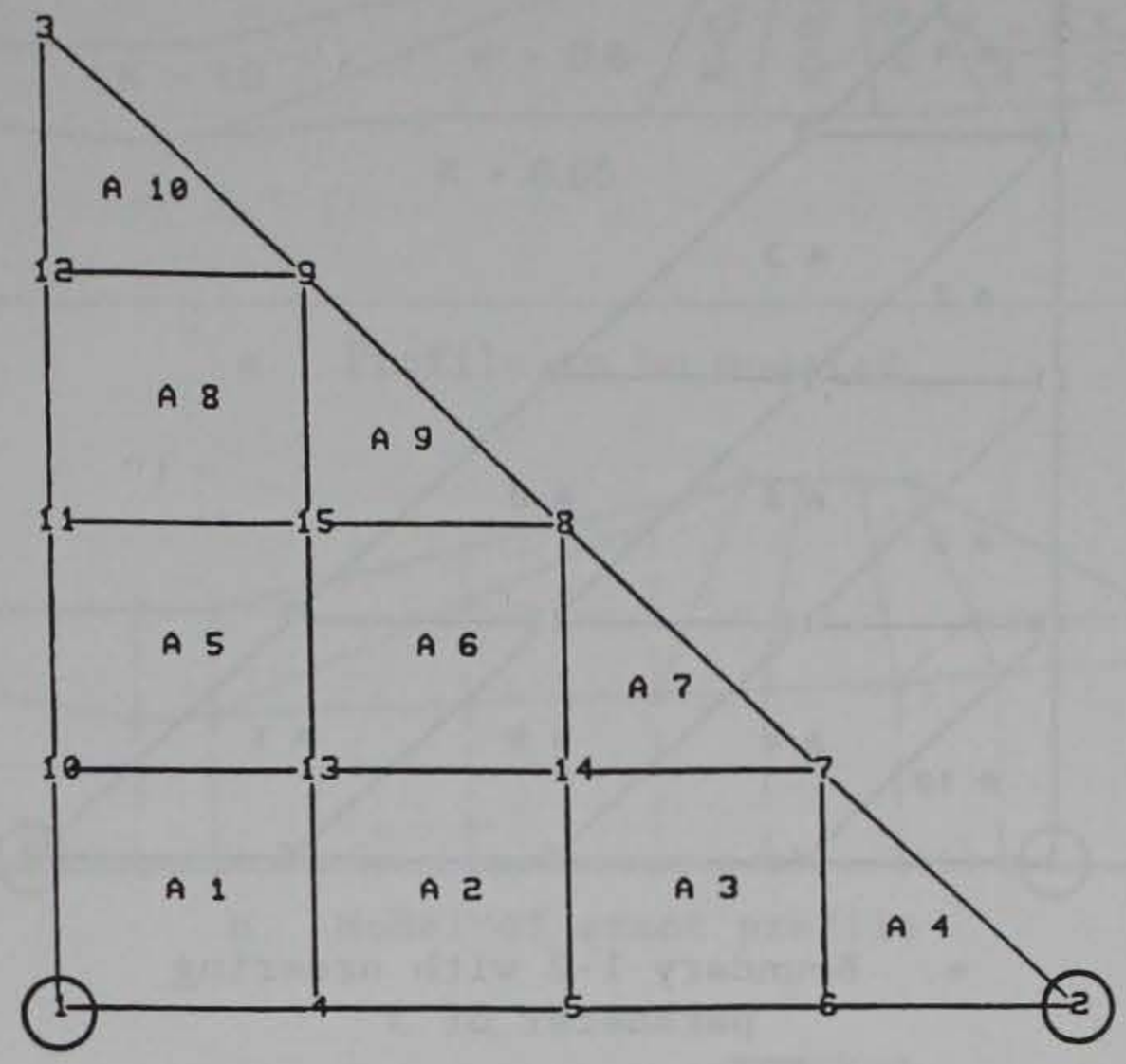



a. Boundary 1-2 with ordering parameter of 1

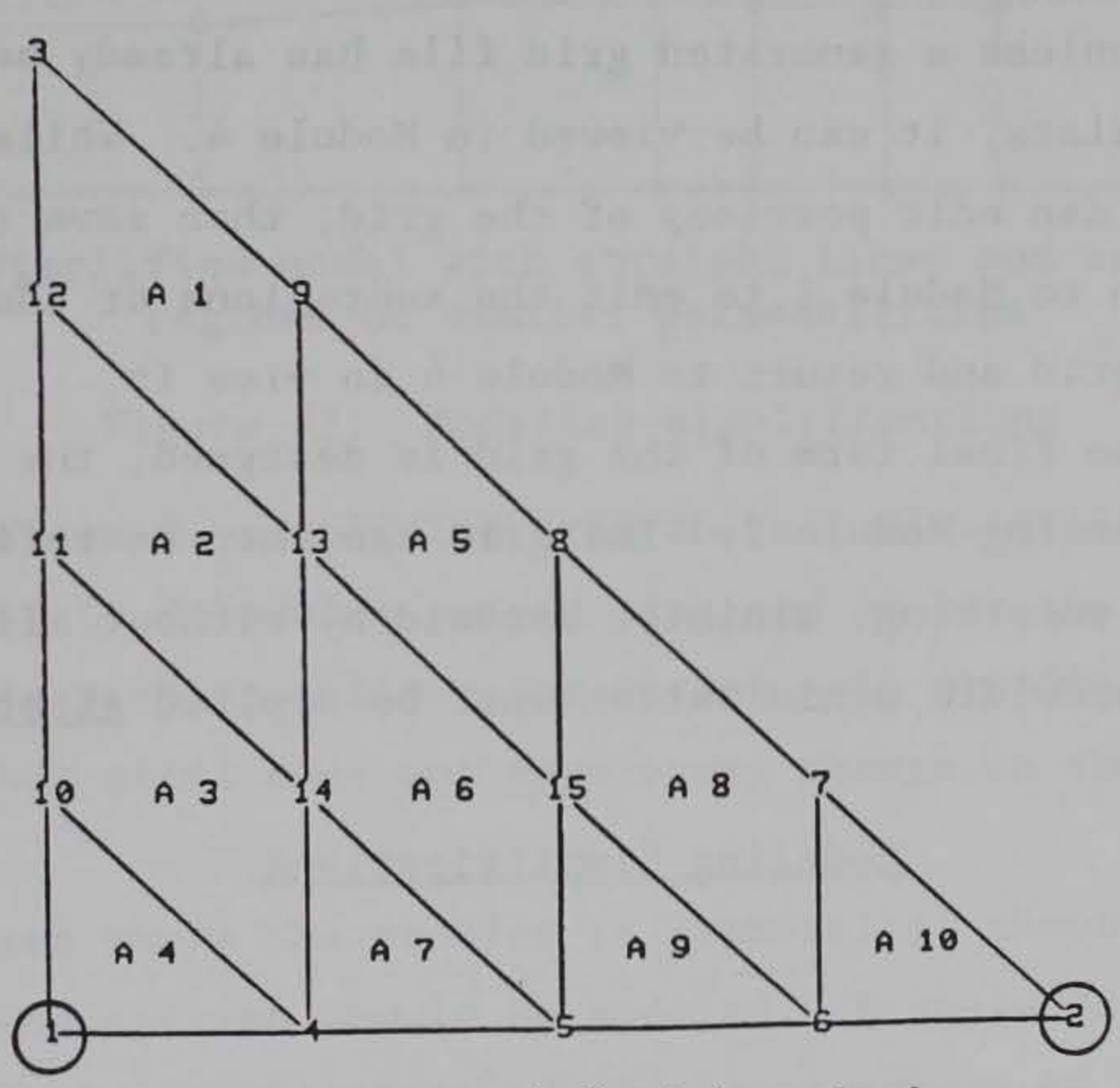



b. Boundary 1-2 with ordering parameter of 2

**Figure 61. Use of the ordering parameter (Continued)**

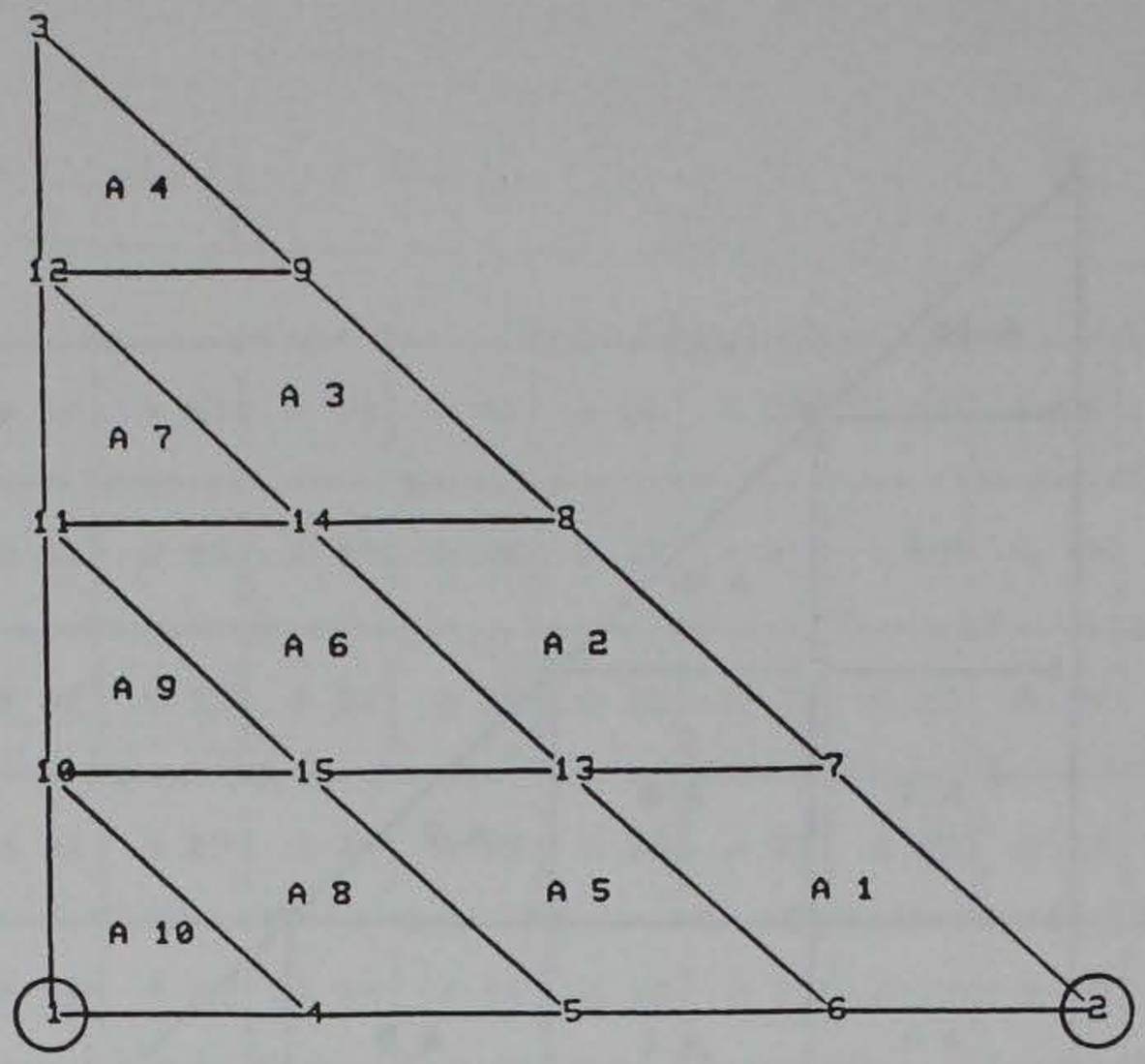



c. Boundary 1-2 with ordering parameter of 1




d. Boundary 1-2 with ordering parameter of 2

Figure 61. (Continued)




e. Boundary 1-2 with ordering parameter of 3

Figure 61. (Concluded)

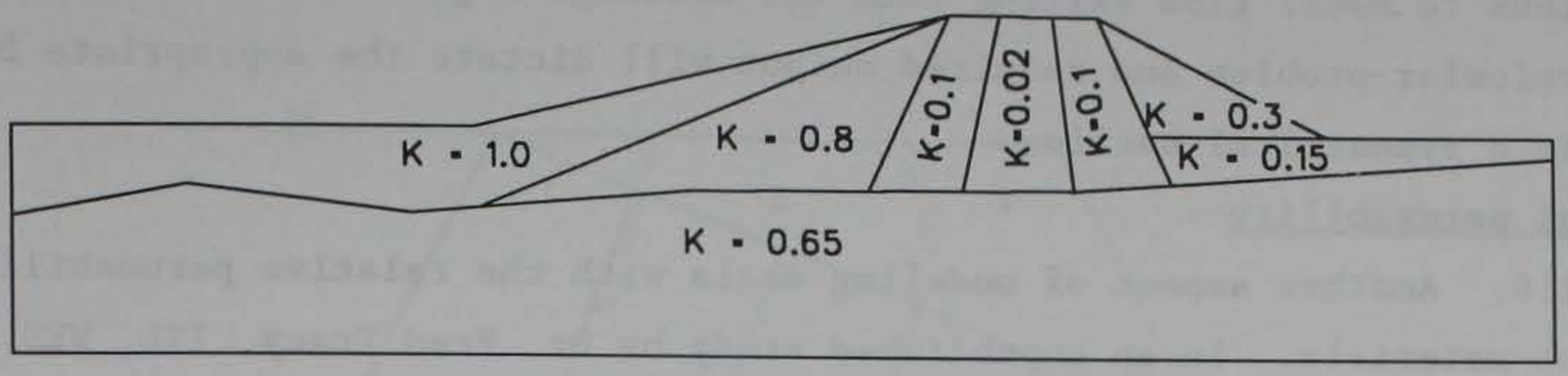
although they can be. Module 1 must be used first to input (or restart) and generate the grid unless a generated grid file has already been created. Once a generated grid exists, it can be viewed in Module 4. While still in Module 4, the user can edit portions of the grid, then save this grid. Or, the user can return to Module 1 to edit the subregions or additional nodes, then regenerate a grid and return to Module 4 to view it.

113. When the final form of the grid is designed, the BC should be applied to it by running Module 2. The grid can then be refined in Module 3 (remove triangles, smoothing, minimize bandwidth) without affecting the applied BC. The bandwidth minimization must be applied after BC are applied.

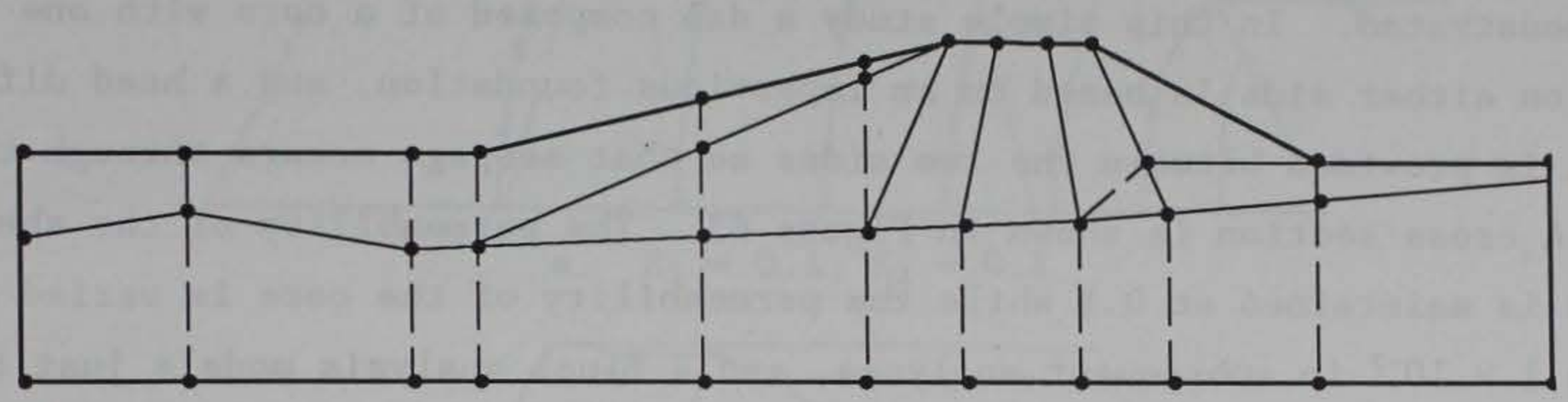
## Modeling Simplifications

### Geometry of model

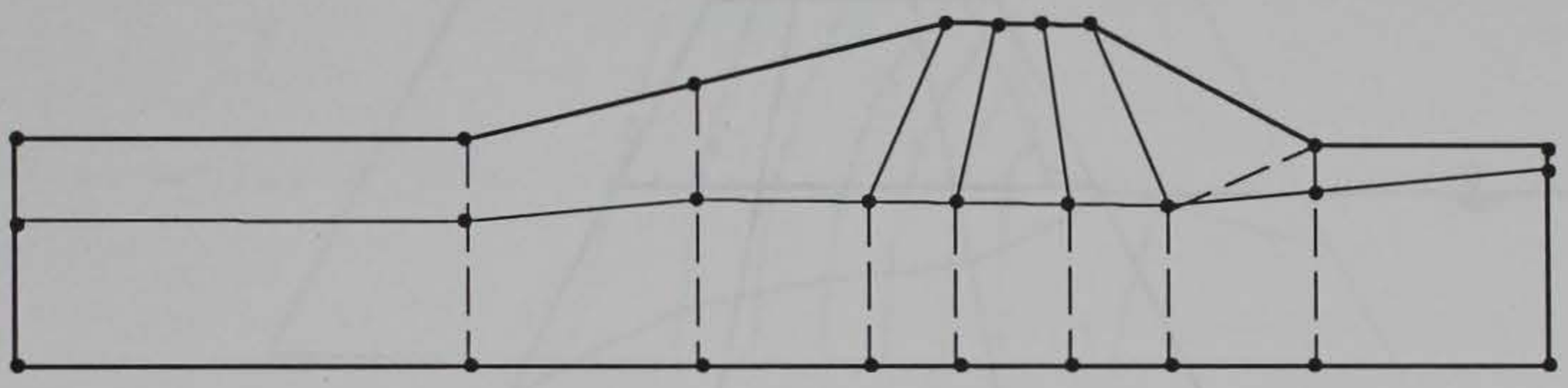
114. In some cases the region to be analyzed can be well represented by a model which does not follow its exact profile. The profile shown in Figure 62a can be modeled in detail as in Figure 62b or simplified as in Figure 62c. The simpler model will provide similar results to those of the detailed model, but with much less work in preparing the input. In Part II, Example




a. Profile to be modeled



b. Model of exact profile



c. Simplified model with straight lines and combined regions of similar permeabilities

Figure 62. Modeling simplifications

Problem 2, the section is simplified from the actual profile for an initial model which is used to determine proper size and BC for the final model. The final model in this problem follows the actual soil profiles in a more detailed manner, but still does not copy every change in the soil layer elevation.

115. In cases where the problem is symmetrical about a center line, only one-half of the section should be modeled. Example Problem 5, Part II, is such a case. It is important to provide appropriate BC along the center-line boundary to obtain a representative model. For a flow net to be continuous across the center line, the boundary nodes can be assigned the head condition so that flow lines intercept the boundary. Then, when the flow net is mirrored about the center line, the flow lines continue across the

boundary. In Example 5 of Part II, the center-line boundary was treated as impervious to model flow exiting into the drainage region under the channel. The particular problem and required output will dictate the appropriate BC to apply in a symmetrical section.

Material permeability

116. Another aspect of modeling deals with the relative permeability of adjacent materials. In an unpublished study by Dr. Fred Tracy, ITL, WES, who developed CSEEP, the relative effect of different permeabilities on head drop is demonstrated. In this simple study a dam composed of a core with one shell layer on either side is based on an impervious foundation, and a head differential is provided between the two sides so that seepage occurs through the dam. A cross section is shown in Figure 63. The permeability of the shell layers is maintained at 0.1 while the permeability of the core is varied from 0.1 to $1 \times 10^{-7}$ in subsequent analyses, and a final analysis models just the core material alone. The results are displayed as head drop through the

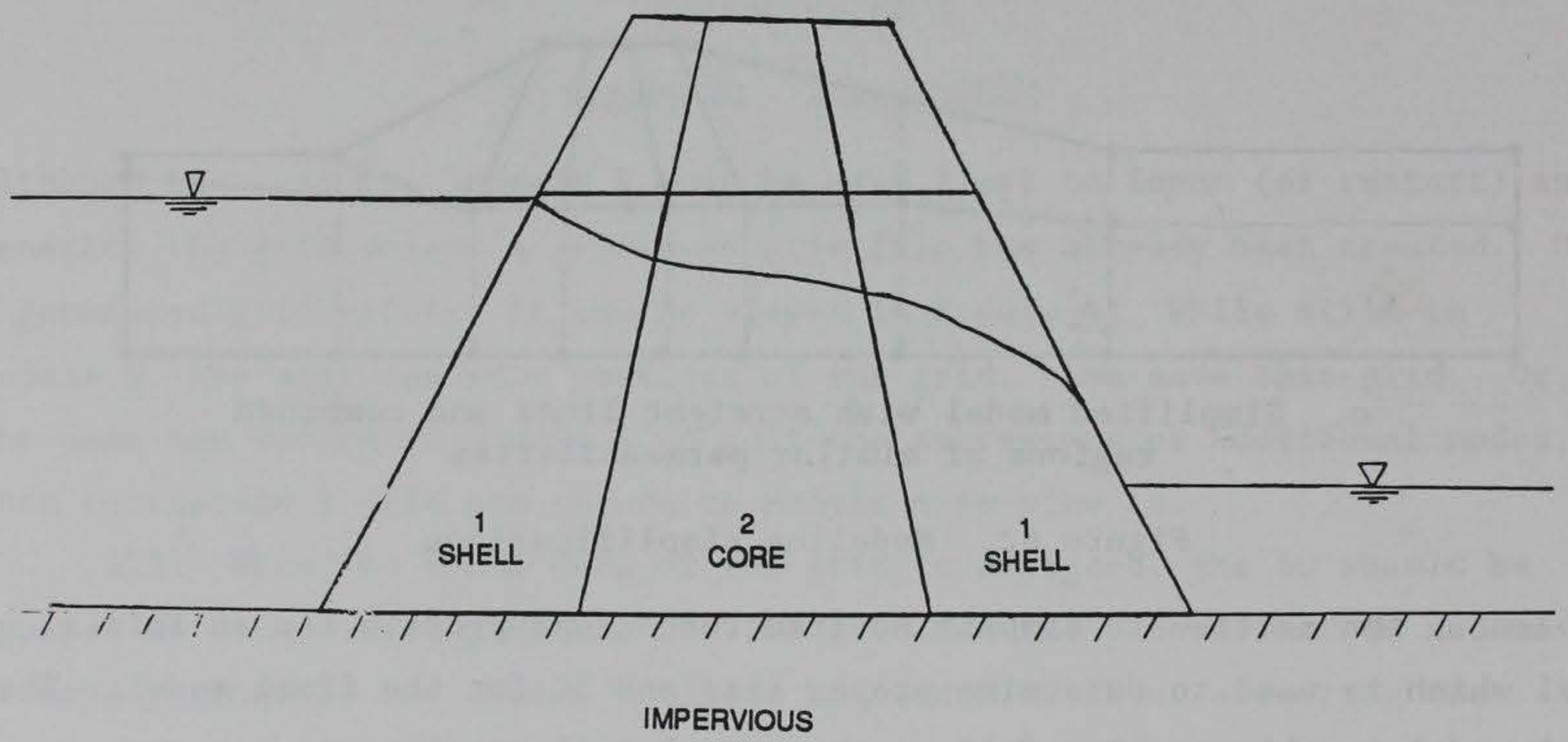
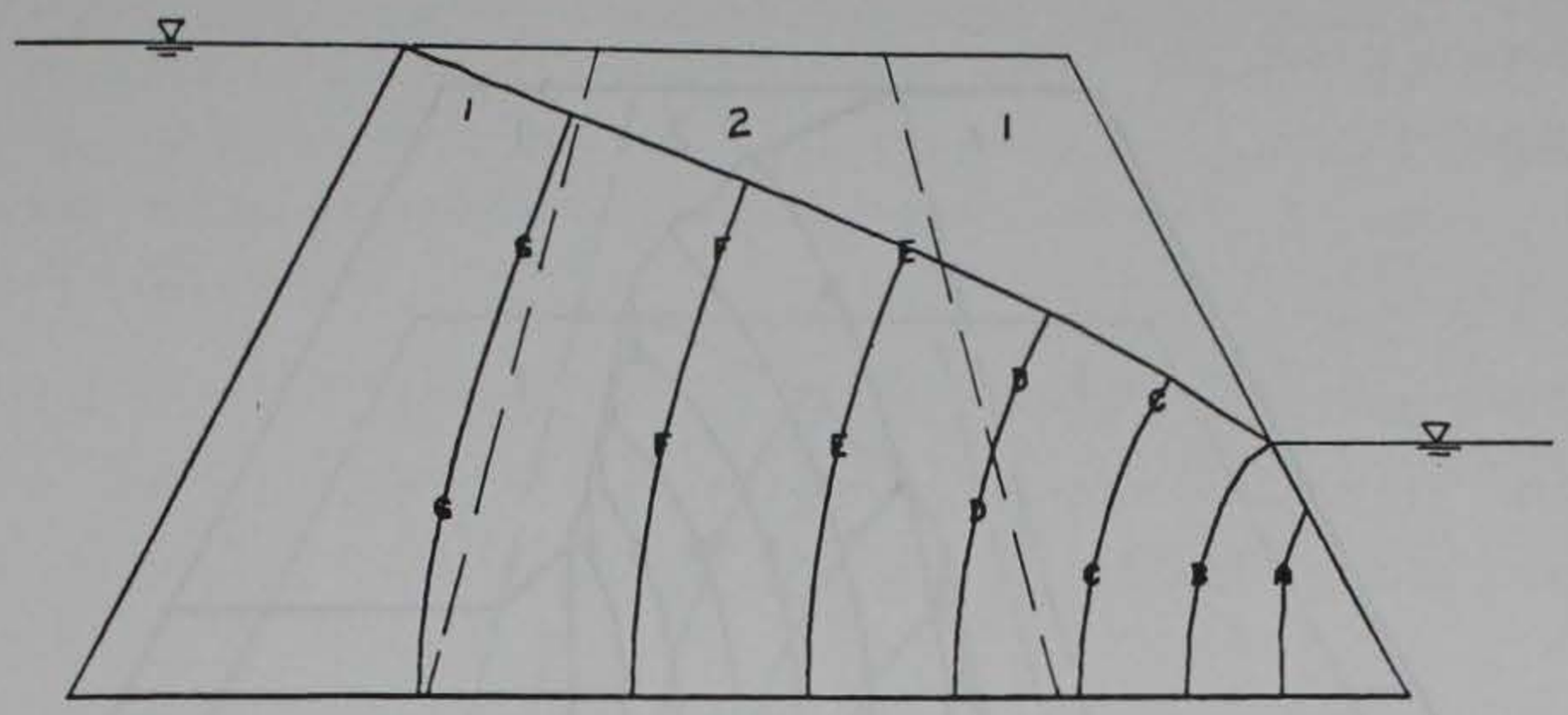


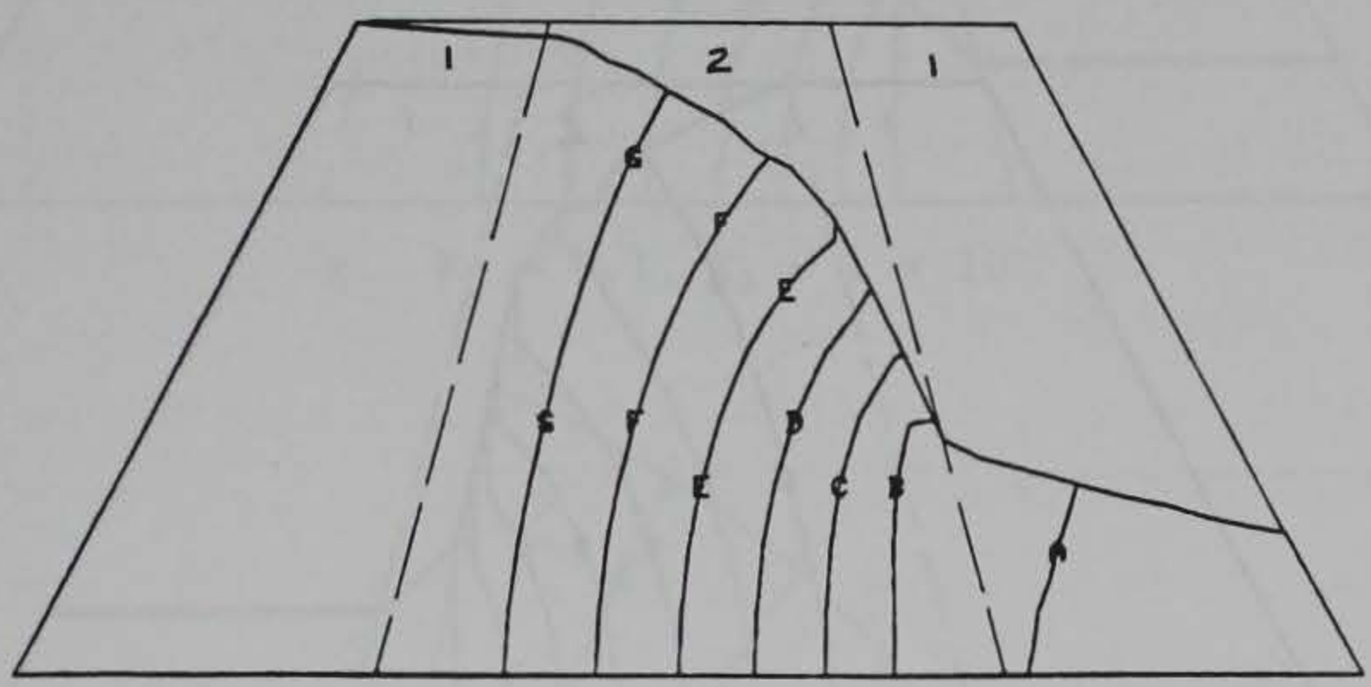

Figure 63. Dam section used to show effects of relative permeability between adjacent materials

materials in Figures 64a through 64h. The head drop in Figures 64a through 64c changes significantly as the core permeability decreases from $10^{-1}$ to $10^{-3}$. However, in Figures 64c through 64g the head drop is virtually the same; it occurs at uniform intervals through the core of the dam with a nearly negligible drop in the shell layers. In Figure 64h with only the core modeled, the head contours are almost identical to those in Figures 64c through 64g.

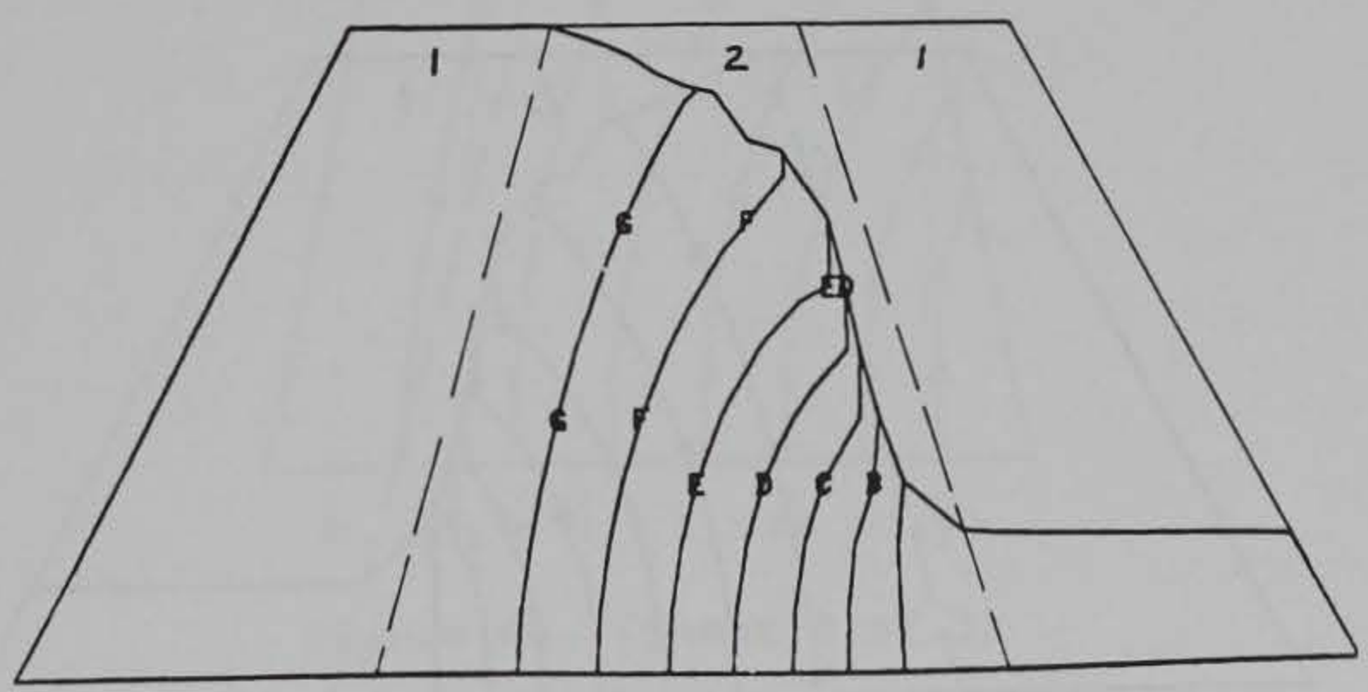
117. Two significant features are revealed in these results:




a. $K_1 = 0.1$, $K_2 = 0.1$

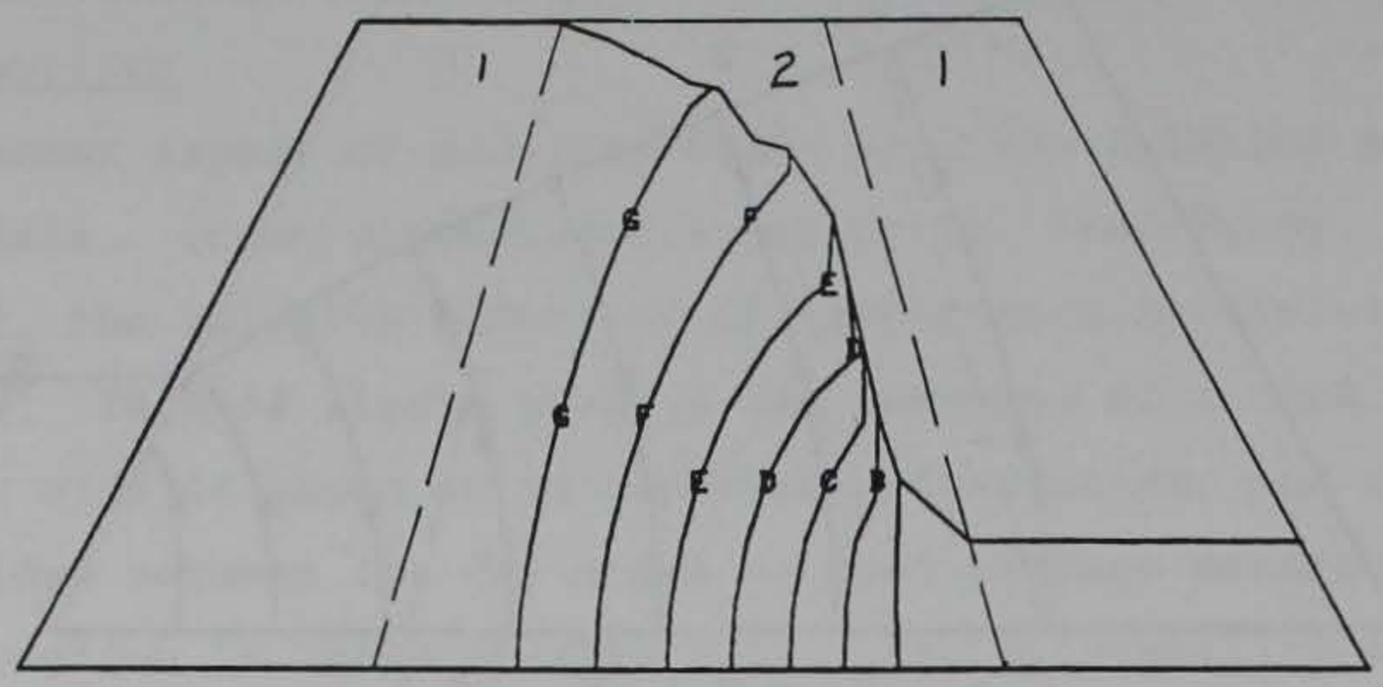



b. $K_1 = 0.1$, $K_2 = 0.01$

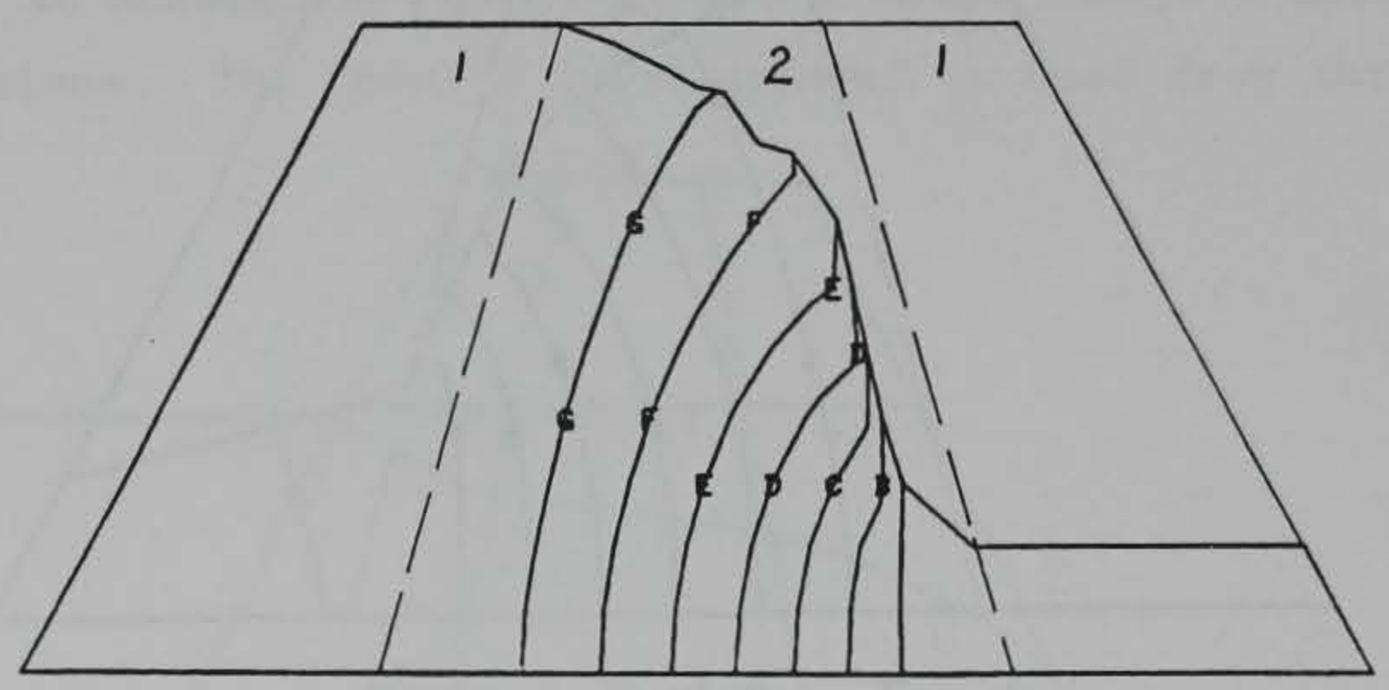



c. $K_1 = 0.1$, $K_2 = 0.001$

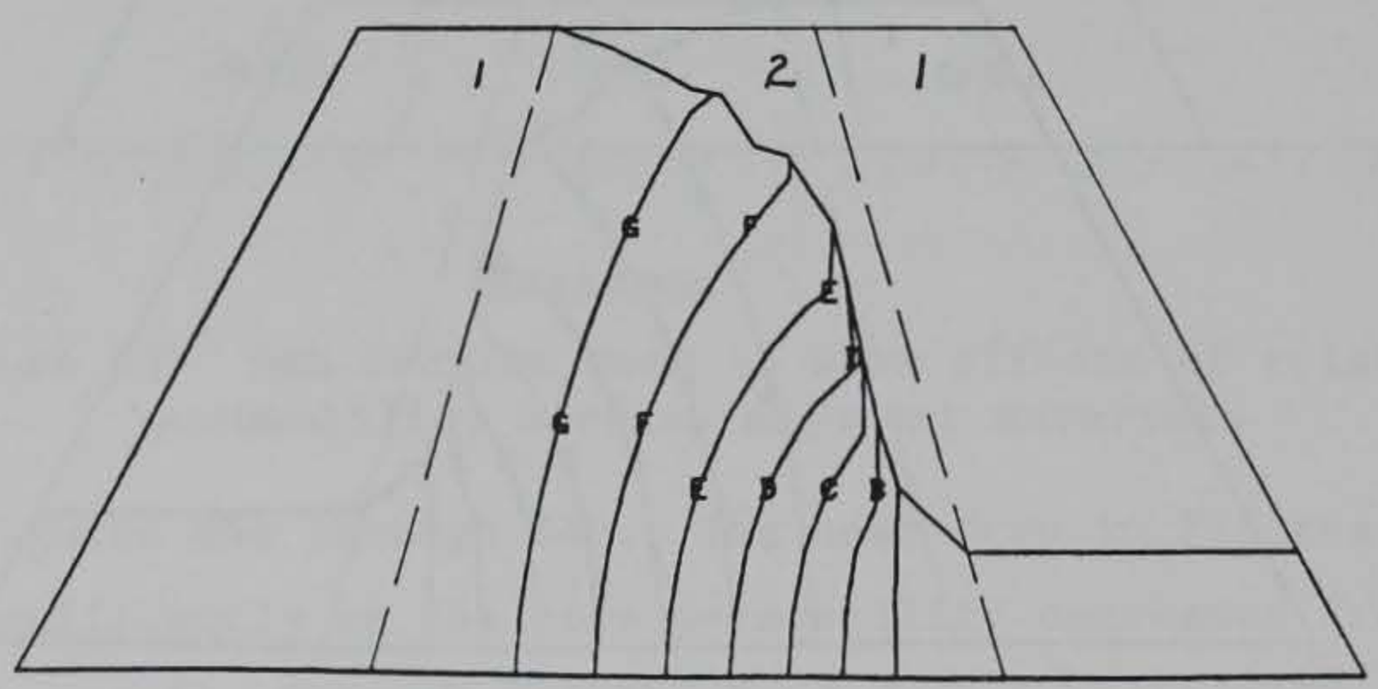
Figure 64. Total hard contour through example dam section (Sheet 1 of 3)




d. $K_1 = 0.1$, $K_2 = 0.0001$

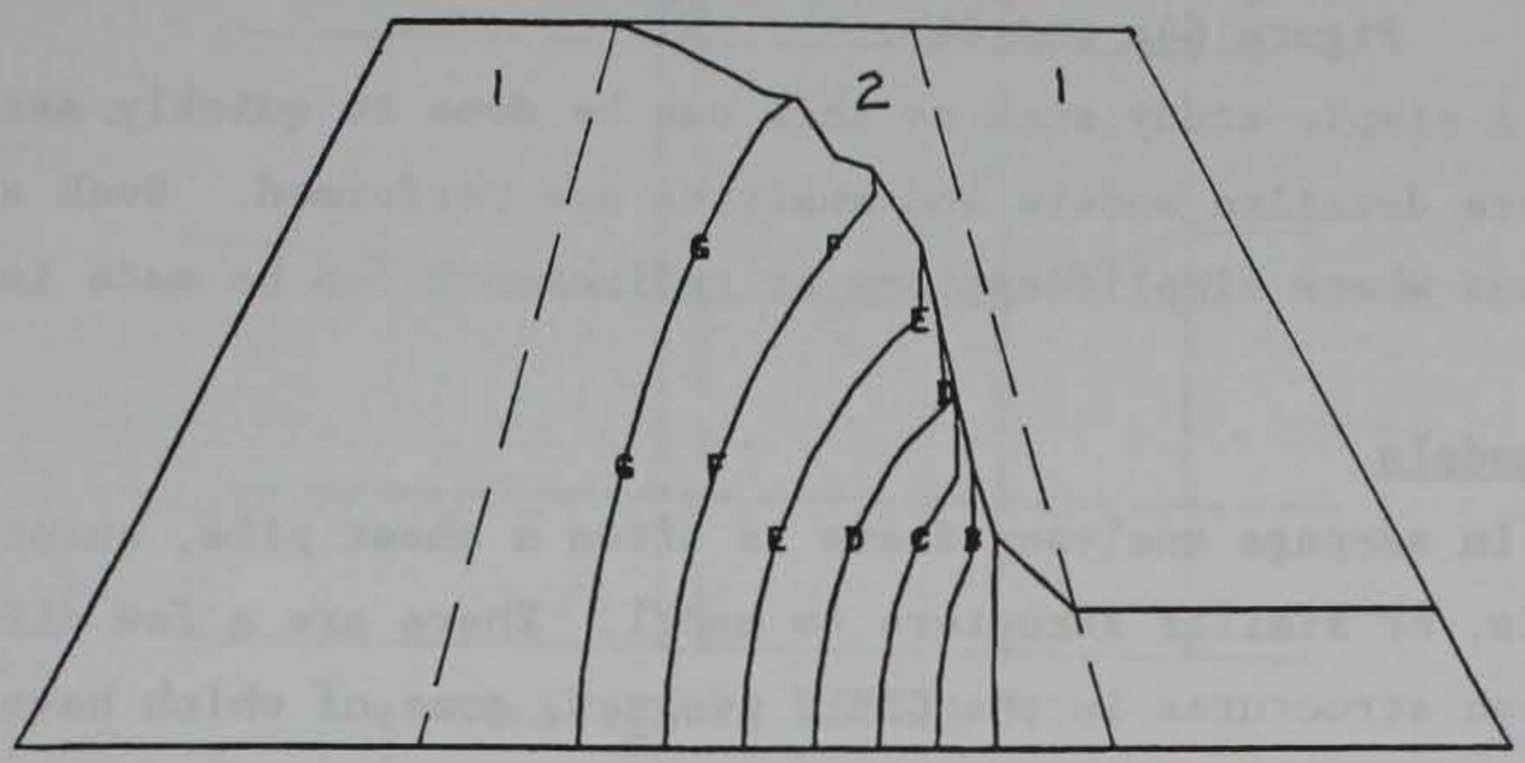



e. $K_1 = 0.1$, $K_2 = 0.00001$

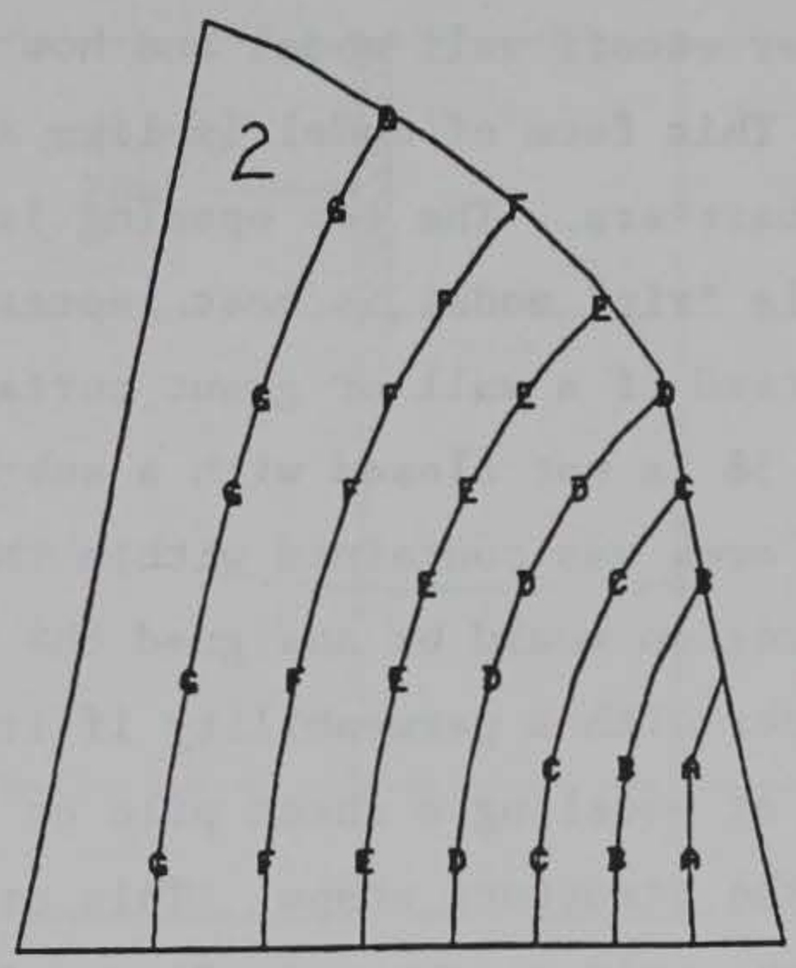



f. $K_1 = 0.1$, $K_2 = 1 \times 10^{-6}$

Figure 64. (Sheet 2 of 3)




g. $K_1 = 0.1$, $K_2 = 1 \times 10^{-7}$




h. $K_2 = 0.1$ (core only)

Figure 64. (Sheet 3 of 3)

a. For permeability differences between adjacent materials of $10^{-2}$ or more, the material with the higher permeability may not need to be modeled at all because essentially all head drop occurs in the region of lower permeability. In this case just the core could have been modeled, with similar results to any of the cases in Figures 64c through 64g.

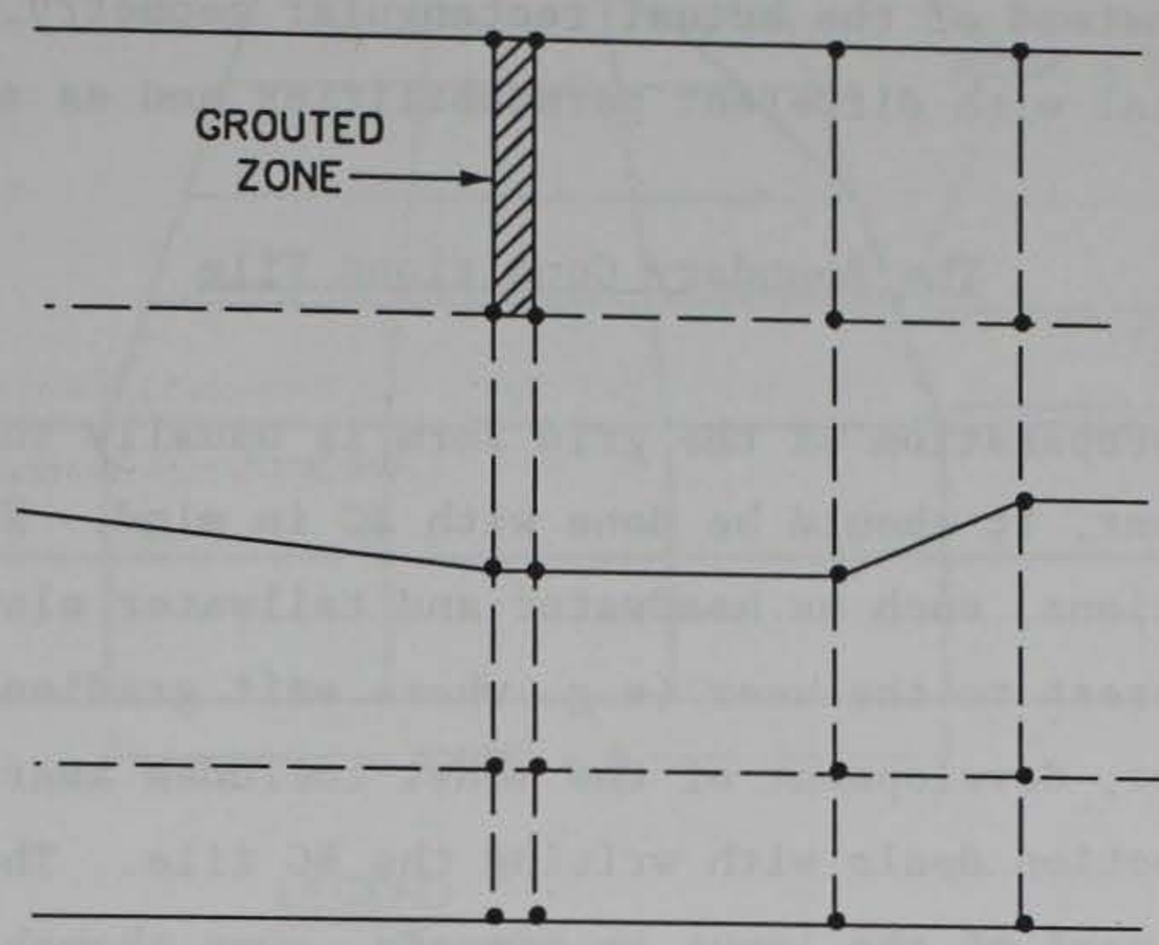
b. A permeability difference of just $10^{-1}$ between two adjacent materials can be enough to significantly alter the head drop through the region. This is seen by comparing the plots of Figure 64a and 64b.

118. A simple study such as this can be done to quickly assess one's project before detailed models and analyses are performed. Such a study would indicate areas where simplifications or refinements can be made in the grid and BC.

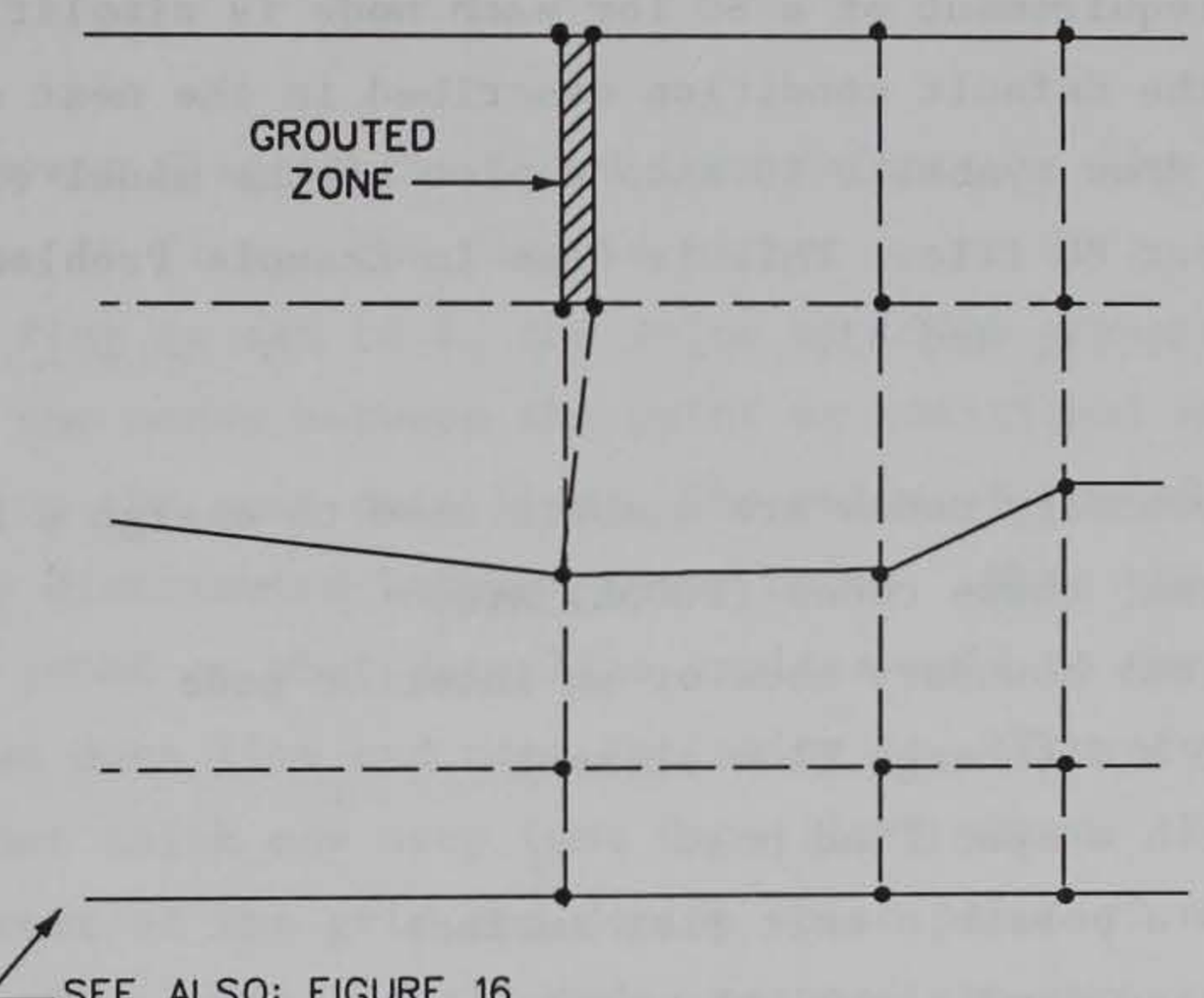
Sheet-pile models

119. In seepage analyses there is often a sheet pile, cutoff wall, grout curtain, or similar structure to model. There are a few different ways to model these structures in the CSEEP program, some of which have been used in the examples. In Example Problem 2, Part II, Figure 16b shows how the sheet pile was handled in the subregion partitioning. Figure 57 also shows this form of sheet-pile or cutoff wall model and how it can be used as part of a five-sided subregion. This form of model is like a rip in the grid with the sides being impermeable barriers. The top opening is very narrow compared to the length, therefore this "rip" model is best representative of a sheet pile or very thin barrier instead of a wall or grout curtain. The top of the "rip" in the example of Figure 58 is not closed with a subregion line but is open to the outside air. If the area was contained within the grid, the top opening would be closed and the region would be assigned the material air (if impervious) or a material number with a permeability if it was gridded.

120. Another form of modeling a sheet pile or cutoff wall is a more exact representation of the structure shape. This creates more subregion points and lines within the grid as shown in Figure 65a. This form would be used with a structure that is relatively thick compared to its length, such as a cutoff wall. If the grid is deep, one of the subregions below the wall could be tapered to a single line as shown in Figure 65b so that the narrow subregions do not have to be continued throughout the grid below the wall. The top of the wall or grout region should not be enclosed if it is adjacent to the outside boundary of the grid. If it is enclosed it must have air or a material type number assigned to it.




a. Subregions extend below grout zone




SEE ALSO: FIGURE 16
FIGURE 32
FIGURE 57

b. Subregion tapers to end below grout zone

Figure 65. Sheet-pile models

121. A cutoff wall model used in a plan view seepage analysis is shown in Figure 32, Example Problem 3, Part II. Compared to the entire region modeled, the cutoff wall was considered small enough such that it could be modeled as v-shapes instead of the actual rectangular geometry. This region was treated as a material with different permeabilities and as air.

## The Boundary Conditions File

122. While preparation of the grid form is usually the first step in the model development, it should be done with BC in mind. Nodes must be placed at key locations, such as headwater and tailwater elevations and specific areas of interest to the user (e.g. where exit gradients or flow is desired). Therefore, development of the model includes awareness of the BC.

123. This section deals with writing the BC file. The BC file is often the most confusing part of the input to prepare, even though it is the shortest file. The idea is to traverse the exterior boundary of the grid, any interior parts with specified conditions, and name the BC to be applied to each node. The requirement of a BC for each node is simplified by using the repeat flag and the default condition described in the next sections. Often, it is helpful to draw symbolic BC onto a plot of the model or grid to help in preparing the input BC file. This is done in Example Problems 1, 2, and 3, as shown in Figures 5, 17, and 33.

### Boundary codes

124. The boundary codes are numbers used to assign a BC to a node. For the seepage program, these codes (ICODE) are:

0 = impervious boundary node or an interior node

-1 = node of a discharge flow element

1 = node with a specified head

2 = node on a possible exit flow surface

When ICODE = 1 (head condition), the actual head value, relative to the datum, must be listed on the data line following the code. For ICODE = -1, either a flow value is listed on the data line or the discharge velocity for the line segment where discharge occurs must be provided in the input file or the question/answer session of the seepage analysis. For ICODE = 2, the elevation of the node can be listed but is not required. The code of 2 is used in unconfined flow problems for nodes along the possible exit surface including the node at the tailwater elevation. See the example shown in Figure 66.

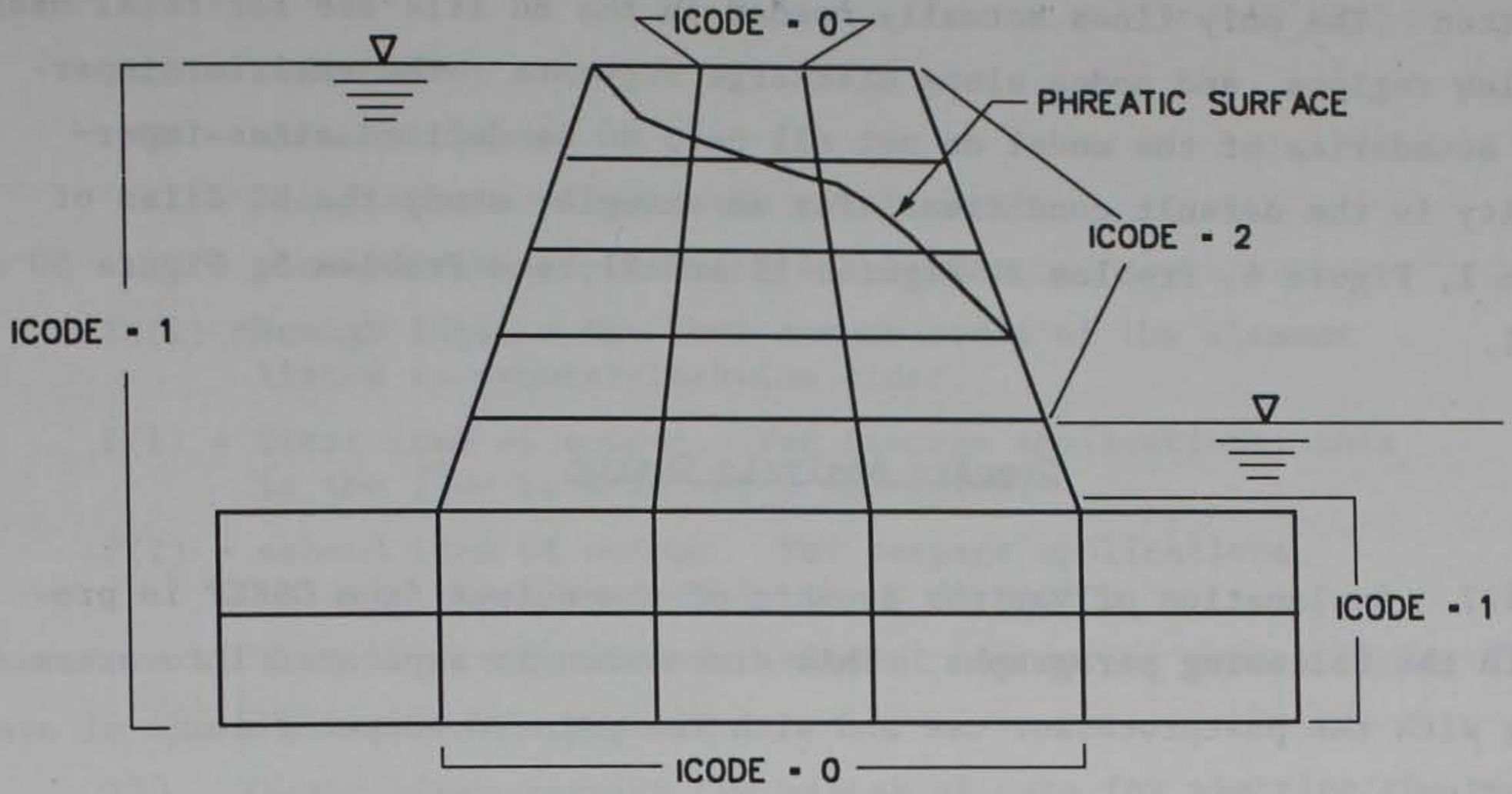



Figure 66. Use of Boundary Code 2 on exit flow surface

Repeat flag

125. The repeat flag is the third item (after the line number) on a line of data in the BC file. The flag is either on or off: '1' is on and '0' is off. When the flag is set to 1, the value of ICODE given on that data line is applied to all the nodes between the point or additional node on that data line and the node on the next data line. The **value** of the BC (e.g. head value) is linearly distributed between these nodes. When the repeat flag is set to zero, then ICODE on that data line applies only to the point or additional node on that data line and none following it. Therefore, when writing the BC file one must think one step (one data line) ahead. Begin with a point at one edge or corner of the grid and decide which point or node to go to next. If the same BC applies to all nodes between the two, the repeat flag is 1.

Default BC

126. For all nodes not specified in the BC file, explicitly or implicitly by the repeat flag, the boundary code of zero (0) is assigned in the preprocessor. For exterior nodes this means an impervious condition. For interior nodes this means a head can occur due to flow. What this means in terms of preparing the BC file is that for most of the nodes, nothing needs to

be written. The only lines actually needed in the BC file are for total head, exit flow regions, and nodes along discharge segments. The exterior impermeable boundaries of the model do not all need to be defined since impermeability is the default condition. For an example, study the BC files of Problem 1, Figure 6, Problem 2, Figures 18 and 21, and Problem 5, Figure 50 of Part II.

## Seepage Analysis Output

127. Explanation of various aspects of the output from CSEEP is provided in the following paragraphs. This discussion is separated into areas dealing with the postprocessor use and with the printed output file information.

### Postprocessor plots

128. Item number. One area that can be confusing with use of the postprocessor plots is the item number. The item number identifies which piece of information in the postprocessor file is to be plotted. In the postprocessor file, nodal data is listed as:

LN NN XX YY F(1) F(2)

where:

LN = line number

NN = node number

XX = x-coordinate

YY = y-coordinate

F(1) = first item of output. For seepage applications, this is the head value.

F(2) = second item of output. For seepage applications, this is the percent available head.

Therefore, if item 1 is requested for node contour or number plots, the total head is plotted.

129. Element data in the postprocessor file are listed as:

LN NN XX YY IX(1) IX(2) IX(3) IX(4) F(1) F(2)

where:

LN = line number

NN = element number

XX = x-coordinate of centroid of element

YY = y-coordinate of centroid of element

IX(1) through IX(4) = the four corner nodes of the element listed in counterclockwise order.

F(1) = first item of output. For seepage applications, this is the flow rate in the x direction.

F(2) = second item of output. For seepage applications, this is the flow rate in the y direction.

Therefore if item 1 is requested for element contour or number plots, flow rate in the x direction is plotted.

130. Vector plots require two pieces of data for plotting the vector but only one item number is provided by the user. Requesting item 1 for a vector plot automatically uses item 1 and item 2 from the postprocessor file. By requesting item 2 for a vector plot, the third and fourth data items are used for plotting the vector. (In the postprocessor file from the seepage analysis, there are only two data items for nodes and elements. Other applications may have more. Therefore, the only valid request is for item 1.

131. If the postprocessor is used in other applications, such as force-displacement analysis or heat transfer analysis, the item numbers mean different things. For example, in a force-displacement analysis, item 1 for nodal data might mean displacement in the x-direction, item 2 might mean displacement in the y-direction. For element data we could have:

item 1 = x-stress

item 2 = y-stress

item 3 = major principal stress

item 4 = minor principal stress

item 5 = shear stress

and so forth. The meaning of the item number depends of how output from the analysis program is written to the postprocessor file. The postprocessor file and program can handle up to six items of data for both nodes and elements.

132. Typical plots for seepage analyses are: contours of nodal head (C, N, 1 - responses to questions in postprocessor); vector plot of element flow (V, E, 1); and numbers plot of nodal head values (N, N, 1). Some plots are relatively meaningless or of little use for seepage applications, such as a vector plot of nodal heads (in which the vector formed by items 1 and 2 is

computed - total head and percent available head), and the program may stop execution if such a plot is requested.

133. Flow nets. Flow net computation requires a great deal more computer time and memory than analyses without one. For relatively simple problems of two or less materials, a flow net can usually be computed and plotted. However, many problems present complexities that make the formation of a flow net in CSEEP an incredible, if not impossible, problem. In some of these cases a flow net can be obtained, but it is so scrambled, or the ratio of flow lines to head drops is so great that it is of minimal use. For problems like this, plots of head contours and flow vectors are usually sufficient to obtain an idea of the behavior.

134. In the printed output, a second set of node heads and element flows is printed if a flow net is computed. These are only for flow net use and not to be read as the seepage analysis computations.

135. The flow net option was added to the program after the reports were published. When a flow net is requested for plotting by the postprocessor, the following question appears:

"COMPUTED SHAPE FACTOR IS 6/10
SPECIFY NF AND NE DESIRED"

where

NF = number of flow lines (in this example, 6), and
NE = number of equipotential lines (in this example, 10)

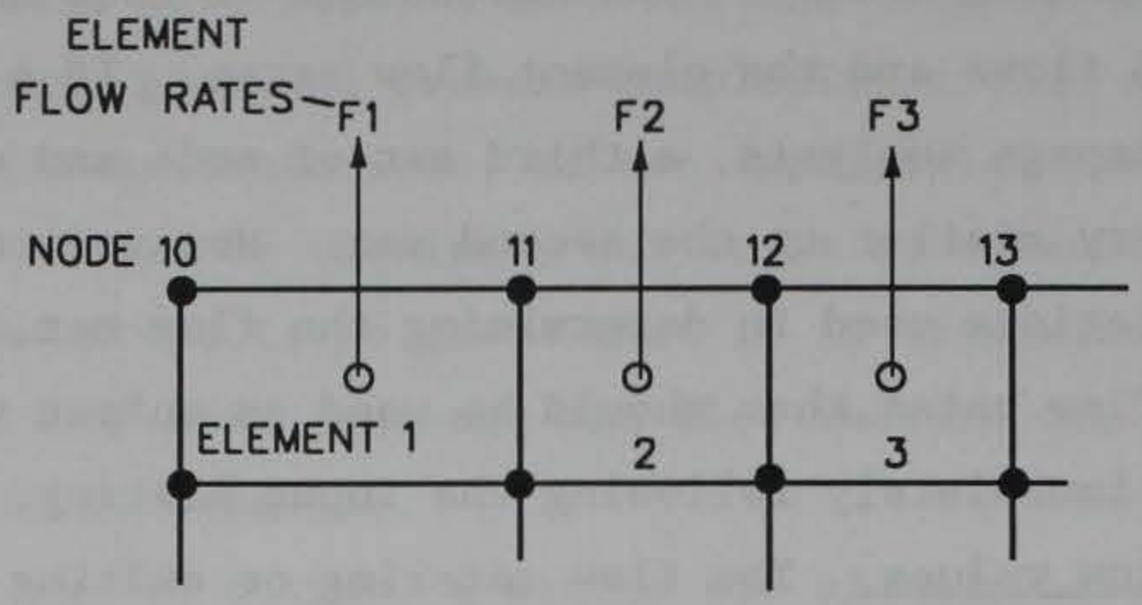
The ratio shown (in this example, 6/10) is computed by the program. The user can enter these same numbers (e.g. "6 10" - the slash should not be entered) or multiples or factors of these numbers (e.g. "12 20" or "3 5").

136. Plotting or Printing Graphics. On the personal computer version of CSEEP, there are two options currently available for obtaining a hard copy of graphics for either the pre- or postprocessor. They are the HP Laserjet series and the Epson FX series. When a desired plot is on the screen, the user holds the Shift key and presses the Print Screen key, and the desired plot will be produced. The list of printers plotters is expanded each time capabilities are developed to print to another type of output device. To find out the current version date of CSEEP and its capabilities for printing/plotting the graphics, one should call the Engineering Computer Program Library (601/634-2581).

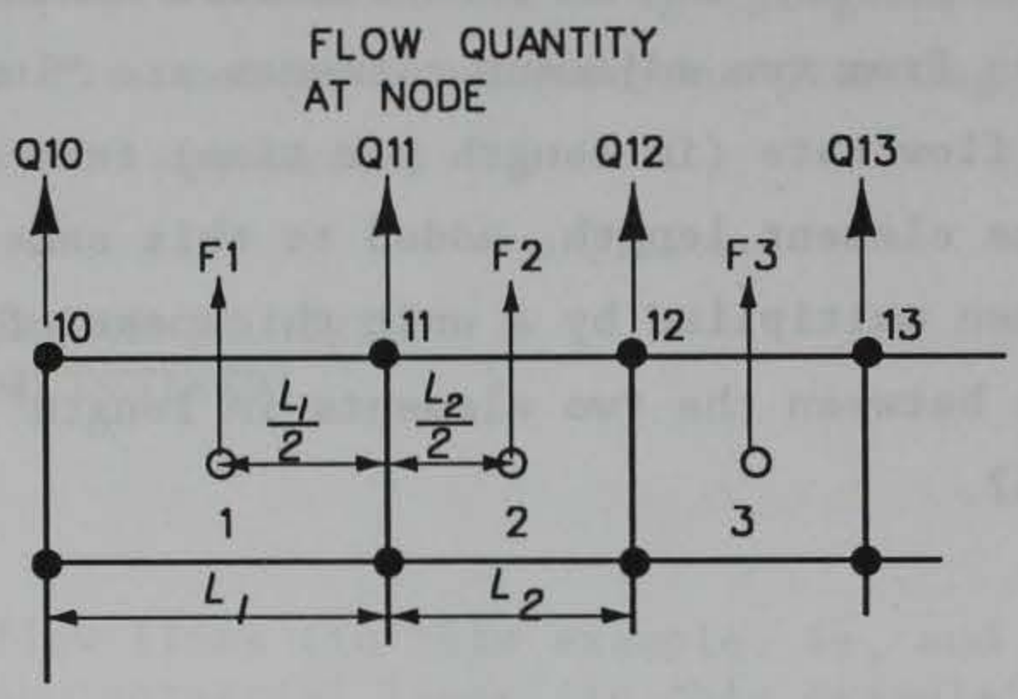
Printout file

138. Sections of output. The printed output file from the seepage analysis is printed in sections of node and element data. The first set of node and element data is simply the input data (node coordinates, BC, element centroid, and surrounding nodes). The second set of node and element data is the nodal heads and flows and the element flow rates. If a flow net is requested in the seepage analysis, a third set of node and element data is printed which is very similar to the second set. However, this contains results from computations used in determining the flow net. The final nodal heads and element flow rates that should be used as output values are listed in the second set, immediately following the input listing.

139. Node flow values. The flow entering or exiting each node on entrance or exit boundaries is printed in the node output section. This may be confusing because flow rate is an element quantity and head is computed at the nodes. This is explained in the postprocessor manual and briefly reviewed here. The flow rates from two adjacent elements are "lumped" at one node as a flow quantity; the flow rate (in length per time) from one element is multiplied by one-half the element length, added to this same quantity for the adjacent element, then multiplied by a unit thickness of the model to get flow quantity at the node between the two elements in length$^3$ per unit time. This is shown in Figure 67.




a. Boundary elements and their flow rates




EQUATION:

$$Q11 = \left\{ \left[ (F1) \times \left( \frac{L_1}{2} \right) \right] + \left[ (F2) \times \left( \frac{L_2}{2} \right) \right] \right\} \times (\text{UNIT LENGTH OF THICKNESS})$$

UNITS:

$$\text{LENGTH}^3/\text{TIME} = \left\{ \left[ (\text{LENGTH/TIME}) \times \text{LENGTH} \right] + \left[ (\text{LENGTH/TIME}) \times \text{LENGTH} \right] \right\} \times (\text{LENGTH})$$

b. Computation of node flow quantity which is reported in nodal output for nodes on the entrance and exit flow surfaces

Figure 67. Computation of nodal flow rates in printed output

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