Groundwater Module in *Slide*

2D finite element program for ground water analysis

Verification Manual

Version 2.2

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1. Shallow unconfined flow with rainfall

Problem description

The problem considered in this section involves the infiltration of water downward through soil. It is characterized by a boundary of flow domain also known as a free surface. Such a problem domain is said to be unconfined.
Water may infiltrate downward through the soil due to rainfall or artificial infiltration. Rainfall can be presented as a uniform discharge P (m/s), defined as the amount of water per unit area that enters the aquifer per unit time. Figure 1.1 shows the problem of flow between two long and straight parallel rivers, separated by a section of land. The free surface of the land is subjected to rainfall.

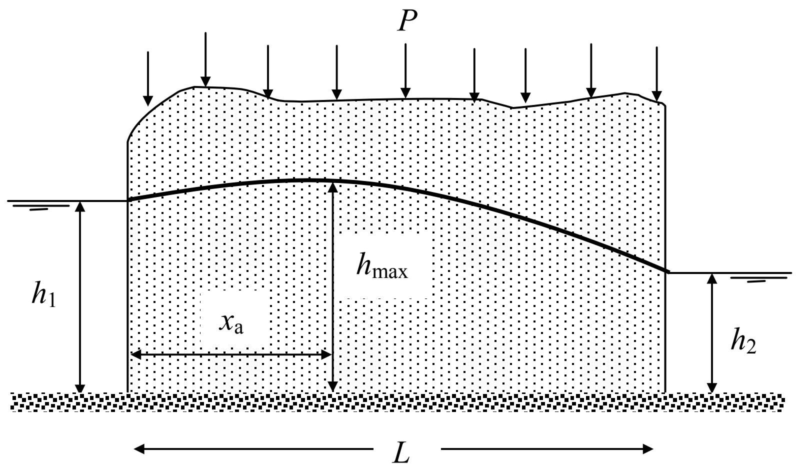


Figure 1.1. Model geometry

The equation for flow can be expressed as

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = \nabla^2 \phi = -P \tag{1.1}$$

For one-dimensional flow, such as that encountered in the present example, solution of equation (1.1) after application of the appropriate boundary conditions yields the horizontal distance, x_a, at which the maximum elevation of the free surface in Figure 1.1 is located, as [1]

$$x_a = \frac{L}{2}\left(1 - \frac{k}{P}\frac{h_1^2 - h_2^2}{L^2}\right) \tag{1.2}$$

The corresponding maximum height for the free surface, $h_{\max}$, can be calculated as

$$h_{\max} = \sqrt{h_1^2 - \frac{x_a}{L}\left(h_1^2 - h_2^2\right) + \frac{P}{k}\left(L - x\right)x} \tag{1.3}$$

1.2 *Slide* model and results

The *Slide* model for the problem is shown in Figure 1.2.

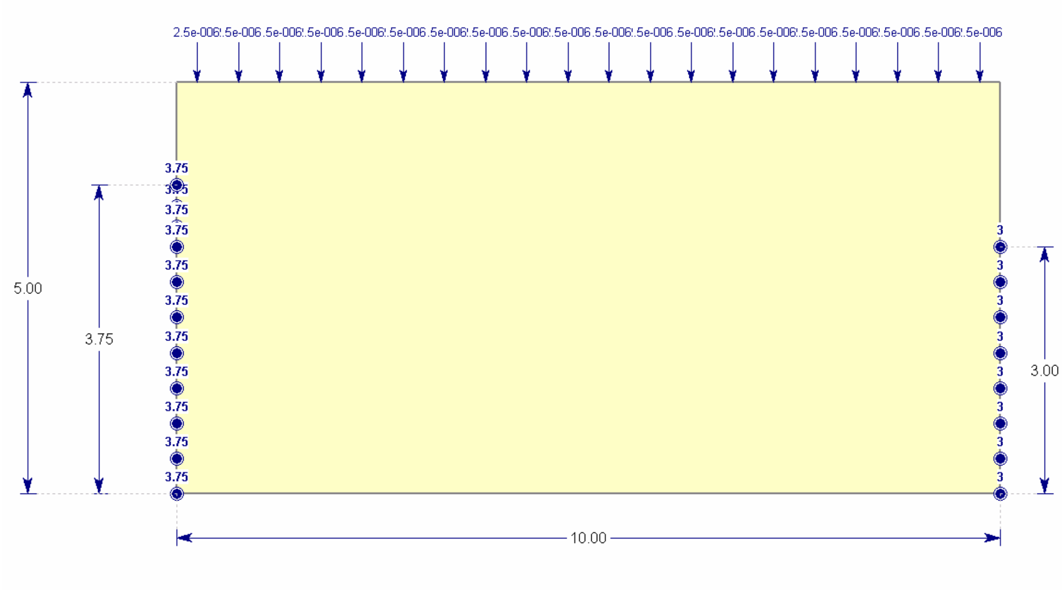


Figure 2.2 *Slide* model

The *Slide* model uses the following input parameters:

- h_1 = 3.75m, h_2 = 3.0m (flow heads at the river boundaries),
- L =10.0m (separation between the rivers),
- P = 2.5e-6 m/s (rate of discharge), and
- k = 1.0e-5 (hydraulic conductivity).

The problem is modelled using three-noded triangular finite elements. The total number of elements used was 225 elements.

Figure 1.3 shows contours of pressure head with the coordinates (x_a, h_{max}) of point at which the maximum height of the free surface occurs.

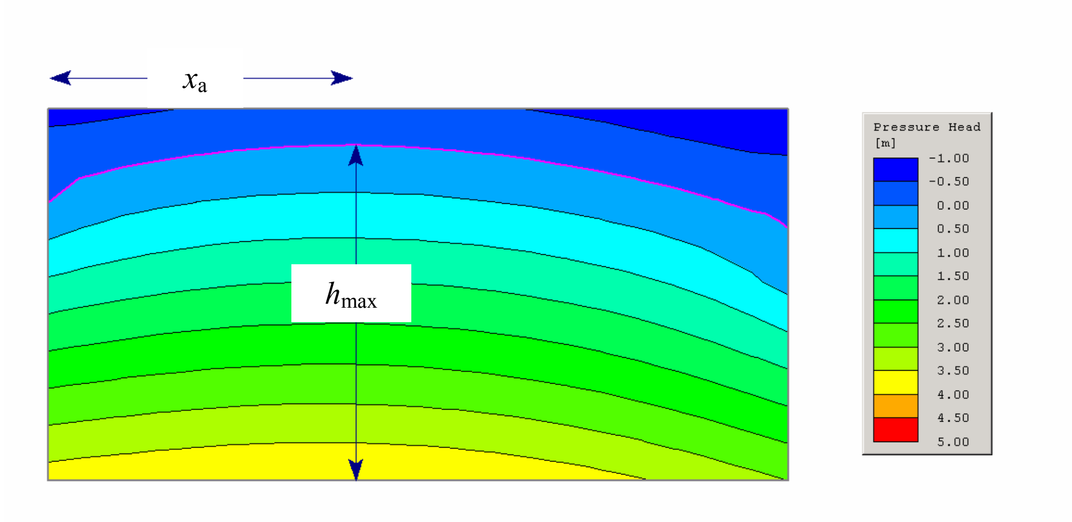


Figure 2.3 Pressure head contours

The table below compares the results from *Slide* with those calculated from equations 1.2 and 1.3

Parameter	*Slide*	Equations (1.2-1.3)
x_a	4.06	3.98
h_{max}	4.49	4.25

The *Slide* results are in close agreement with the analytical solution. If necessary, a finer mesh discretization could be used to improve the results of *Slide*.

1.3 References

1. Haar, M. E. (1990) *Groundwater and Seepage*, 2nd Edition, Dover

Note: See file Groundwater#01_1.sli (regular mesh), Groundwater#01_2.sli (uniform mesh)

2. Flow around cylinder

2.2 Problem description

This example examines the problem of uniform fluid flow around a cylinder of unit radius as depicted in Figure 2.1.

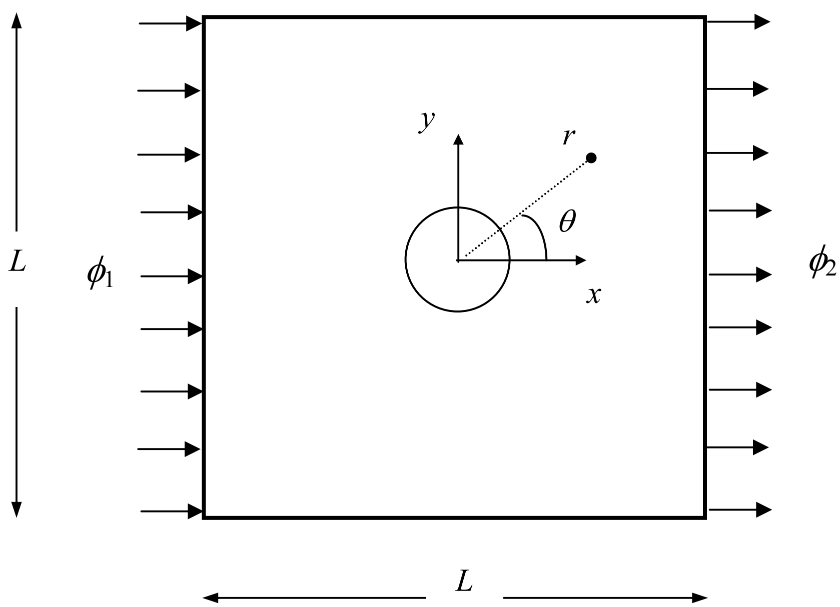


Figure 2.1 Model geometry

The closed form solution for this problem is given in Ref. [1]. This analytical solution gives the total head values at any point in the problem domain as

$$\phi = U\left(r + \frac{a^2}{r}\right)\cos\theta + 0.5 \tag{2.1}$$

where U is the uniform undisturbed velocity = $\frac{\phi_1 - \phi_2}{L}$, $r = \sqrt{x^2 + y^2}$ and a is the radius of cylinder, and θ is the anti-clockwise angle measured from the x axis to the field point.

2.2 *Slide* model and results

The *Slide* model for the geometry is shown in Figure 2.2.

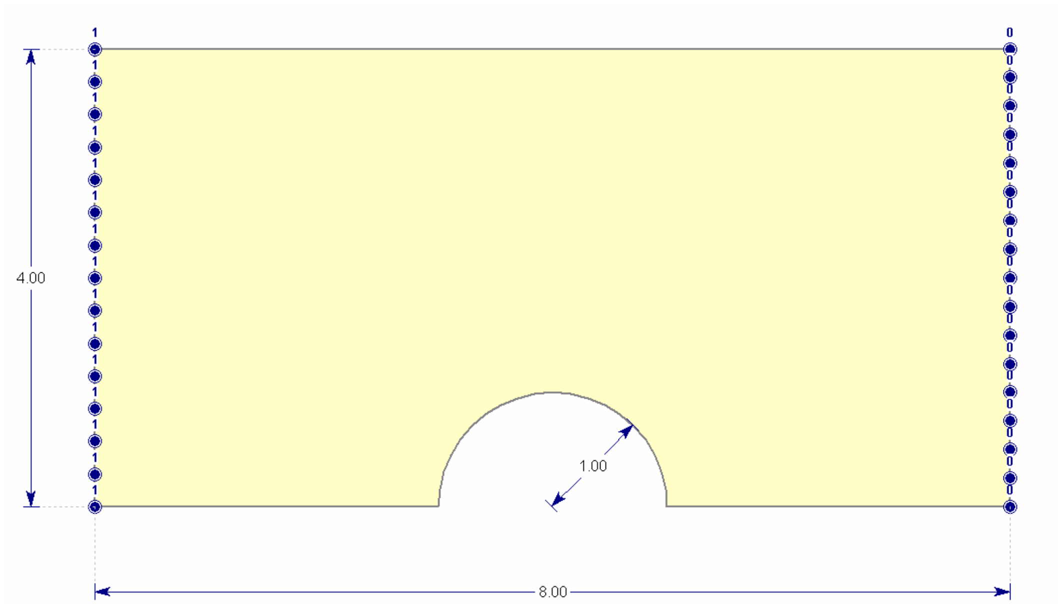


Figure 2.2 *Slide* model

It uses the following input parameters:
ϕ_1 = 1.0m, ϕ_2 = 0m (initial flow values at the left and right boundaries, respectively),
L =8.0m (length of the domain),
This problem assumes fully saturated material with hydraulic conductivity of 1.0x10^{-5}.

Owing to the symmetry of the problem around the *x*-axis, only one half of the domain is discretized in the *Slide* model. The half domain is represented with 442 six-noded triangular elements.

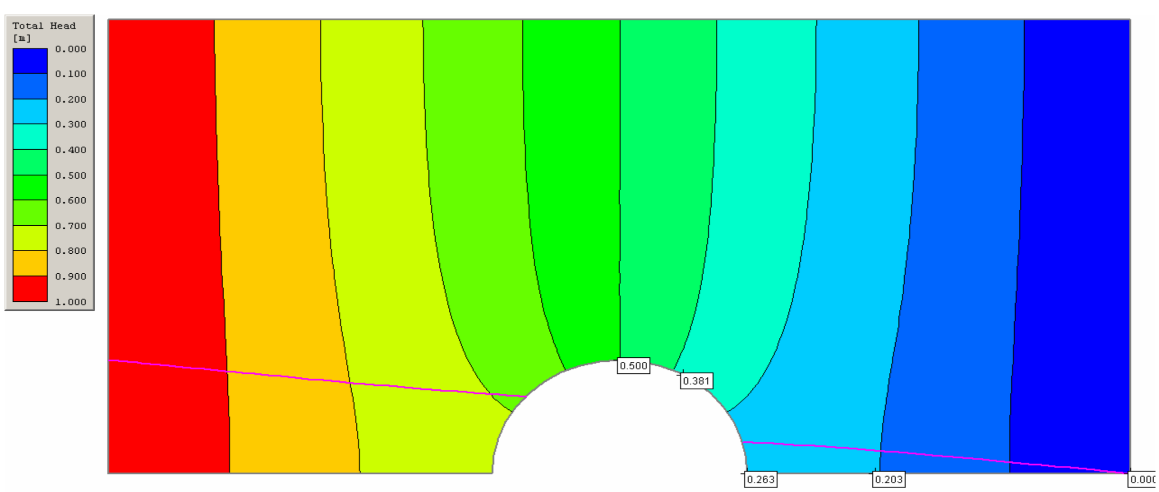


Figure 2.3 Total head contours

Figure 2.3 shows contours of total head with the values at a number of specified locations in the domain. These results from *Slide* are compared with those provided in Ref. [2]. The *Slide* results were within 4% of those provided in Ref [2], and also close to values calculated from equation (2.1)

The following table compares the results from *Slide* with those calculated from equation 2.1 and those presented in Ref [2]

Coordinate of Points in Problem Domain		Flow Results from *Slide*	Flow Results from Equation (2.1)	Ref. [2]
x	*y*			
4	1	0.5000	0.5000	0.5000
4.5	0.866	0.3810	0.3743	0.3780
5	0	0.2630	0.2500	0.2765
6	0	0.2030	0.1875	0.2132
8	0	0.0000	-0.0312	0.0000

2.3 References

1. Streeter, V.L. (1948) *Fluid Dynamics*, McGraw Hill
2. Desai, C. S., Kundu, T., (2001) *Introductory Finite Element Method,* Boca Raton, Fla. CRC Press

Note: See file Groundwater#02.sli

3. Confined flow under dam foundation

3.1 Problem description

The problem considered is a simple example of confined flow. It was selected to help assess the performance of *Slide* on confined flow problems.

Figure 3.1 shows a dam that rests upon a homogeneous isotropic soil (Ref. [1]). In the example, the walls (entity 1) and base (entity 2) of the dam are assumed to be impervious. The water level is 5m, upstream of the dam, and 0m downstream.

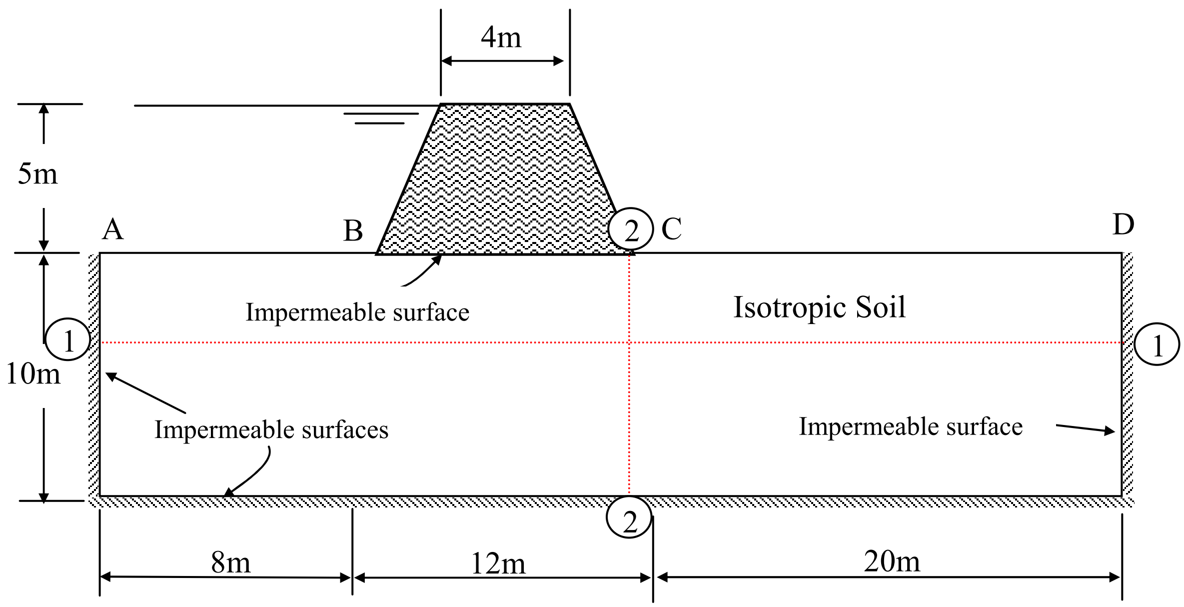


Figure 3.1 Model geometry

The flow is considered to be two-dimensional with negligible flow in the lateral direction. The flow equation for isotropic soil can be expressed as

$$\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2} = 0 \tag{3.1}$$

Equation 3.1 can be solved either using a numerical procedure or a flow net. Flow net techniques are well documented in groundwater references.

The accuracy of numerical solutions for the problem is dependent on how the boundary conditions are applied. For the particular example in this document, two boundary conditions are applied:

- No flow occurs across the impermeable base, and

- The pressure heads at the ground surface upstream and downstream of the dam are solely due to water pressure

3.2 *Slide* model and results

The model created in *Slide* for this problem, with the mesh used, is shown in Figure 3.2.

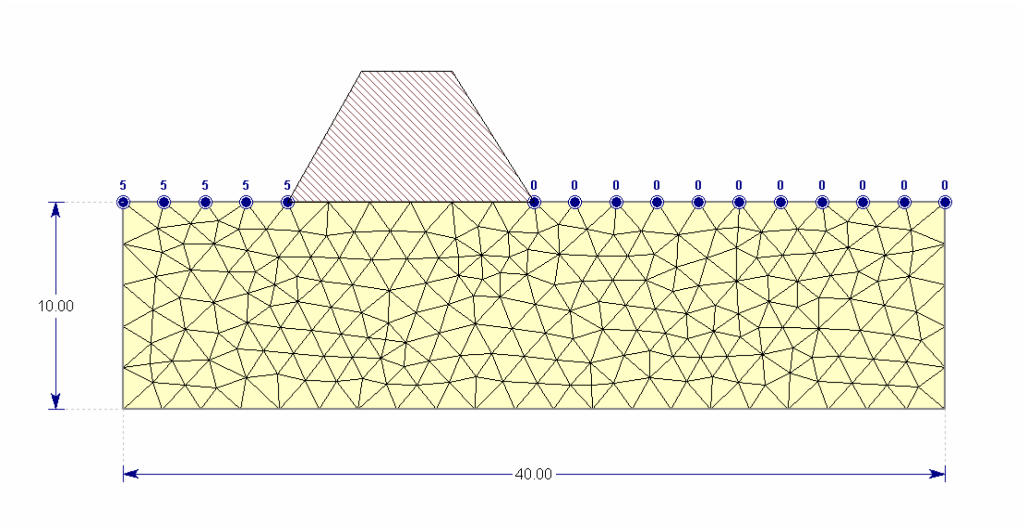


Figure 3.2 *Slide* model

The following boundary conditions were used for the model:

- The total head along the line segment, upstream of the dam, that lies between points A and B (see Figure 3.1), is equal to 5m
- The total head along the line segment, downstream of the dam, that lies between points C and D, is equal to 0m

The *Slide* model was discretized using 427 three-noded triangular finite elements. Figures 3.3 and 3.4 show contours of pressure head and total pressure head, respectively.

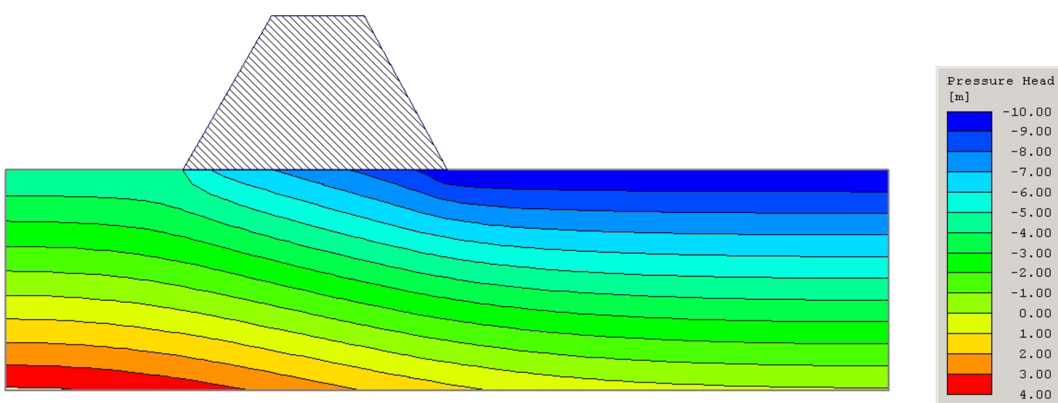


Figure 3.3 Pressure head contours

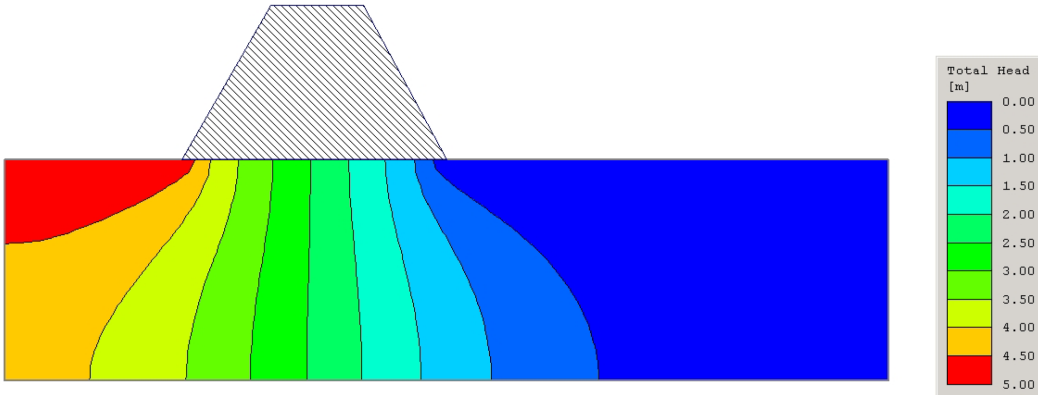


Figure 3.4 Total head pressure contours

Figures 3.5 and 3.6 compare total head pressure values from *Slide* with those obtained from Ref. [1]. These head pressures are calculated at points along line 1-1, which is located 4m below the dam base (see Figure 3.1), and along segment 2-2, a vertical cross section passing through the rightmost base of the dam.

The results from Slide agree closely with those provided in Ref. [1].

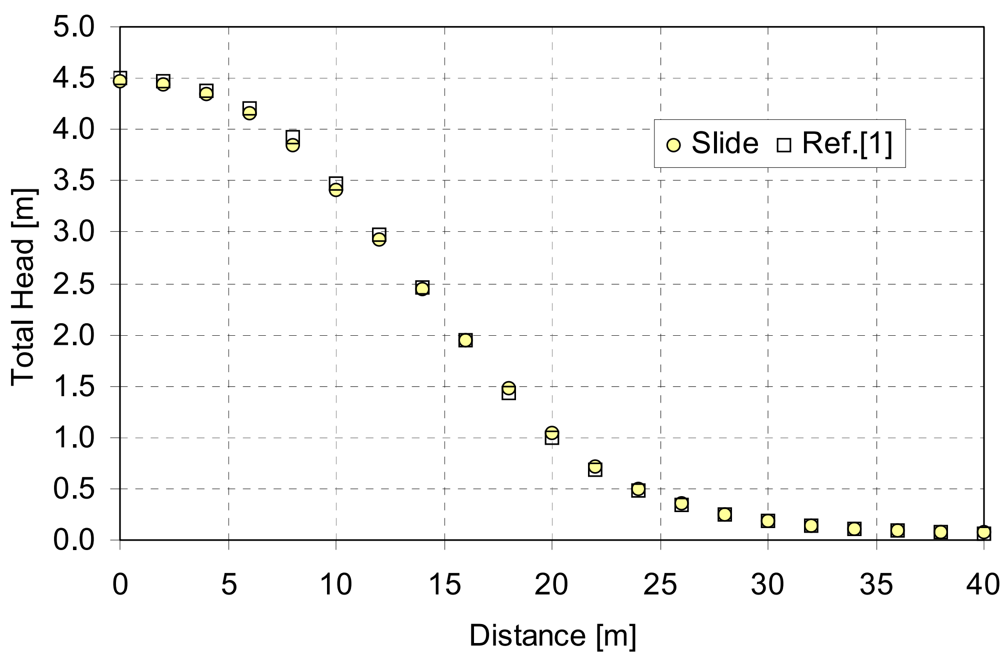


Figure 3.4 Total head variation along line 1-1

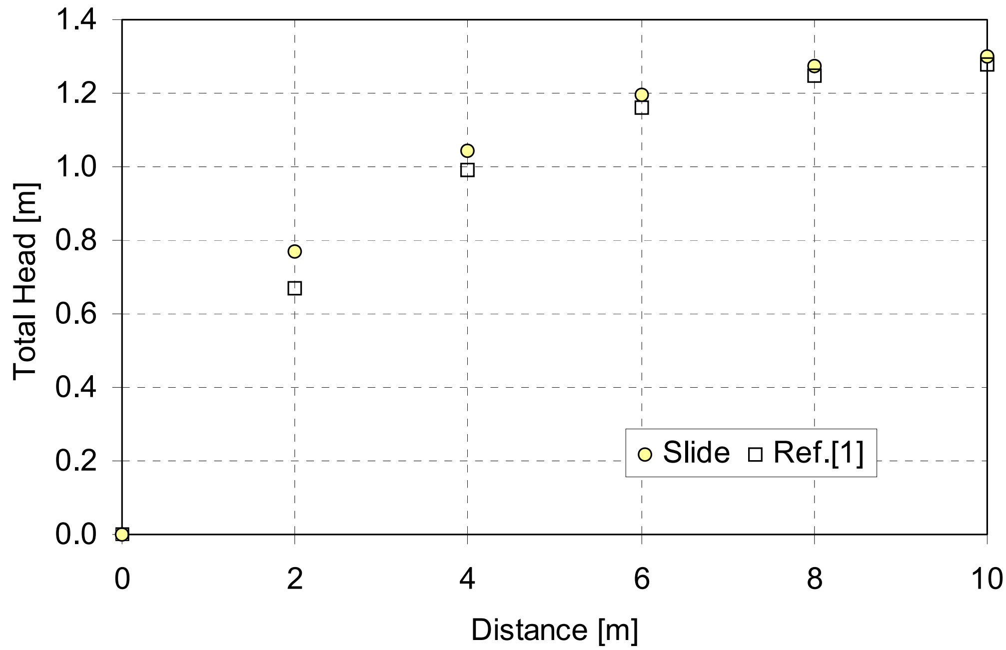


Figure 3.4 Total head variation along line 2-2

3.3 References

1. Rushton, K. R., Redshaw, S.C. (1979) *Seepage and Groundwater Flow*, John Wiley & Sons, U.K.

Note: See file Groundwater#03.sli

4. Steady unconfined flow through earth dam

4.1 Problem description

This example considers the problem of seepage through an earth dam. The task of calculating the shape and length of the free surface (line of seepage) is quite complicated. Some analytical solutions, based on presenting flow nets as confocal parabolas, are available in Ref. [1] and [2].

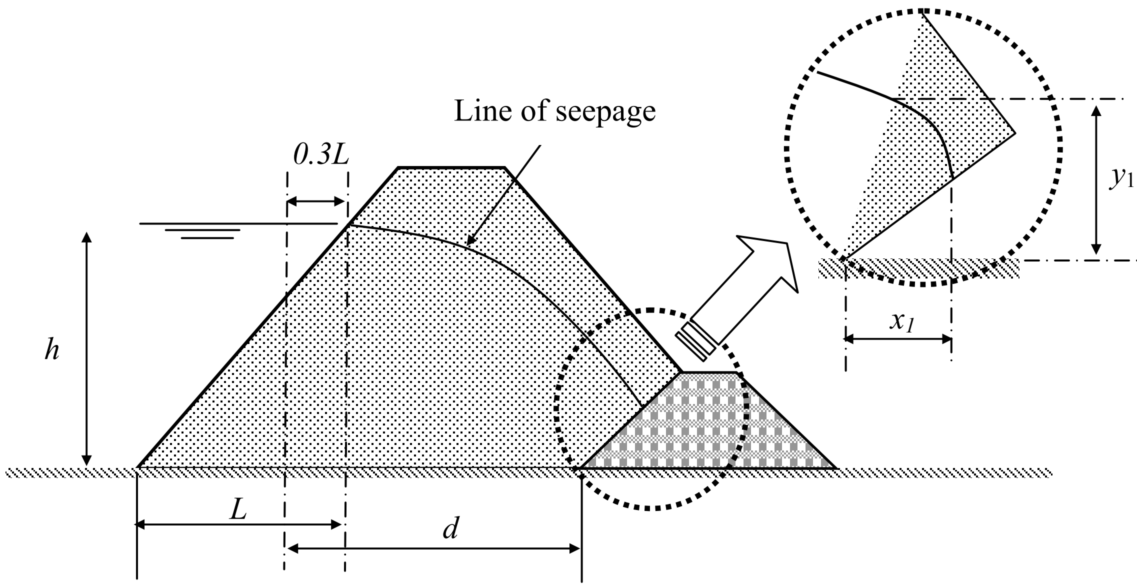


Figure 4.1 Model geometry

Figure 4.1 shows a dam that has a trapezoidal toe drain. By defining the free surface as Kozney's basic parabola (Ref. [1]), we can evaluate y_1, the vertical height of the underdrain, as

$$y_1 = \sqrt{d^2 + L^2} - d \tag{4.1}$$

Then the minimum horizontal length of the underdrain, x_1, equals

$$x_1 = \frac{y_1}{2} \tag{4.2}$$

4.2 *Slide* model and results

The *Slide* model geometry and boundary conditions used in this example are shown in Figure 4.2.

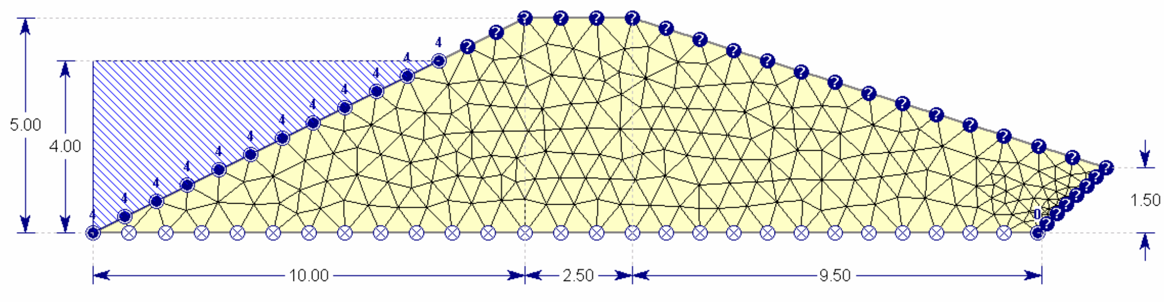


Figure 3.2 *Slide* model

The total head on the upstream face of the dam was taken to be 4m, and the toe drain was located at the downstream toe of the dam, i.e. total head at location (22,0) was taken to be 0. The boundary condition at the toe was assumed undefined, meaning that it initially either had flow, *Q*, or pressure head, *P*, equal to 0. A total number of three-noded triangular finite elements were used to model the problem.

Figures 4.3 and 4.4 show contours of pressure head and total head pressure, respectively.

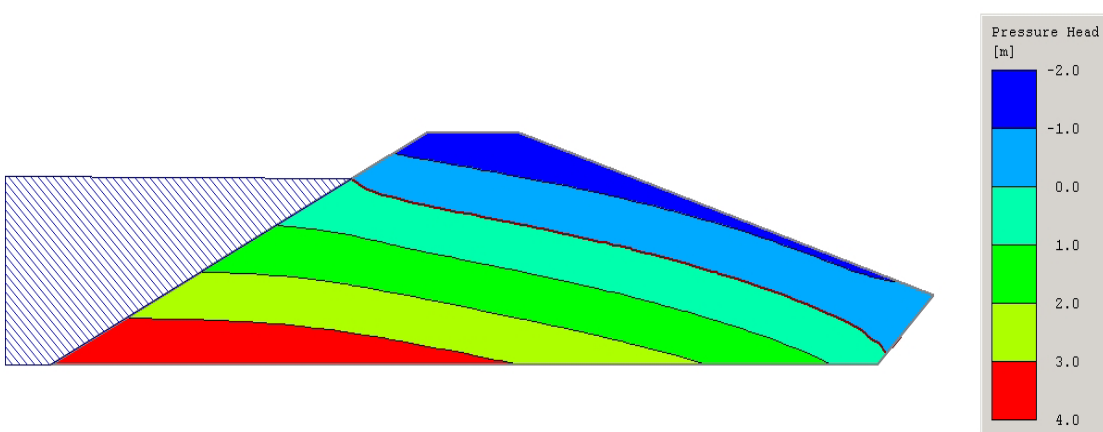


Figure 4.3 Pressure head contours

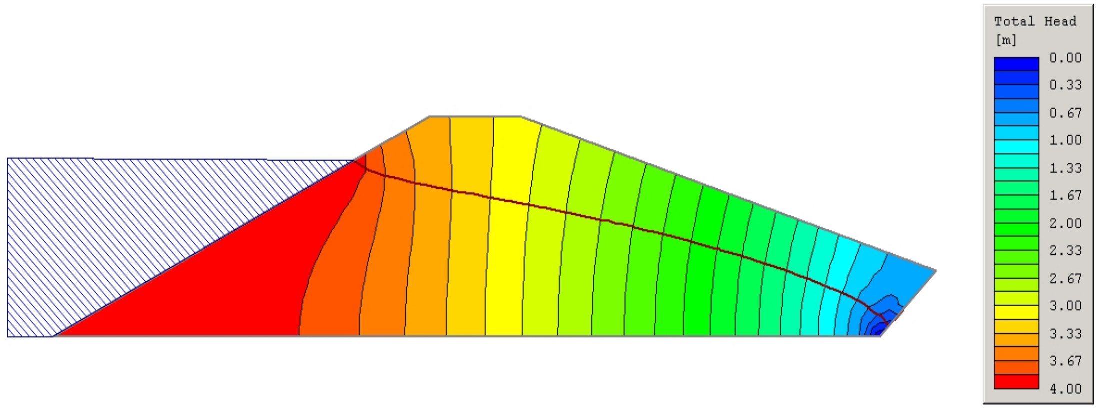


Figure 4.4 Total head pressure contours

The minimum length and height of the underdrain were measured in *Slide* and the results are shown in Figure 4.5

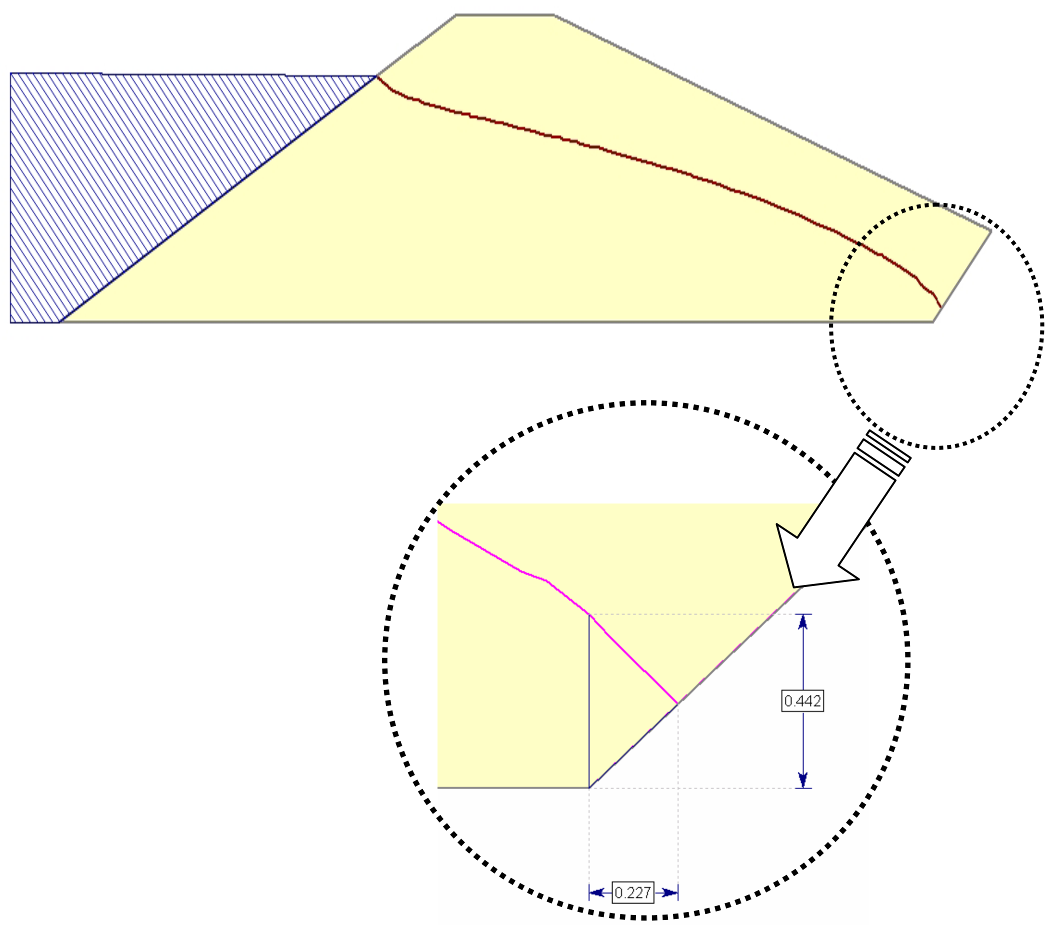


Figure 4.5 Length and height of minimum underdrain

The following table compares the results from *Slide* with those calculated from equations 4.1 and 4.2

Parameter	*Slide*	Equations (4.1-4.2)
x_1	0.227	0.240
y_1	0.442	0.480

As can be seen, the *Slide* results are in close agreement with the equations 4.1 and 4.2.

4.3 References

1. Haar, M. E. (1990) *Groundwater and Seepage*, 2nd edition, Dover
2. Raukivi, A.J., Callander, R.A. (1976) *Analysis of Groundwater Flow*, Edward Arnold

Note: See file Groundwater#04.sli

5. Unsaturated flow behind an embankment

5.1 Problem description

The geometry of the problem considered in this section is taken from FLAC manual [1]. The example is modified slightly to handle two different materials. Two materials are considered with different coefficient of permeability. Figure 5.1 shows the geometry of the proposed model.

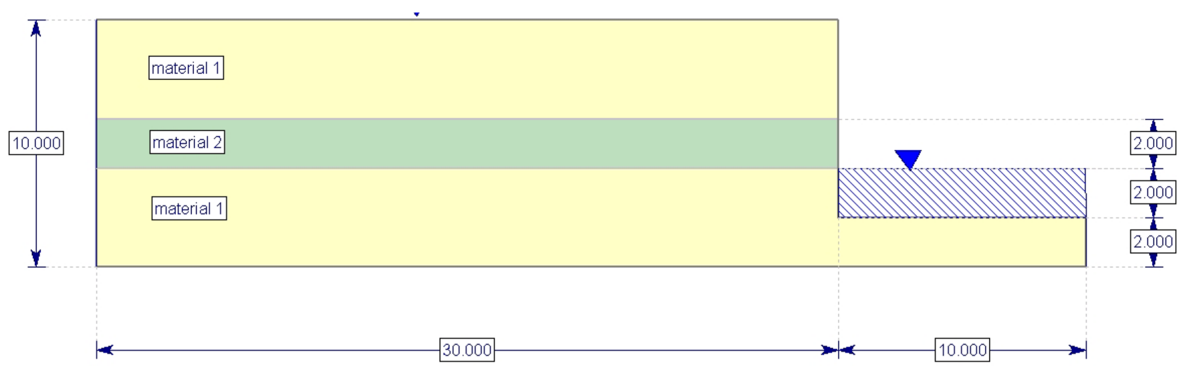


Figure 5.1 Model geometry

5.2 *Slide* model and results

The saturated hydraulic conductivity of material 1 and material 2 is 1×10^{-10} m/sec and 1×10^{-13} respectively. *Slide* model geometry is presented in Figure 5.1. The problem is discretized using 6-noded triangular finite elements. The total number of elements used was 746 elements. The boundary conditions are applied as total head of 10m at the left side and 4m at the right side of the geometry. Zero flow is assumed at the top and at the bottom of the geometry.
Figures 5.2-5.3 show contours of pressure head from Slide and FLAC respectively.

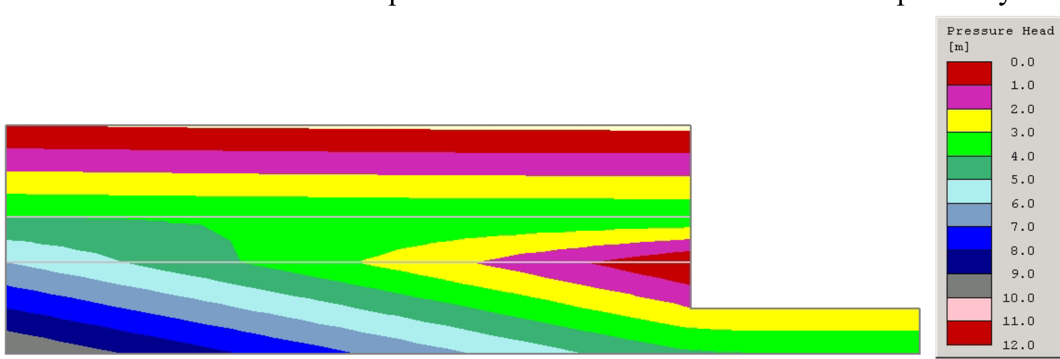


Figure 5.2 Pressure head contours from *Slide*

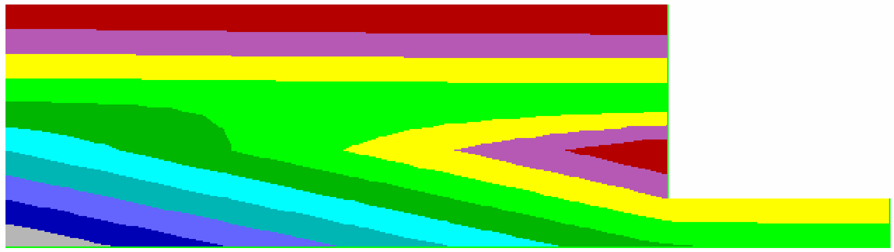


Figure 5.3 Pressure head contours from *FLAC*

Figures 5.4 and 5.5 show the flow lines obtained from *Slide* and *FLAC*

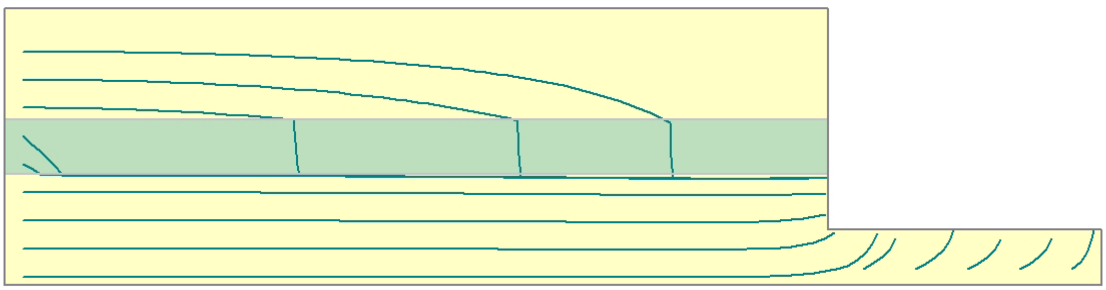


Figure 5.4 Flow lines from *Slide*

Figure 5.5 Flow lines from *FLAC*

The results from *Slide* and *FLAC* compared very well with the predicted performance.

5.3 References

1. FLAC manual, Itassca Consulting Group Inc., 1995

Note: See file Groundwater#05.sli

6. Steady-state seepage analysis through saturated-unsaturated soils

6.1 Problem description

This example considers the problem of seepage through an earth dam. The geometry of the problem considered in this section, which is shown in Figure 6.1, is taken from *Soil Mechanics for Unsaturated Soils* by Fredlund & Rahardjo [1].

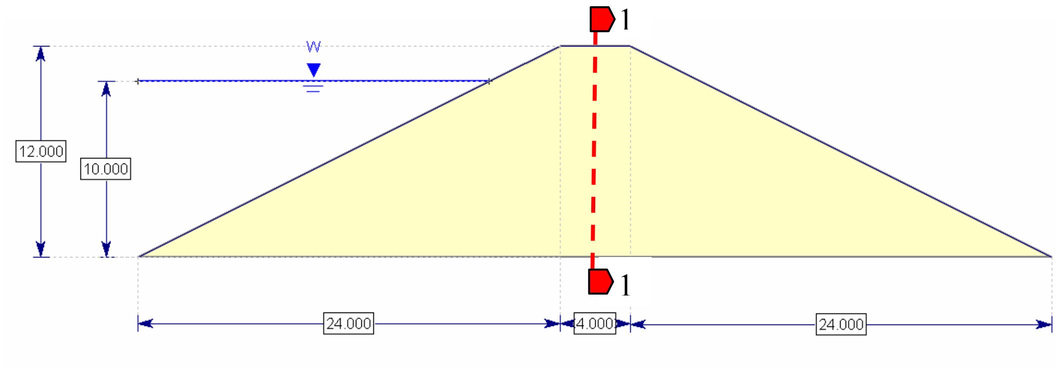


Figure 6.1 Model geometry

6.2 *Slide* model

The problem is discretized using 3-noded triangular finite elements. The total number of elements used was 336 elements. The mesh used for this example was created using mapped mesh option to replicate similar mesh of Ref. [1]. Five different cases are presented in this example as follows:

1. <u>Isotropic earth dam with a horizontal drain</u>

The first case considers an isotropic earth dam with 12m horizontal drain. The permeability function used in the analysis is shown in Figure 6.2

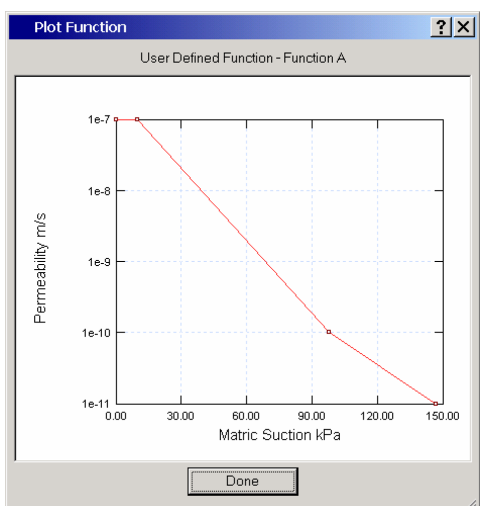


Figure 6.2 Permeability function for the isotropic earth dam

Figure 6.3 presents the flow vectors and the location of the phreatic line from *Slide* ground water model.

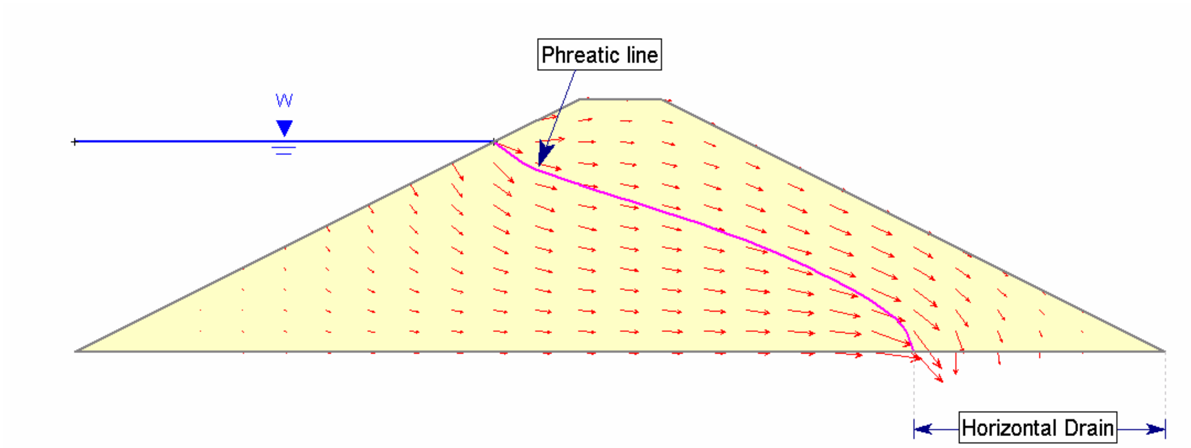


Figure 6.3 Flow vectors

The contours of pressure and total head calculated using finite element method are presented in figures 6.3-6.4 respectively.

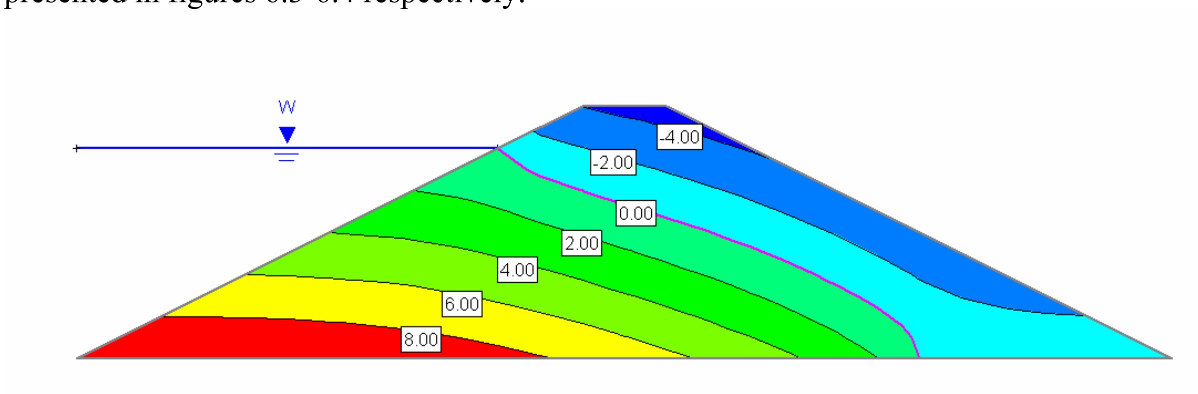


Figure 6.4 Pressure head contours

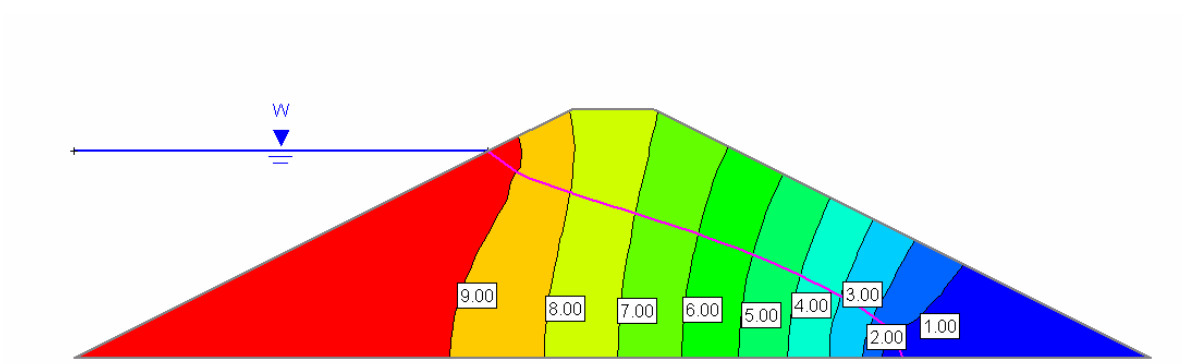


Figure 6.5 Total head contours

Figure 6.6 shows a comparison between slide results and results form Ref. [1] for pressure head distribution along line 1-1.

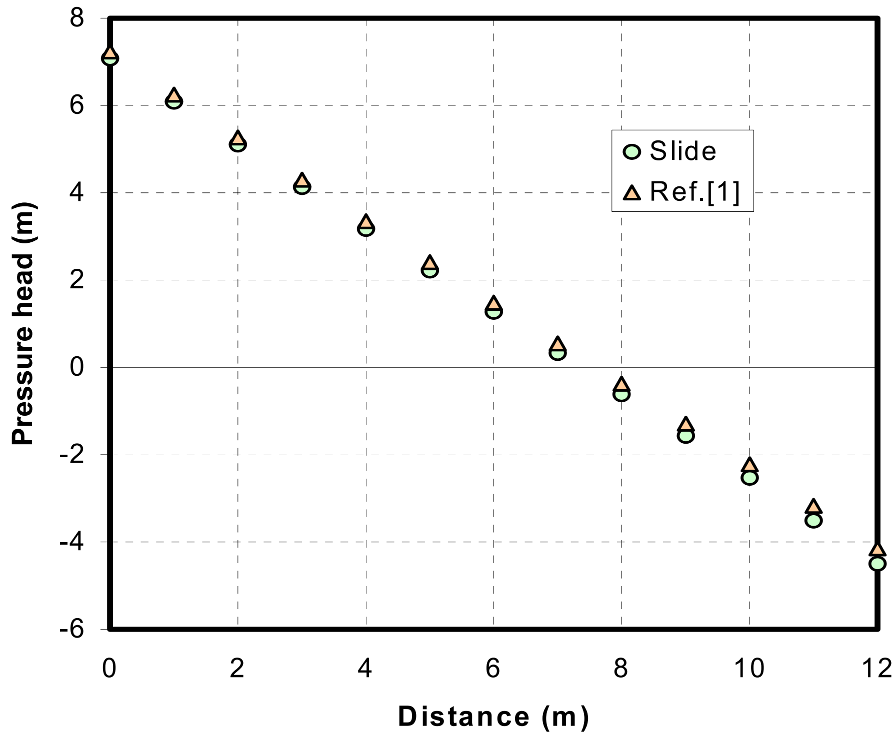


Figure 6.6 Pressure head distribution along line 1-1

Note: See file Groundwater#06_1.sli

2. Anisotropic earth dam with a horizontal drain

The dam is modeled with anisotropic soil with water coefficient permeability in the horizontal direction is assumed to be nine times larger than in the vertical direction. Figures 6.7-6.8 show the contours for pressure head and total head throughout the dam.

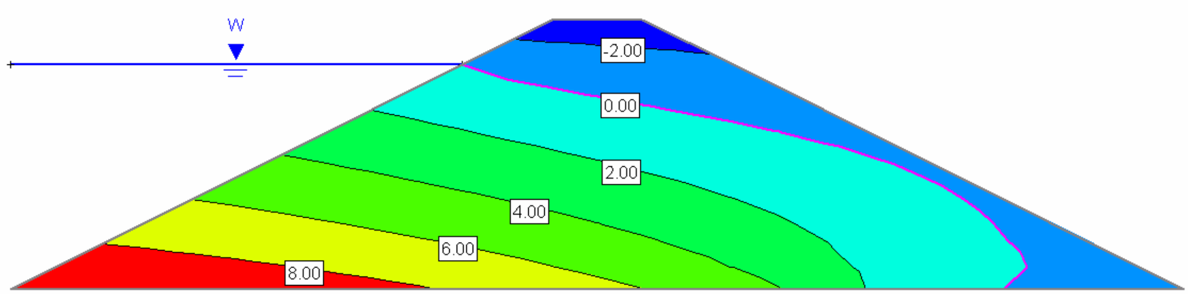


Figure 6.7 Pressure head contours

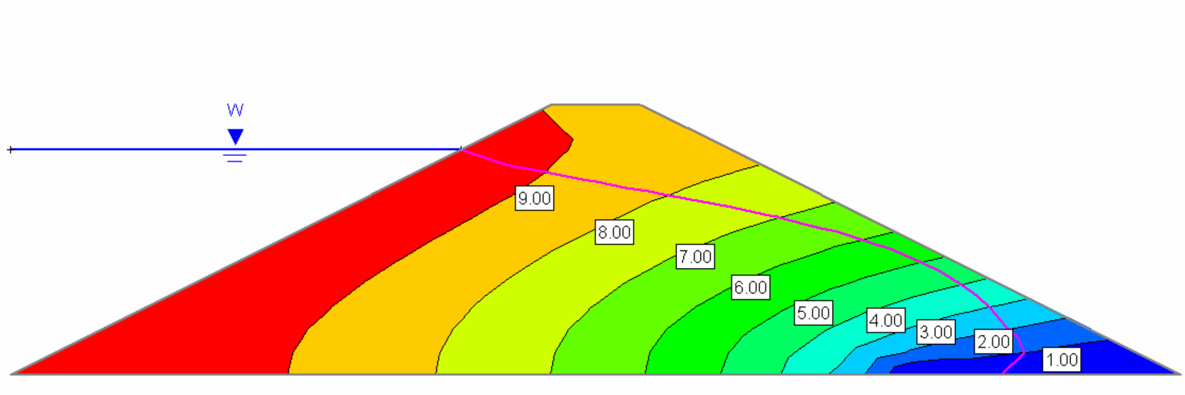


Figure 6.8 Total head contours

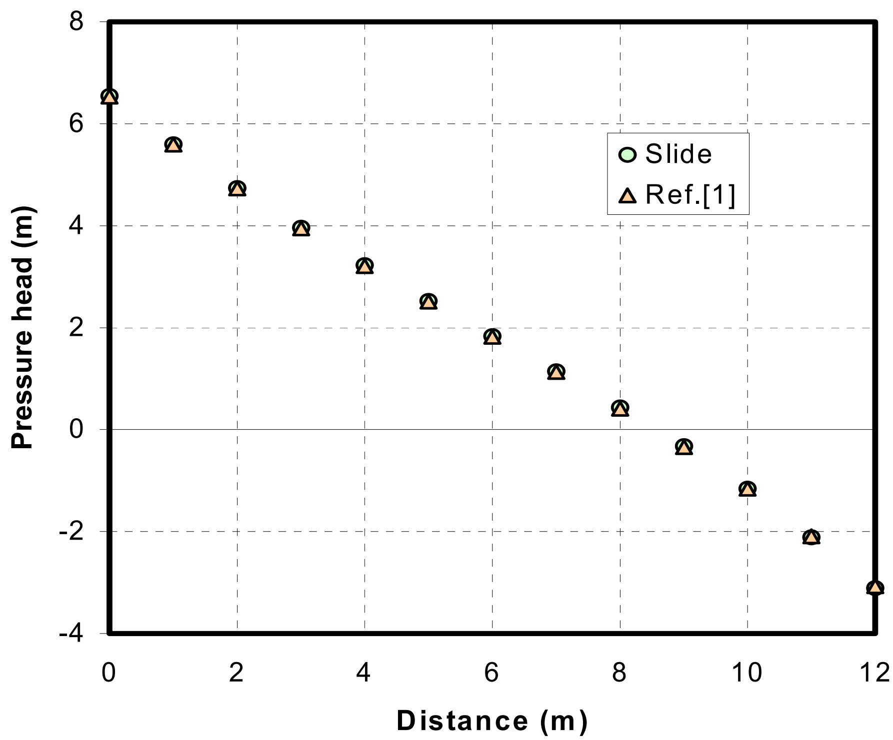


Figure 6.9 Pressure head distribution along line 1-1

Figure 6.9 shows a comparison between slide results and results form Ref. [1] for pressure head distribution along line 1-1.

Note: See file Groundwater#06_2.sli

3. <u>Isotropic earth dam with a core and horizontal drain</u>

The third case considers an isotropic dam having core with lower coefficient of permeability. Figure 6.10 shows the permeability function used for the core material. The results show that the hydraulic head change take place in the zone around the core.

The flow vectors show that the water flows upward into the unsaturated zone and go around the core zone as shown in Figure 6.11. Pressure head and total head contours are presented in Figures 6.12-6.13 respectively.

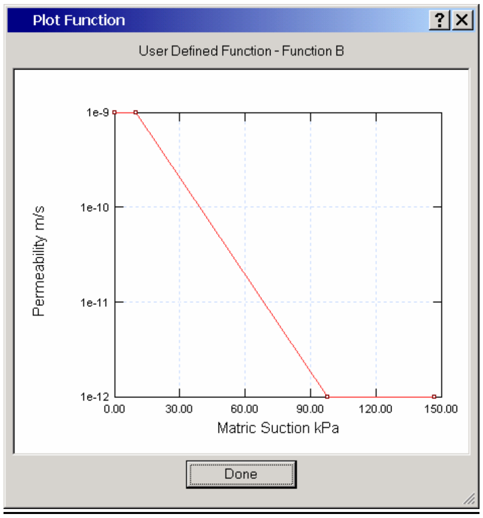


Figure 6.10 Permeability function for the core of the dam

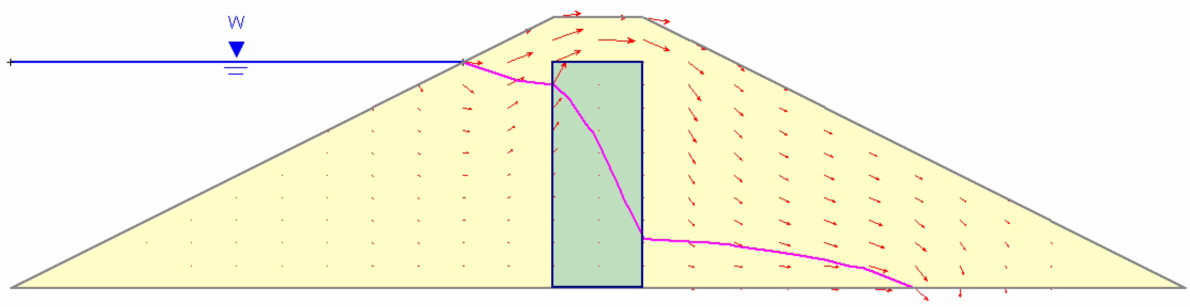


Figure 6.11 Flow vectors

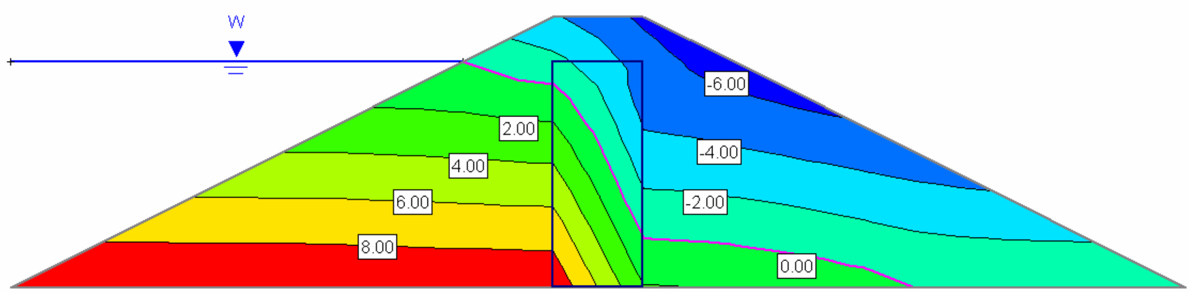


Figure 6.12 Pressure head contours

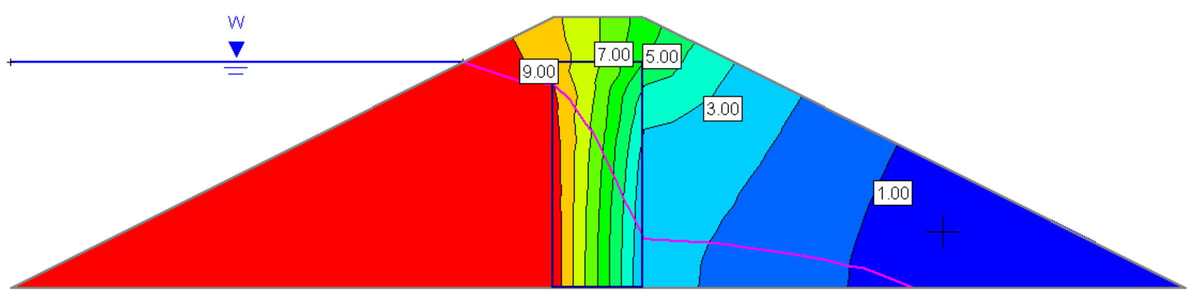


Figure 6.13 Total head contours

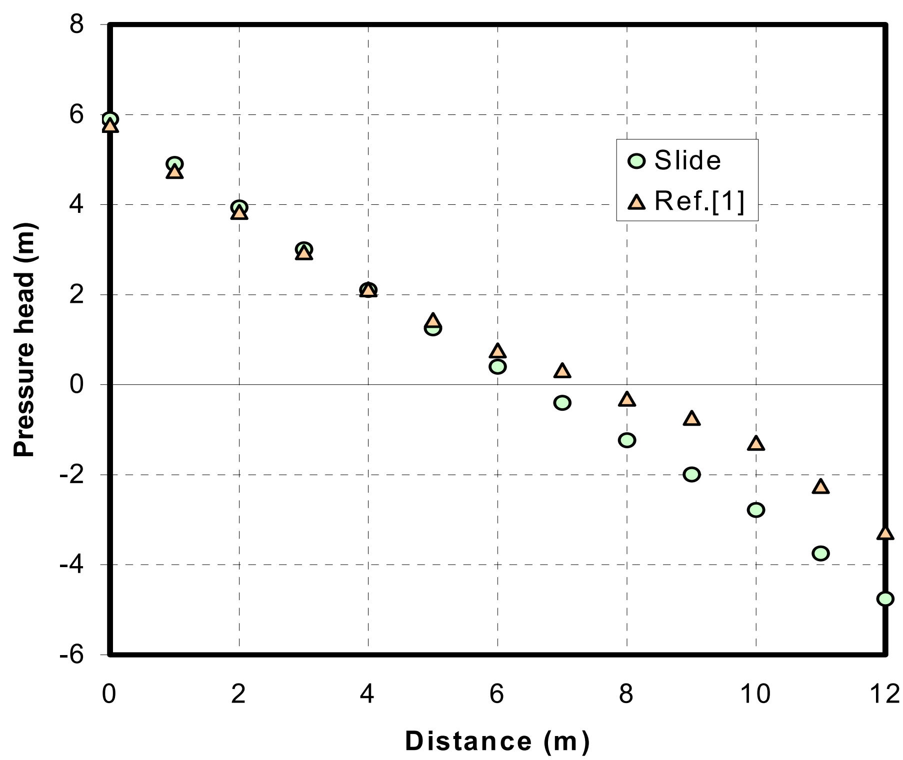


Figure 6.14 Pressure head distribution along line 1-1

Figure 6.14 shows a comparison between slide results and results form Ref. [1] for pressure head distribution along line 1-1.

Note: See file Groundwater#6_4.sli

4. <u>Isotropic earth dam under steady-state infiltration</u>

The fourth case considers the effect of infiltration on the dam shown in Figure 6.15. Infiltration is simulated by applying a flux boundary of $1x10^{-8}$m/s along the boundary of the dam. Pressure head and total head contours are presented in Figures 6.16-6.17 respectively.

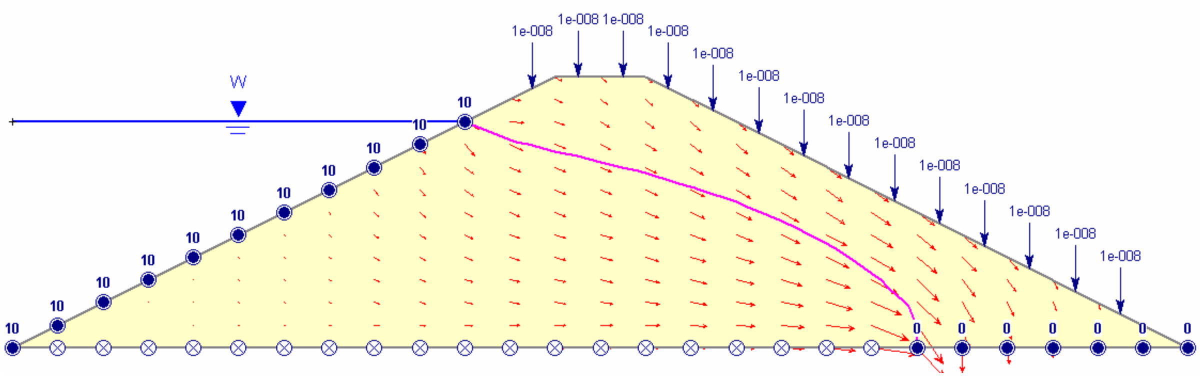


Figure 6.15 Seepage through dam under infiltration

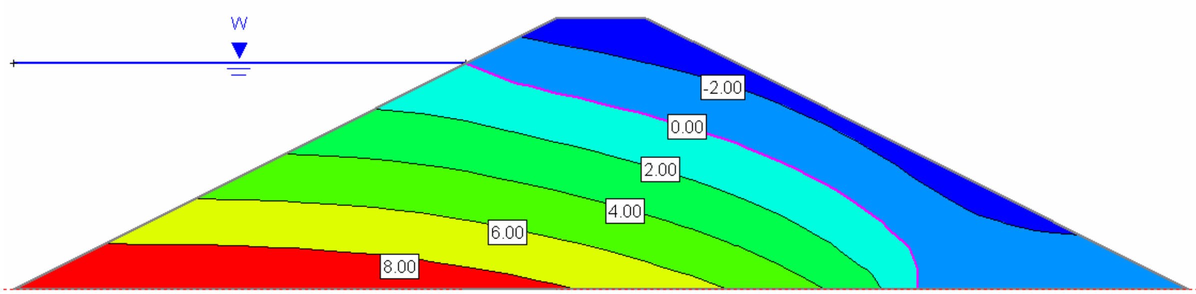


Figure 6.16 Pressure head contours

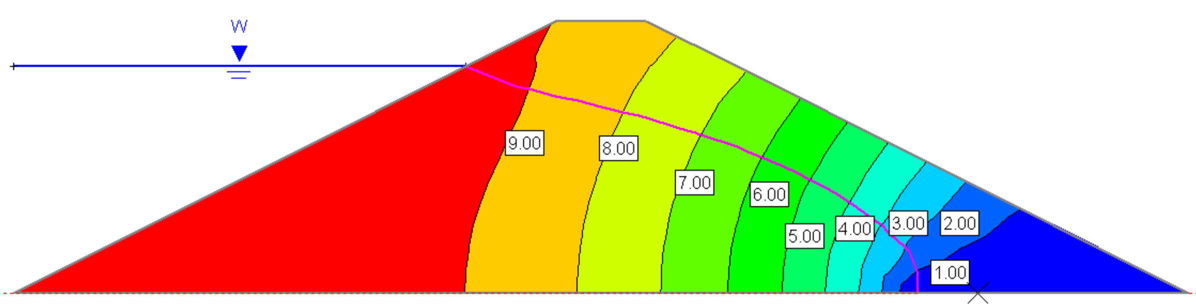


Figure 6.17 Total head contours

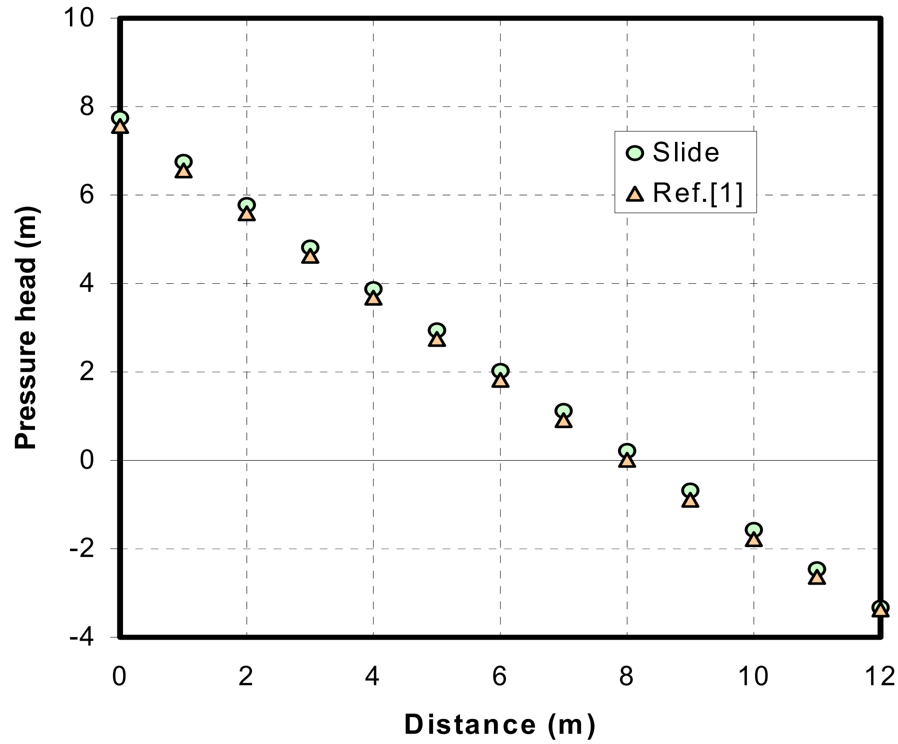


Figure 6.18 Pressure head distribution along line 1-1

Figure 6.18 shows a comparison between slide results and results form Ref. [1] for pressure head distribution along line 1-1.

Note: See file Groundwater#6_5.sli

5. Isotropic earth dam with seepage face

The fifth case demonstrates the use of unknown boundary condition which is usually used for the case of developing seepage faces. The boundary conditions and the phreatic surface are presented in Figure 6.19. Pressure head and total head contours are presented in Figures 6.20-6.21 respectively.

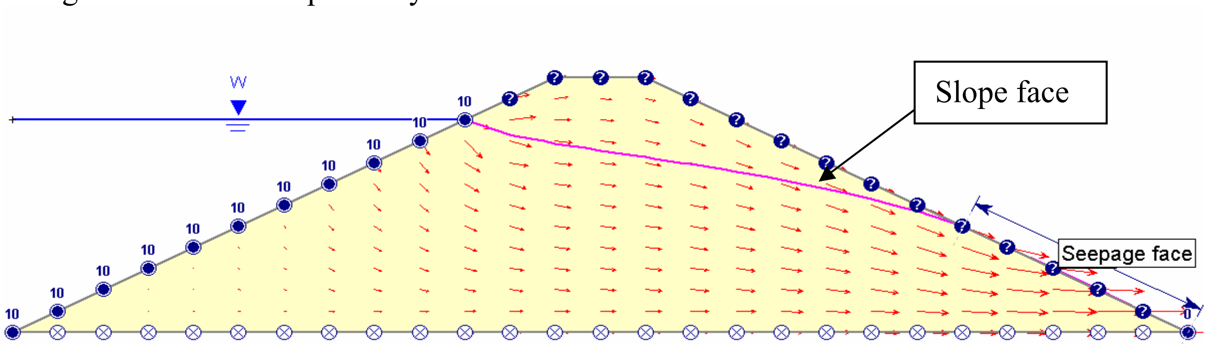


Figure 6.19 Seepage through dam under infiltration

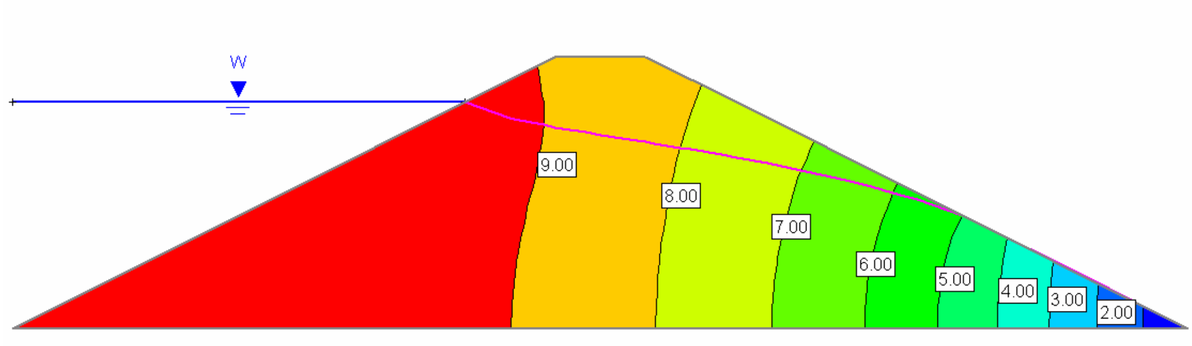


Figure 6.20 Pressure head contours

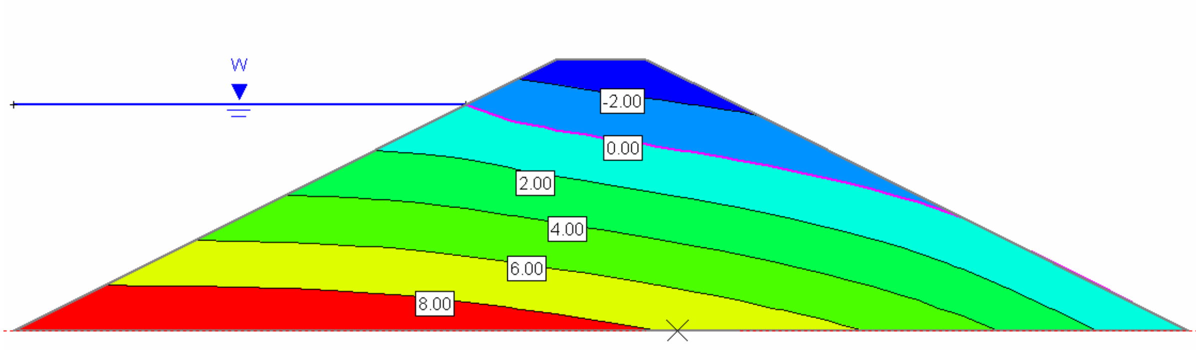


Figure 6.21 Total head contours

Figure 6.22 shows a comparison between slide results and results form Ref. [1] for pressure head distribution along the slope face.

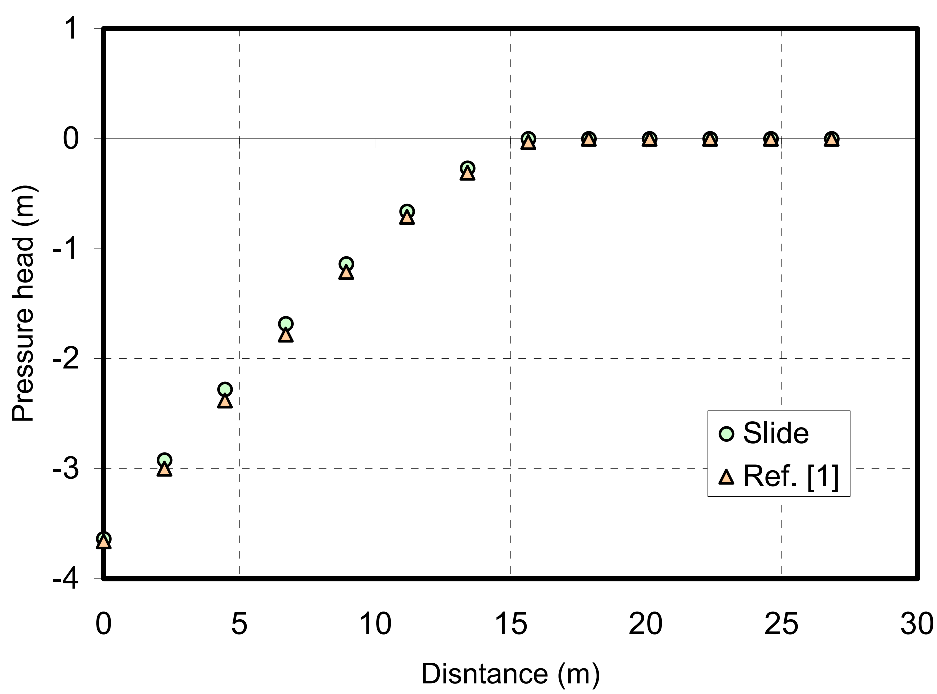


Figure 6.22 Pressure head distribution along slope face

Figure 6.23 shows a comparison between slide results and results form Ref. [1] for pressure head distribution along line 1-1.

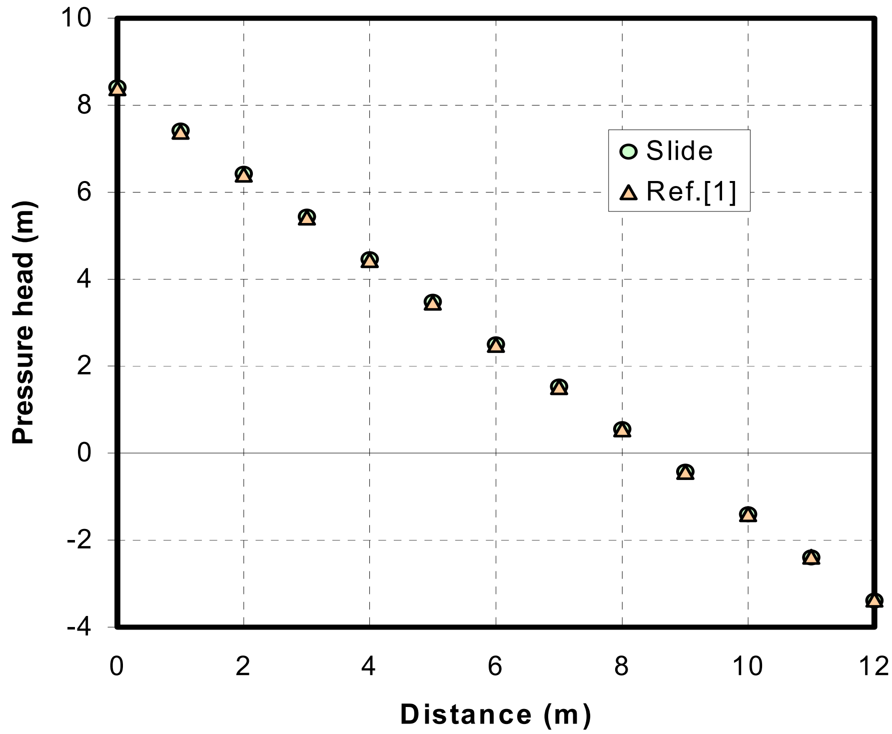


Figure 6.23 Pressure head distribution along line 1-1

Note: See file Groundwater#06_5.sli

6.3 References

1. Fredlund, D.G. and H. Rahardjo (1993) *Soil Mechanics for Unsaturated Soils*, John Wiley

7. Seepage within layered slope

7.1 Problem description

This example considers the problem of seepage through a layered slope. Rulan and Freeze [1] studied this problem using a sandbox model. The material of the slope consisted of medium and fine sand. The fine sand has lower permeability than the medium sand. The geometry of the problem is shown in Figure 7.1 and the two permeability functions used to model the soil is presented in Figure 7.2. These permeability functions are similar to those presented by Fredlund and Rahardjo [2].

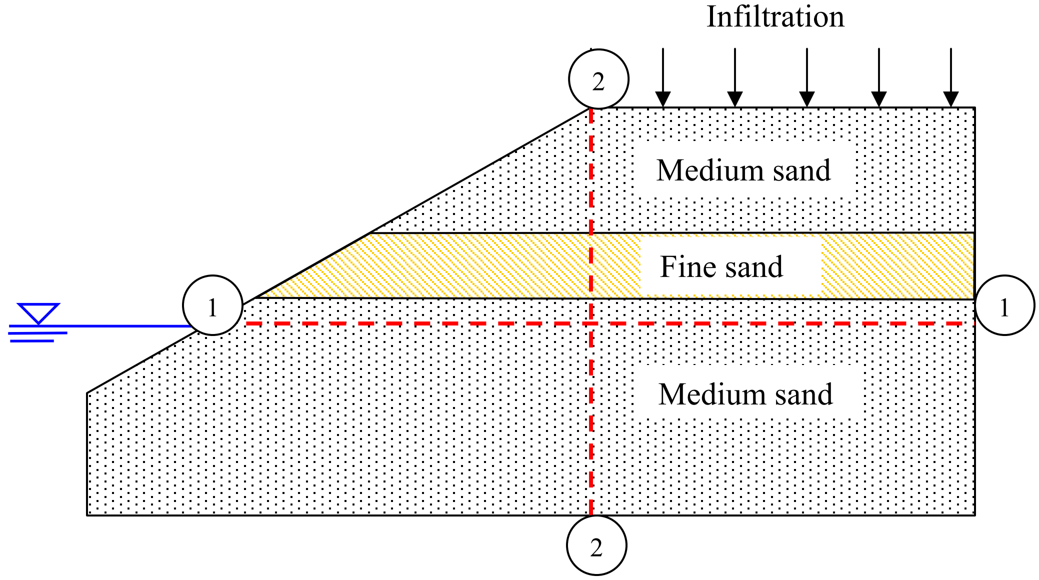


Figure 7.1 Model description

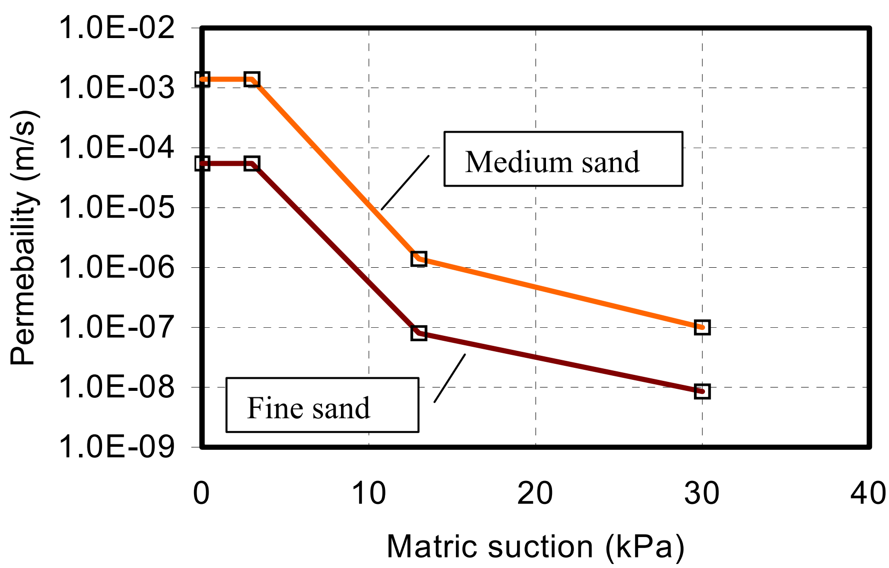


Figure 7.2 Permeability function for the fine and medium sand

7.2 *Slide* model and results

The *Slide* model geometry used in this example is shown in Figure 7.3.

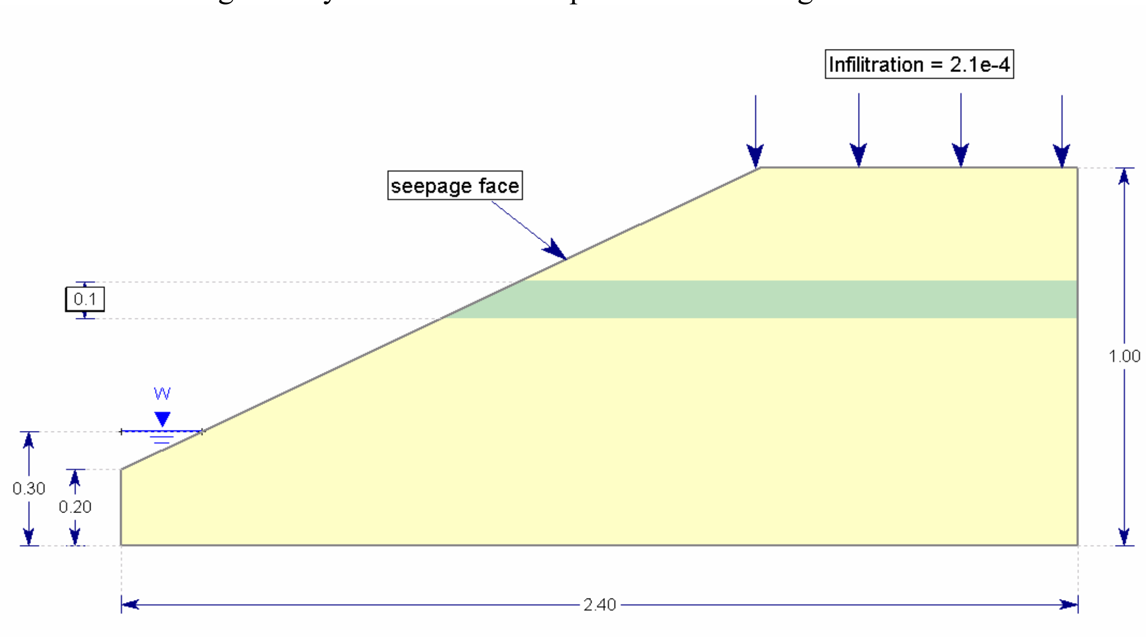


Figure 7.3 *Slide* model

A constant infiltration rate of $2.1\text{x}10^{-4}$ is applied to the top of the side of the slope. The water table is located at 0.3 m from the toe of the slope. The boundary condition at the slope face was assumed undefined, meaning that it initially either had flow, *Q*, or pressure head, *P*, equal to 0. Figure 7.4 shows the location of the calculated water table location and the direction of the flow vectors.

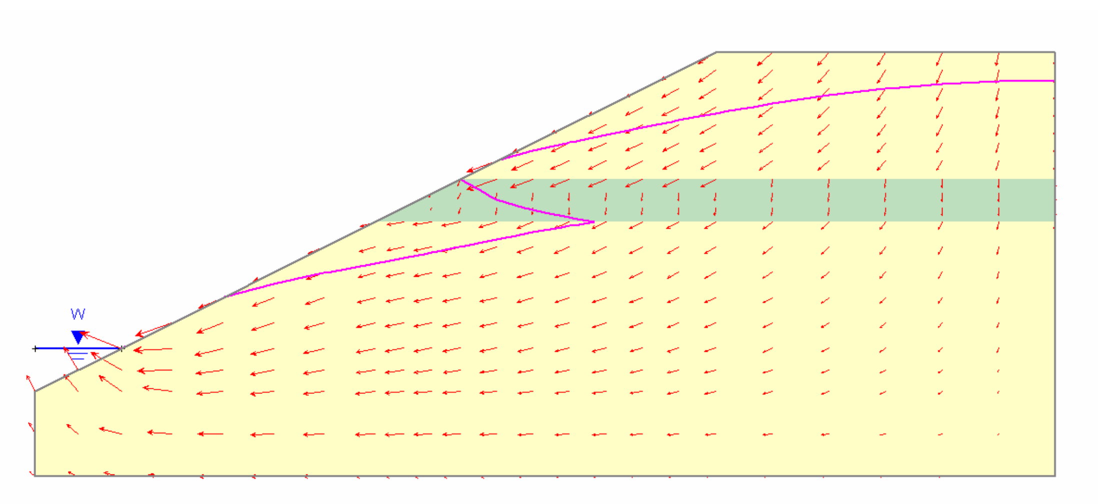


Figure 7.4 Flow vectors

Figures 7.5 and 7.6 show contours of pressure head and total head pressure from *Slide*, respectively.

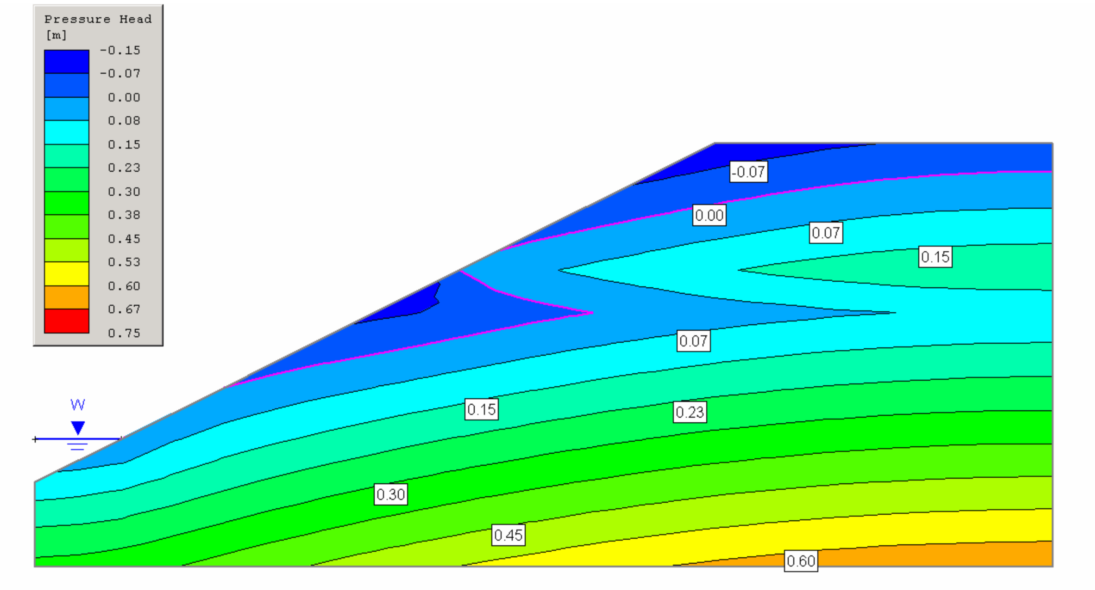


Figure 7.5 Pressure head contours

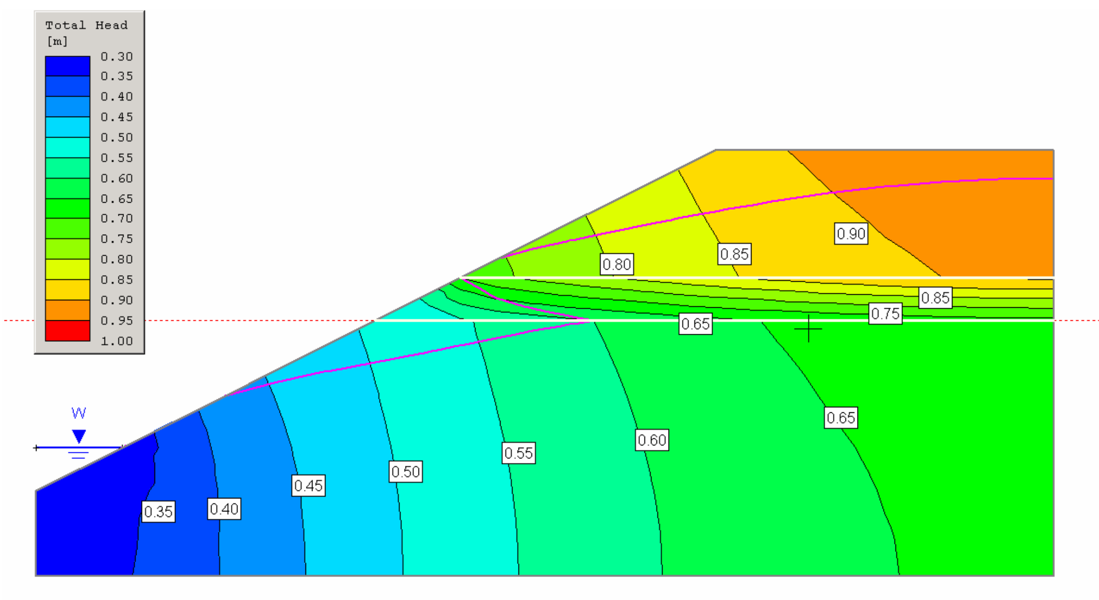


Figure 7.6 Total head contours

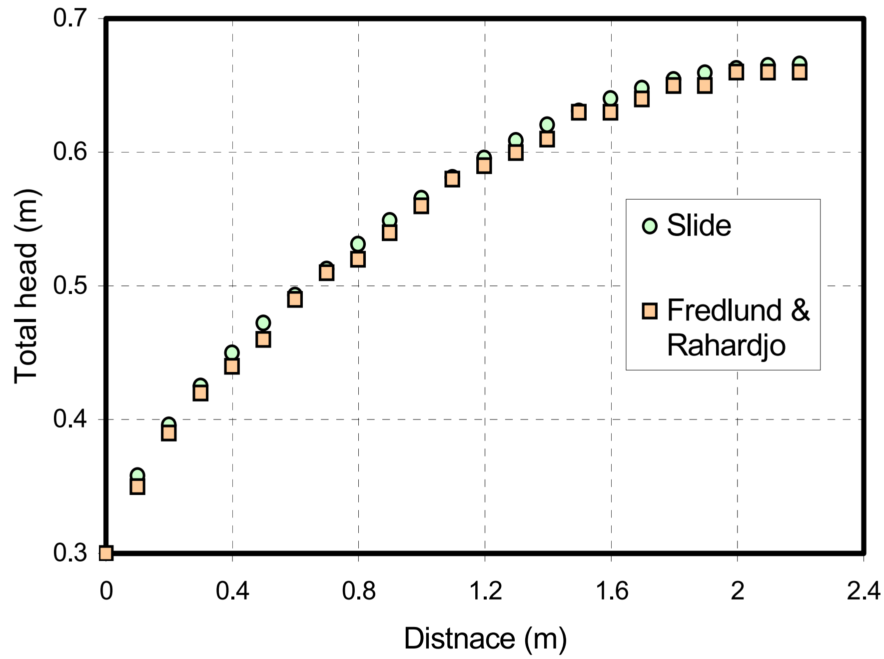


Figure 7.8 Total head variation along line 1-1

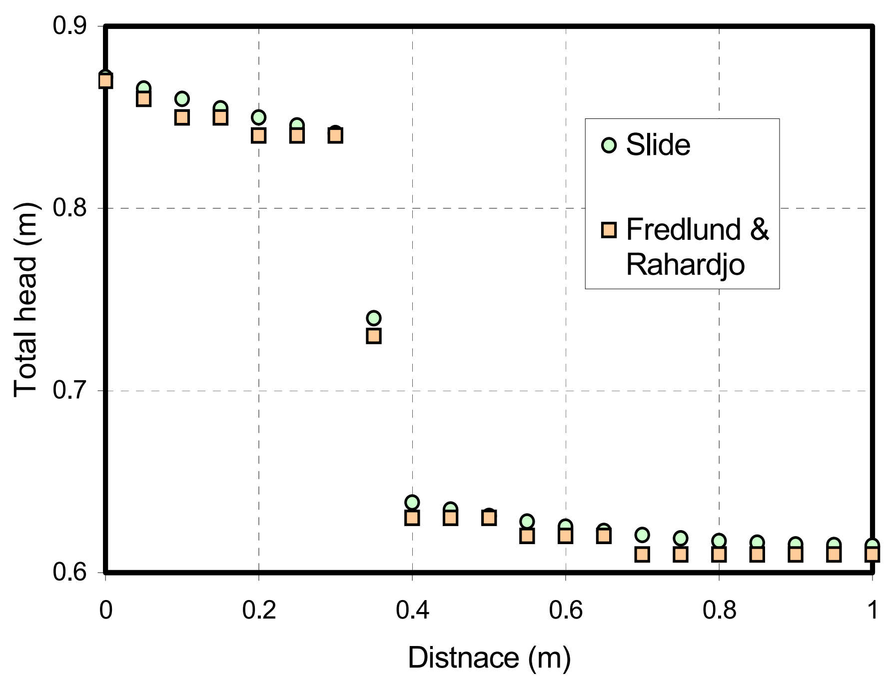


Figure 7.7 Total head variation along line 2-2

7.3 References

1. Fredlund, D.G. and H. Rahardjo (1993) *Soil Mechanics for Unsaturated Soils*, John Wiley

Note: See file Groundwater#07.sli

8. Flow through ditch-drained soils

8.1 problem description

In problems related to ditch-drained aquifers, numerical solutions are often used to predict the level of the water table and the distribution of soil-water pressure. The problem considered in this section involves the infiltration of water downward through two soil layers.
Half-drain spacing with a length of 1m and the depth of the soil to the impermeable level is 0.5m. The ditch is assumed to be water free. Figure 8.1 shows the problem description.

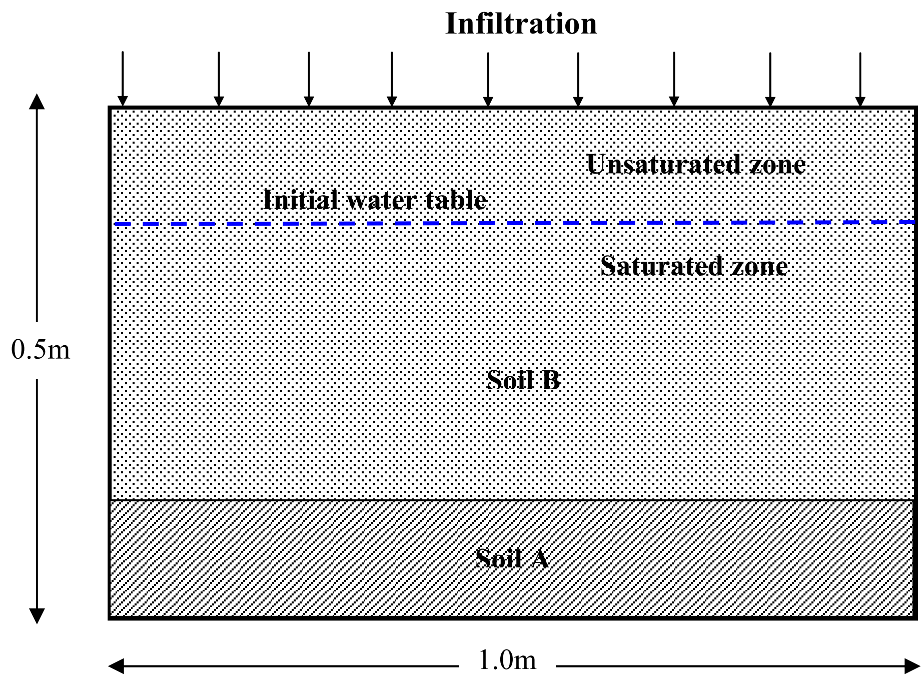


Figure 8.1. Model geometry

The soil properties of the layered system are given in the Table 8.1 simulating a coarse and a fine soil. The lower layer has a thickness of 0.1m. The rate of incident rainfall (infiltration) is taken to be equal to 4.4e-6 m/sec

Soil A	*Relative Conductivity*	1.11e-3 (m/s)
	Gardner's parameters	$a = 1000$, $n = 4.5$
Soil B	*Relative Conductivity*	1.11e-4 (m/s)
	Gardner's parameters	$a = 2777.7$, $n = 4.2$

Table 8.1 Material parameters

8.2 *Slide* model and results

The *Slide* model for the problem is shown in Figure 8.2.

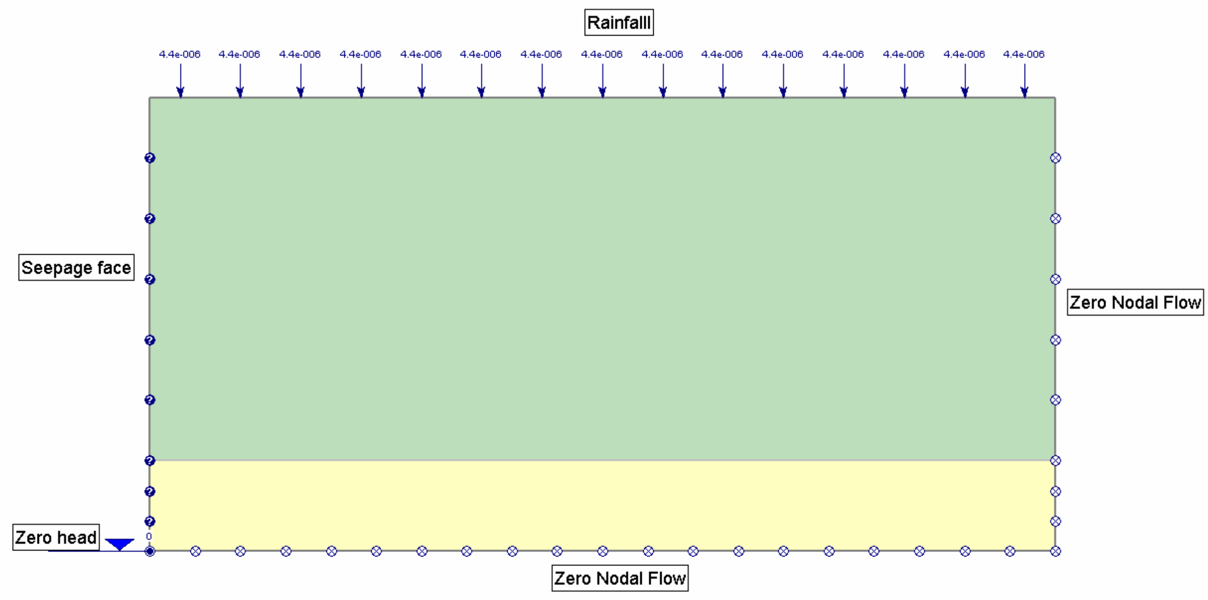


Figure 8.2 *Slide* model

The problem is modelled using three-noded triangular finite elements. The total number of elements used was 459 elements.

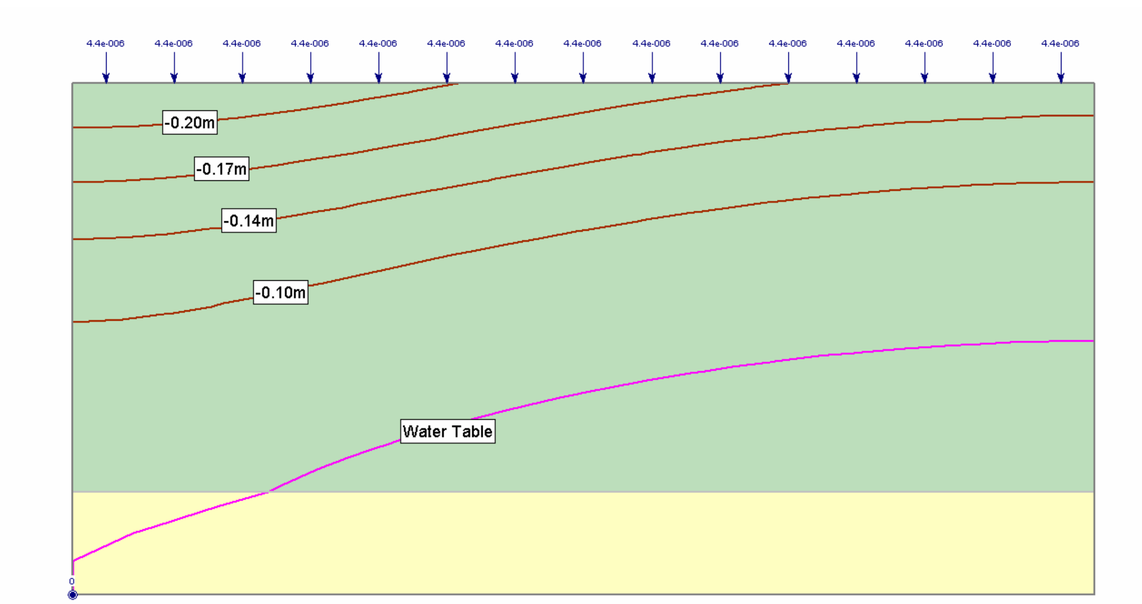


Figure 8.3 The computed unsaturated soil-water regime above the water table

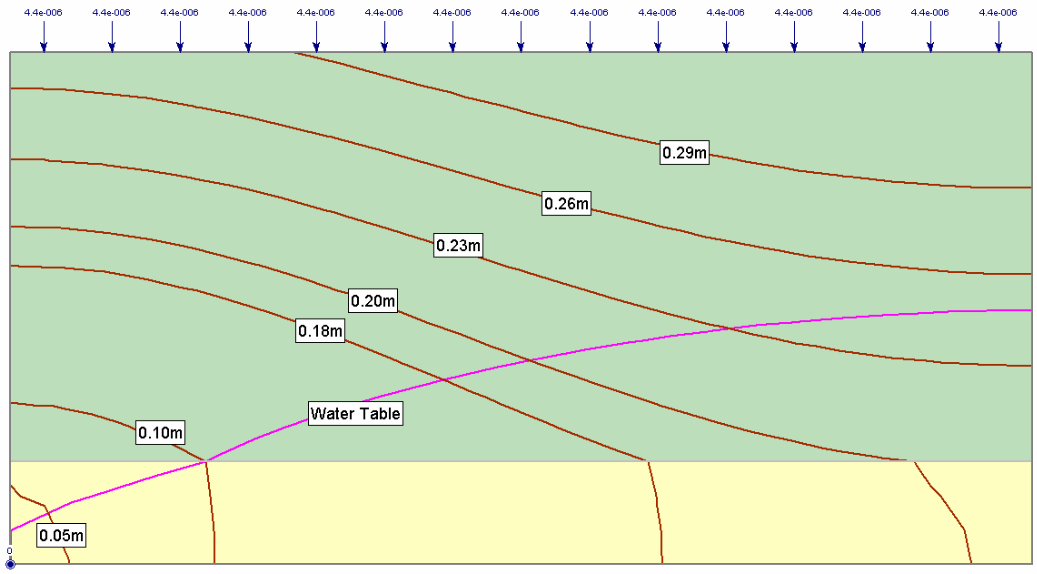


Figure 8.4 The computed total head contours for the drainage situation

Figure 8.3 gives the distribution of the soil-water pressure head for the unsaturated regime above the water table. The computer total head contours are presented in Figure 8.4. The *Slide* results are in close agreement with the solution provided by Gureghian [1].

8.3 References

1. Gureghian A., (1981) "A two dimensional finite element solution scheme for the saturated-unsaturated flow with application to flow through ditch drained soils:" J. Hydrology. (50), 333-353.

Note: See files Groundwater#08.sli

9. Seepage through dam

9.1 Problem description

Seepage flow rate through earth dams are examined in this section. The geometry and material properties for two earth dams are taken from the text book, *Physical and geotechnical properties of soils* by Bowels [1]. Bowles calculated the leakage flow rate through these dams using flow net techniques which neglects the unsaturated flow. Chapuis et. al. [2] solved the same examples using SEEP/W, a finite element software package. In this section, Slide results are compared with Bowles [1] and SEEP/W [2] results.

9.2 *Slide* model and results

1 <u>Homogeneous dam</u>

The seepage rate of homogeneous dam is verified in this section (this example is presented in Bowles, pp.295). Figure 9.1 shows detailed geometry of the dam. The total head of 18.5 is applied on the left side of the dam and the seepage flow rate is calculated on the right side of the dam. A customized permeability function is used to model the material conductivity for the saturated-unsaturated zone (Figure 9.2). This hydraulic conductivity function is similar to the one presented in Chapius et al. [2]. The dam is discretized using 4-noded quadrilateral finite elements. A total of 391 finite elements are used for the mesh.

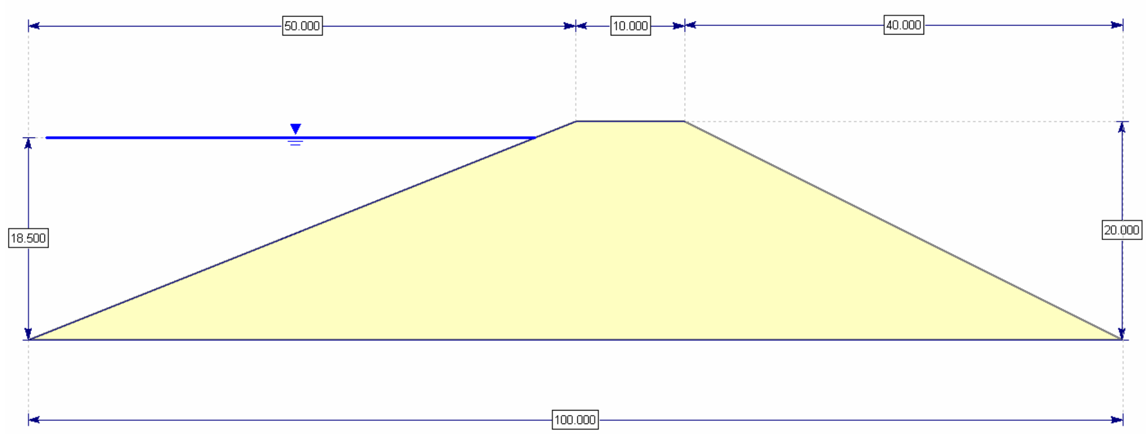


Figure 9.1 Homogeneous dam geometry details

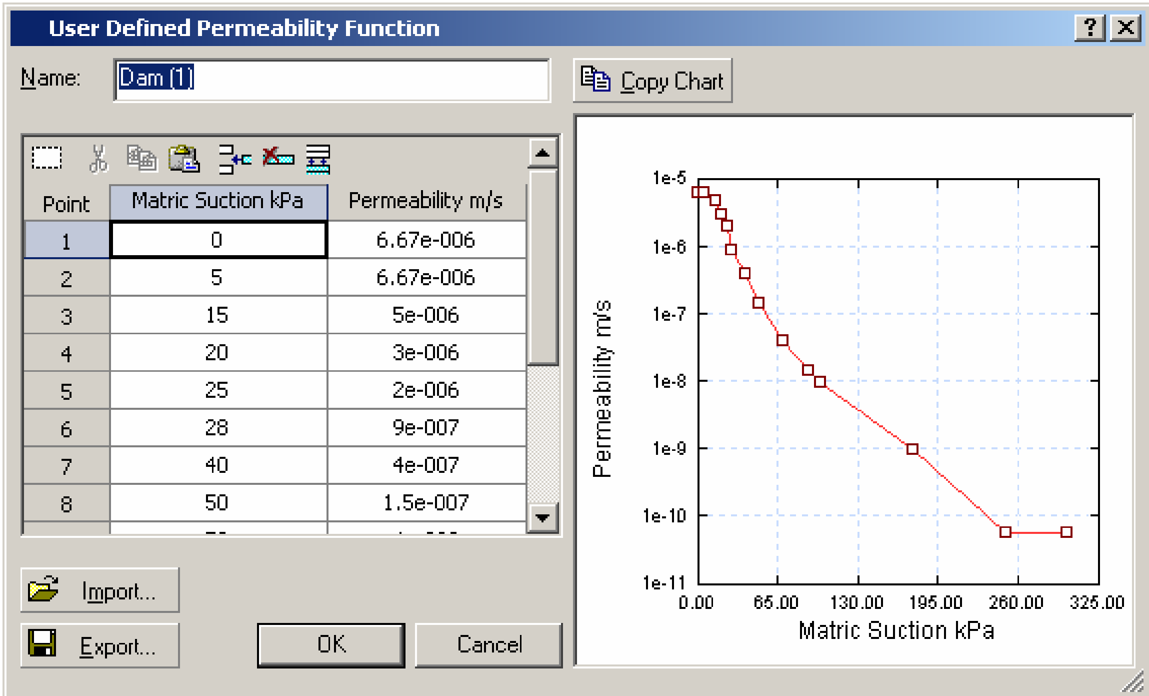


Figure 9.2 Permeability function for the isotropic earth dam

Slide gave a flow rate of Q = 1.378x10^{-3} m^3/(min.m) which compared well with the flow rate estimated by Bowels [1], which used two approximate methods that neglect the unsaturated flow. Bowels' two methods gave Q = 1.10x10^{-3} and 1.28x10^{-3} m^3/(min.m). Chapuis et al. [2] solved the same example using finite element software SEEP/W. The flow rate calculated using SEEP/W was 1.41x10^{-3} m^3/(min.m) for a mesh of 295 elements and a flow rate of 1.37x10^{-3} m^3/(min.m) for a mesh of 1145 elements.

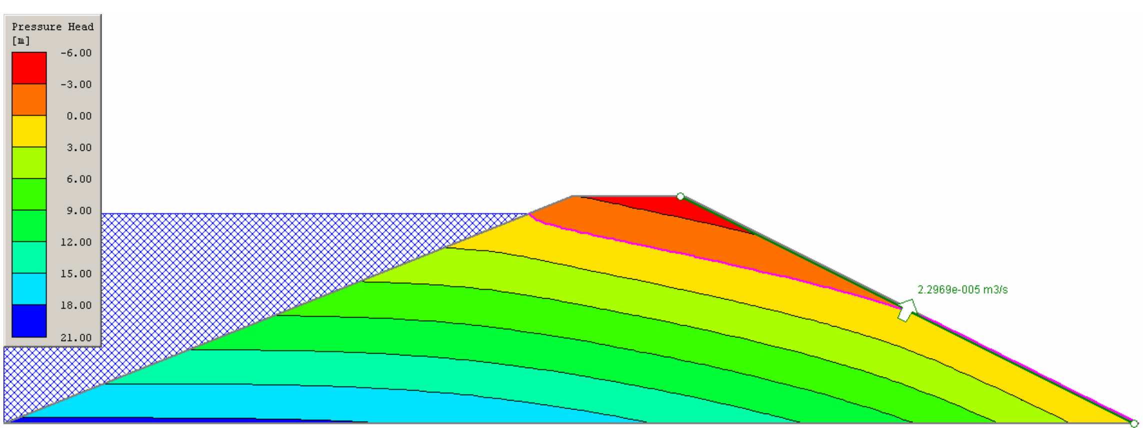


Figure 9.3 Pressure head contours

Figure 9.3 presents the flow vectors and the location of the phreatic line from *Slide* ground water model. Figure 9.4 shows the contours of total head with flow lines in the homogenous dam.

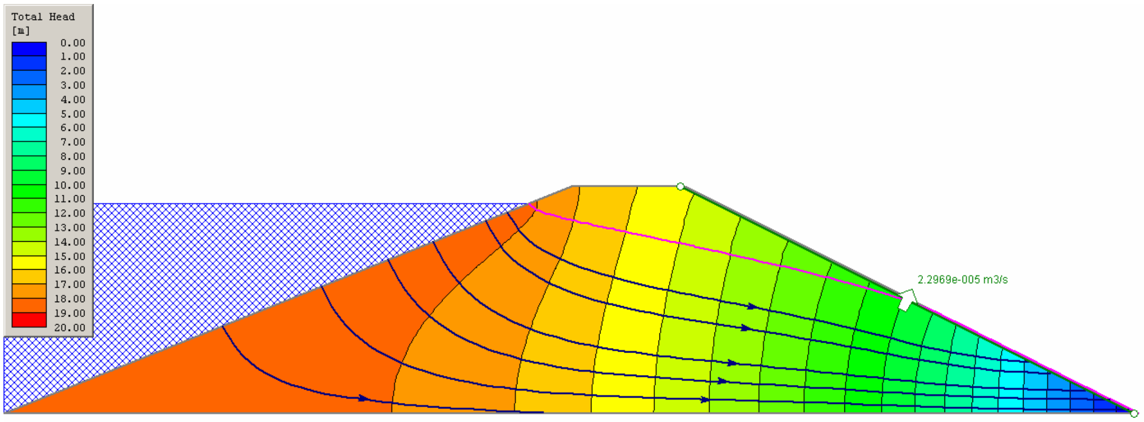


Figure 9.4 Total head contours with flow lines

Note: See file Groundwater#09_1.sli

2 Dam with impervious core

The second problem in this section considers a dam with an impervious core (Figure 9.5). The hydraulic function for the dam and the drain material are assumed to have a variation shown in Figure 9.6

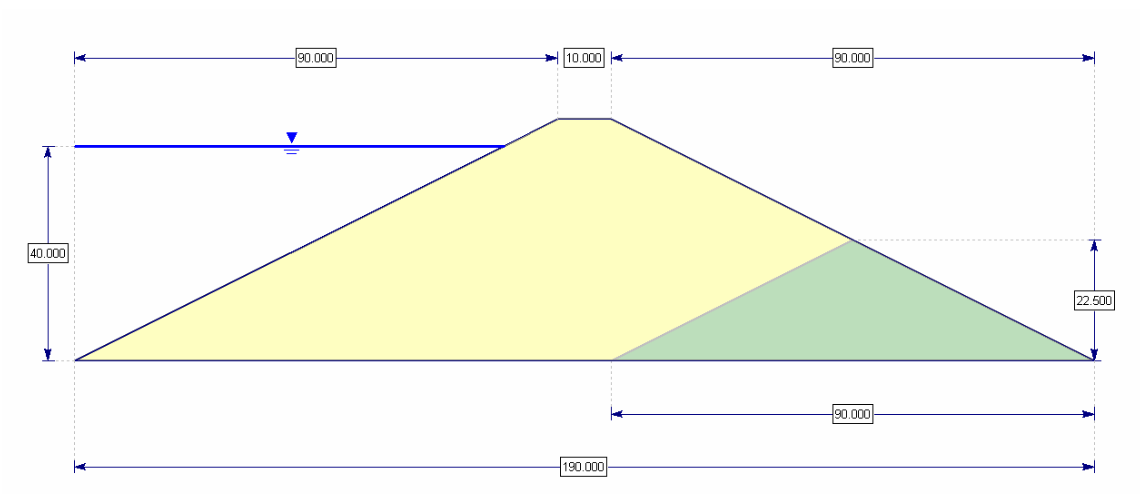
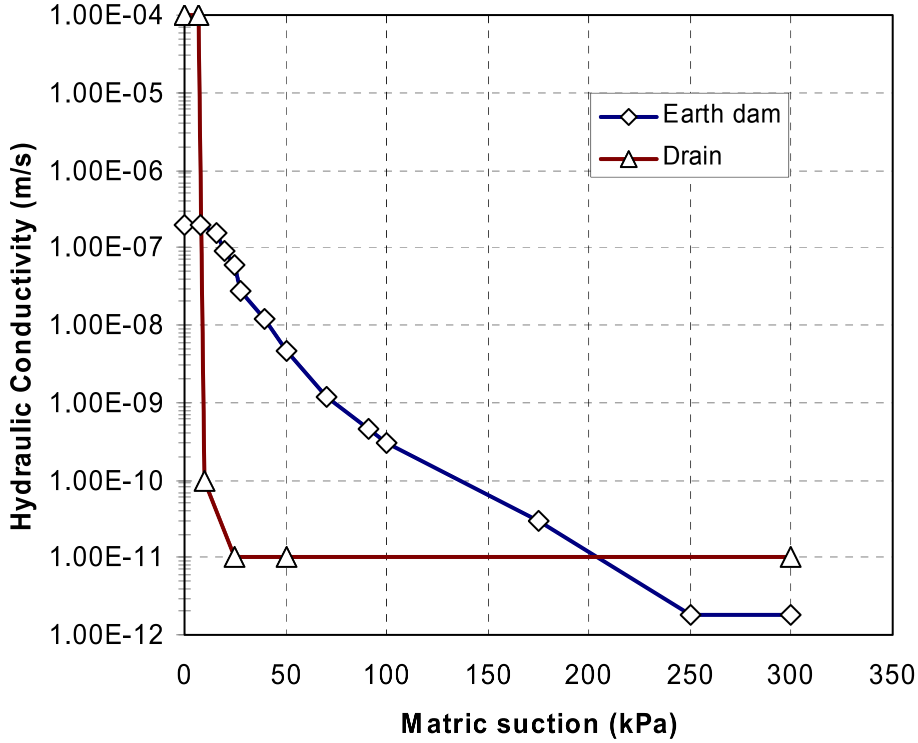


Figure 9.5 Dam with impervious core geometry detail



Slide gave a flow rate of Q = 4.23x10^{-6} m^3/(min.m) which compared well with the flow rate estimated by Bowels [1], Q = 3.8x10^{-6} m^3/(min.m). Chapuis et al. [2] solved the same example using finite element software SEEP/W. The flow rate calculated using SEEP/W was 5.1x10^{-6} m^3/(min.m) for a coarse mesh and a flow rate of 4.23x10^{-6} m^3/(min.m) for a finer mesh of 2328 elements.

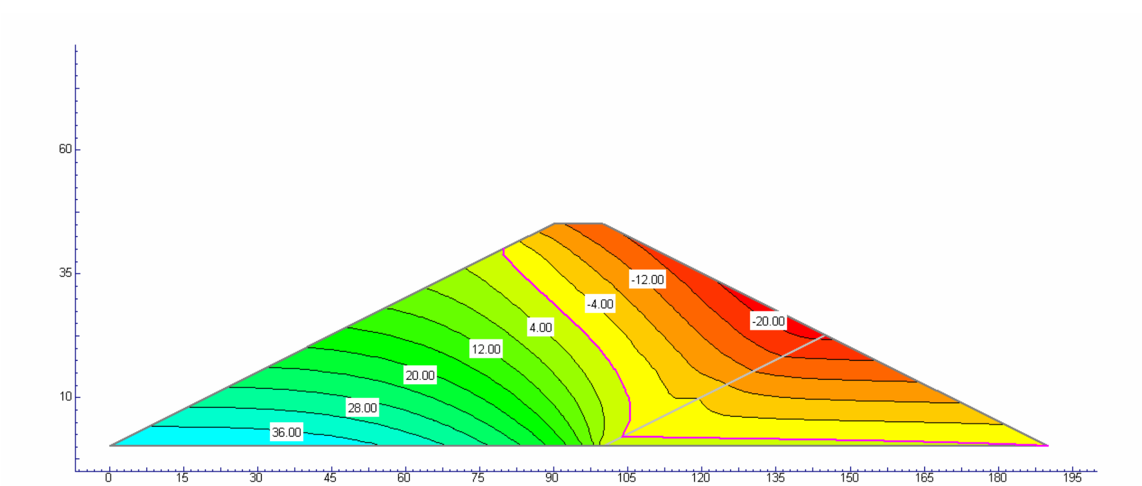


Figure 9.7 Pressure head contours

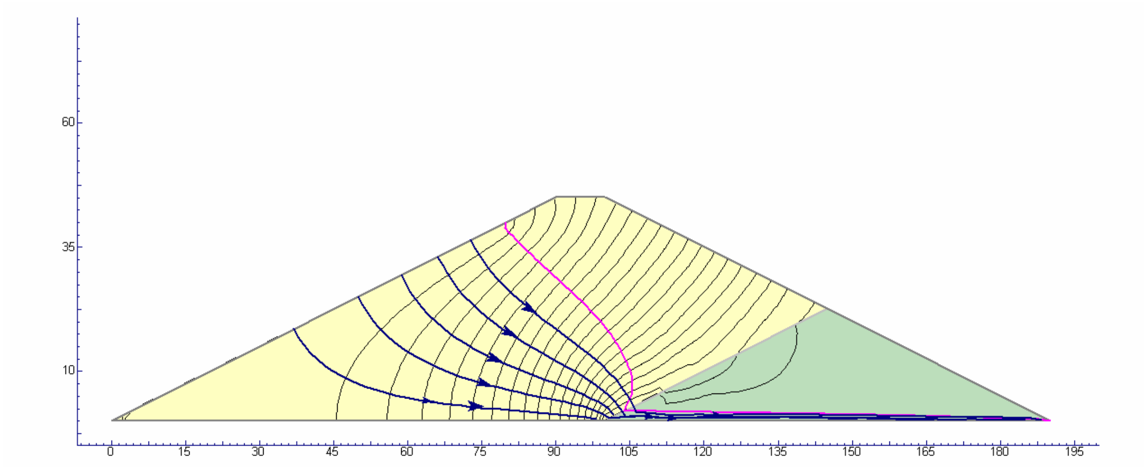


Figure 9.8 Total head contours with flow lines

Note: See file Groundwater#09_2.sli

9.3 References

2. Bowles J.E., (1984) *Physical and geotechnical properties of soils*. 2nd Ed. McGraw Hill, New York.
3. Chapuis, R., Chenaf D, Bussiere, B. Aubertin M. and Crespo R. (2001) "A user's approach to assess numerical codes for saturated and unsaturated seepage conditions", Can Geotech J. **38**: 1113-1126.

10. Steady-state unconfined flow using Van Genuchten permeability function

10.1 Problem description

An unconfined flow in rectangle domain was analyzed in this section. The sensitivity of seepage face height to the downstream height is examined. Van Genuchten [1] closed form equation for the unsaturated hydraulic conductivity function is used to describe the soil properties for the soil model. A Dupuit-Forcheimer model [2], which assumes equipotential surfaces are vertical and flow is essentially horizontal, is also used for comparison.

10.2 *Slide* model and results

A 10mx10m square embankment has no-flow boundary conditions on the base and at the top. The water level at the left is 10m. Four different water levels (2, 4, 6 and 8m) at the downstream are considered. The soil has the saturated conductivity of $K_s = 1.1574\text{x}10^{-5}\,\text{m/sec}$. The values of the Van Genuchten soil parameters are $\alpha = 0.64\,\text{m}^{-1}$, $n = 4.65$. The geometry and the mesh discretization are presented in Figure 10.1.

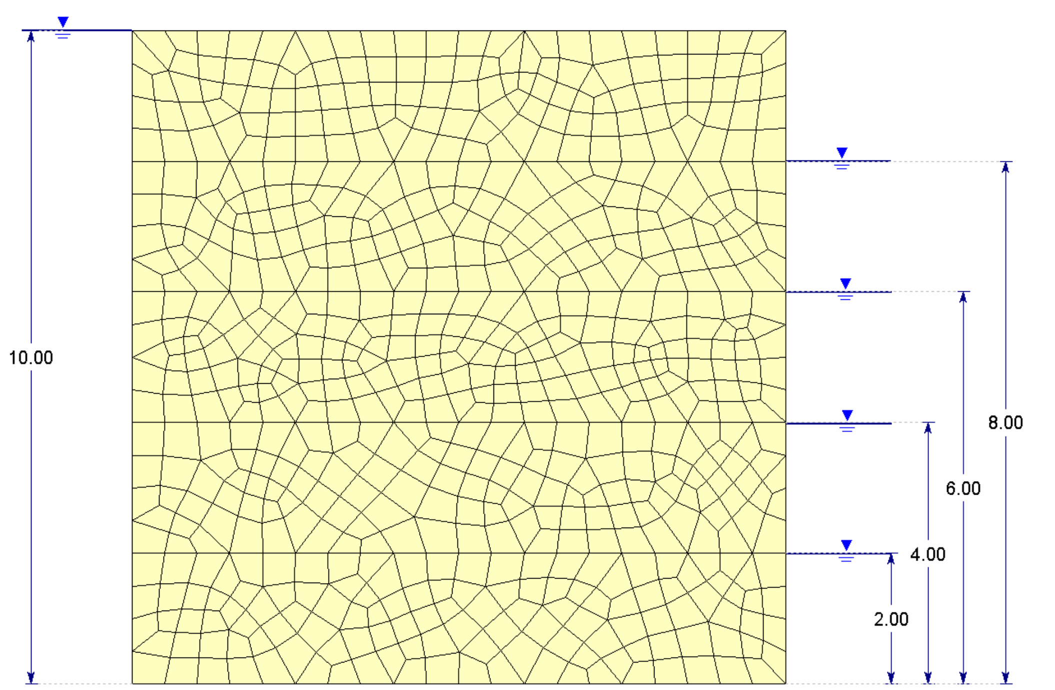


Figure 10.1 Model mesh descritization

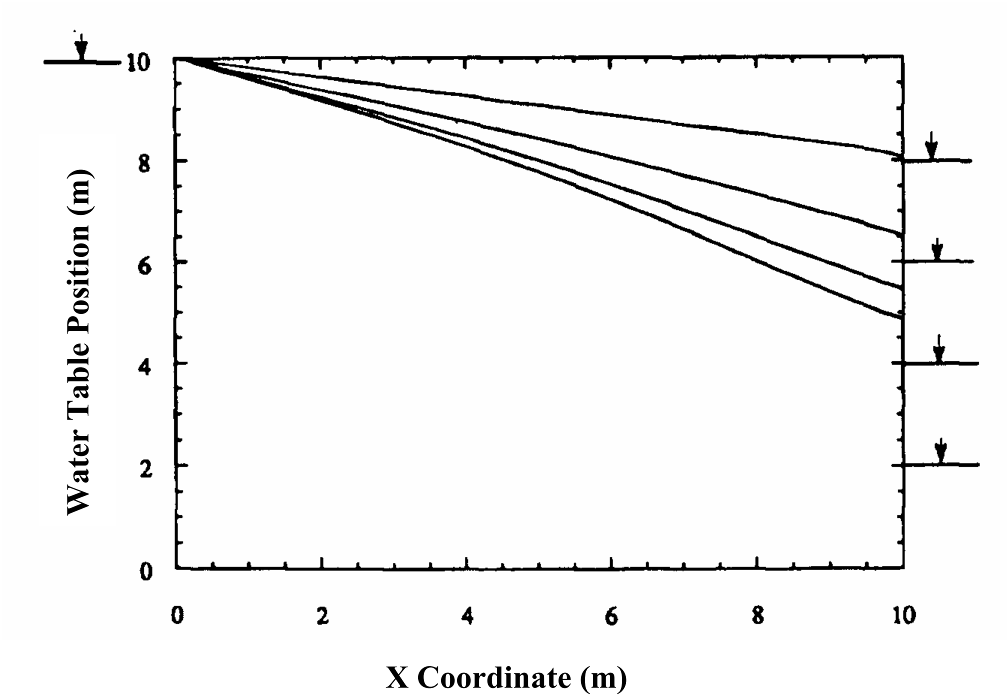


Figure 10.2 Phreatic surfaces variation to changing downstream water level [2]

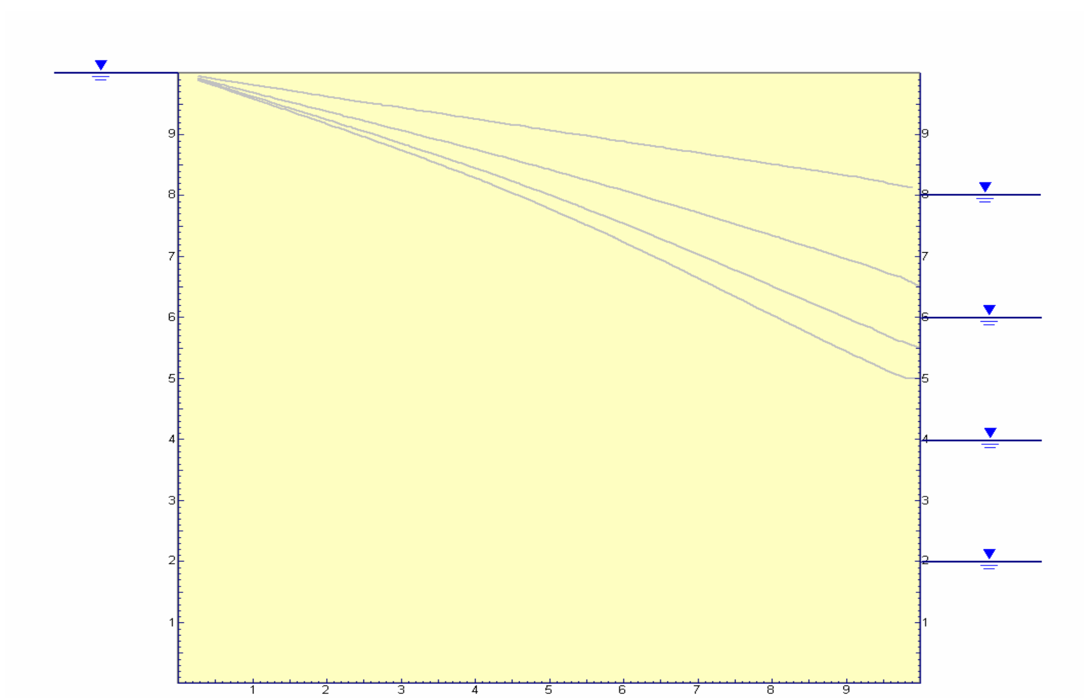


Figure 10.3 Phreatic surfaces variation to changing downstream water level predicted from *Slide*

Figures 10.2-10.3 show the variation of the phreatic surface predicted by changing downstream water level from Ref [2] and Slide respectively. These figures show that the absolute length of the seepage face decreases significantly with an increase in the water level at the downstream the results. Table 10.1 presents comparison of discharge values and seepage face from Ref. [2] and Slide.

Table 10.1 Discharge and seepage results

	Model dimension (mxm)	Tailwater level (m)	Discharge (m/sec)	Seepage face (m)
Clement et. al. [2]	10x10	2	6.0764×10^{-5}	4.8
Slide	10X10	2	6.0659×10^{-5}	5.0

Note: See file Groundwater#10_1.sli, Groundwater#10_2.sli, Groundwater#10_3.sli, Groundwater#10_4.sli

10.3 References

4. Genuchten, V. M (1980) "A closed equation for predicting the hydraulic conductivity of unsaturated soils" , Soils Sci Soc Am J. **44**: 892-898

5. Clement, T.P, Wise R., Molz, F. and Wen M. (1996) "A comparison of modeling approaches for steady-state unconfined flow", J. of Hydrology **181**: 189-209

11. Earth and rock-fill dam using Gardner permeability function

11.1 Problem description

Seepage in a uniform earth and rock-fill dam is examined in this section. Nonlinear model is used to represent the seepage flow above and below the free surface. The Gardner's nonlinear equation [1] between permeability function k_w and pressure head is used in this section and it can be presented as

$$k_w = \frac{k_s}{1 + ah^n}$$

where: a and n are the model parameters
h = pressure head (suction)
k_w = permeability
k_s = saturated permeability

11.2 *Slide* model and results

1. Uniform earth and rock-fill dam

Figure 11.1 shows detailed geometry of the dam. The upstream elevation head is 40m and the downstream elevation head is 0m. The geometry of the dam is taken from Ref. [2], the slope of upstream is 1:1.98 and the slope of the downstream is 1:1.171 (Figure 11.1). The Gardner's model parameters are taken as $a = 0.15$ and $n = 6$.

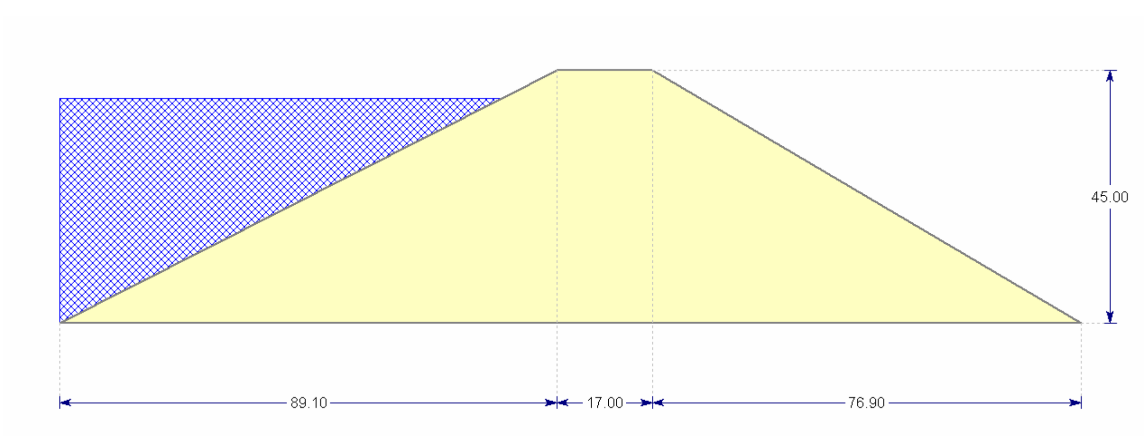


Figure 11.1 Dam geometry

Zhang et. al. [2] used general commercial software ABAQUS to analyze the earth dam and the results showed that the calculated elevation of release point is 19.64m. Same dam geometry is studied using Slide and the calculated elevation of release point is 19.397m, see Figure 11.2.

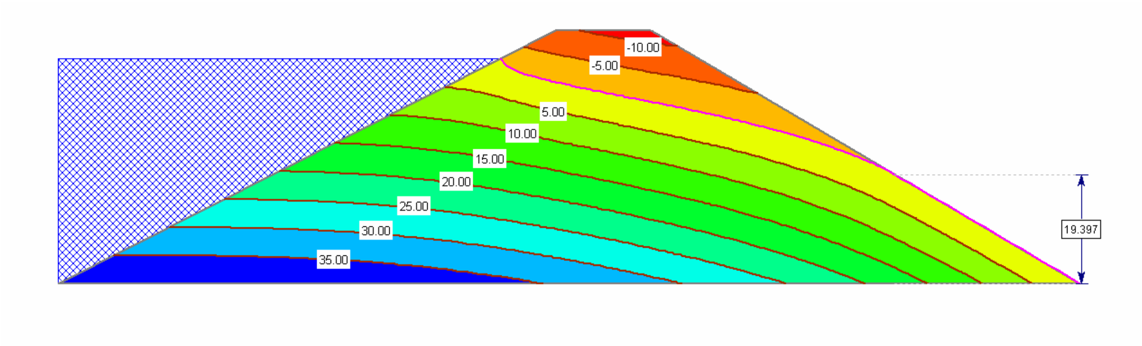


Figure 11.2 Pressure head contours

Note: See file Groundwater#11_1.sli

2. Nonhomogeneous earth and rock-fill dam

Figure 11.3 shows a dam with permeable foundation and toe drain [2]. The permeability coefficient of the foundation of sand layer is 125 times of the earth dam and blanket. The toe drain has a large value of permeability coefficient which is 10000 times larger than the permeability function of the dam. Table 11.1 shows the Gardner's parameters for the different model layers.

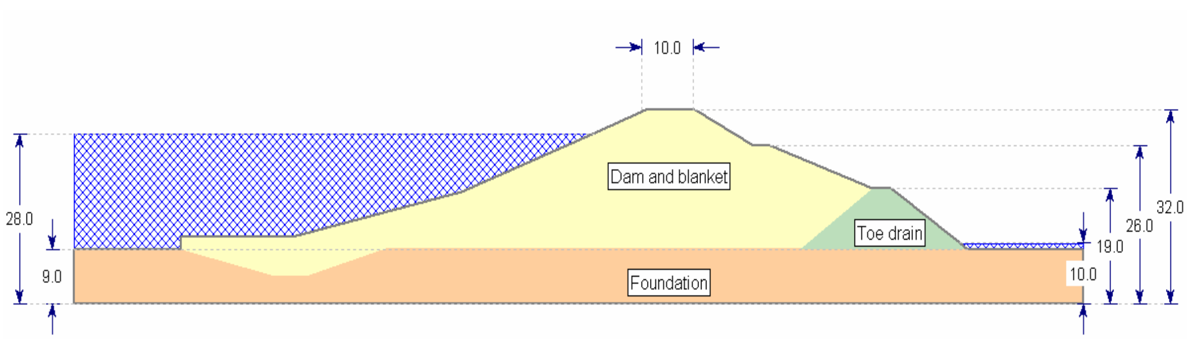


Figure 11.3 Dam geometry [2]

Table 11.1 Layers material parameters

Layer	K_s (m/sec)	*a*	*n*
Dam	$1x10^{-7}$	0.15	2
Foundation	$1.25x10^{-5}$	0.15	6
Toe drain	$1x10^{-3}$	0.15	6

Figures 11.4-11.5 shows the distribution of the total head contours from Ref.[2] and Slide respectively. Slide results were in a good agreement with those obtained from ABAQUS.

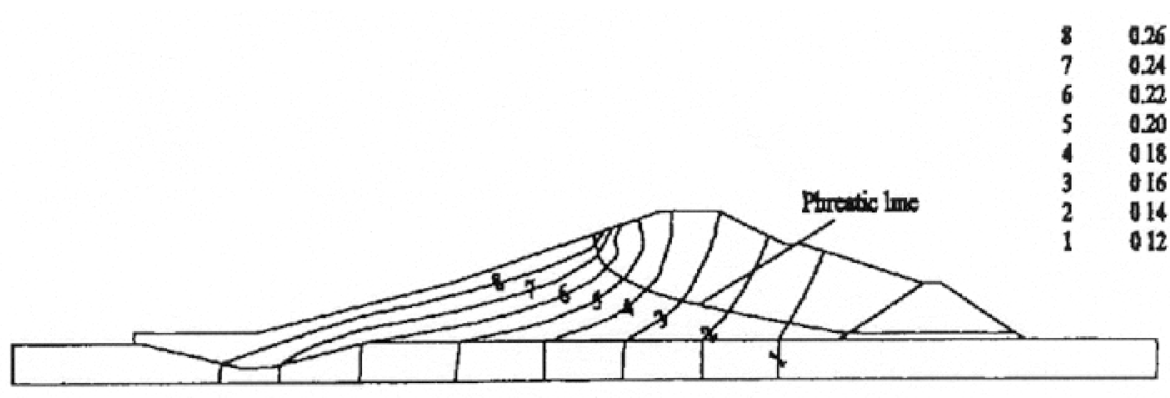


Figure 11.4 Total head (unit 10^2m) from Zhang et. al. [2]

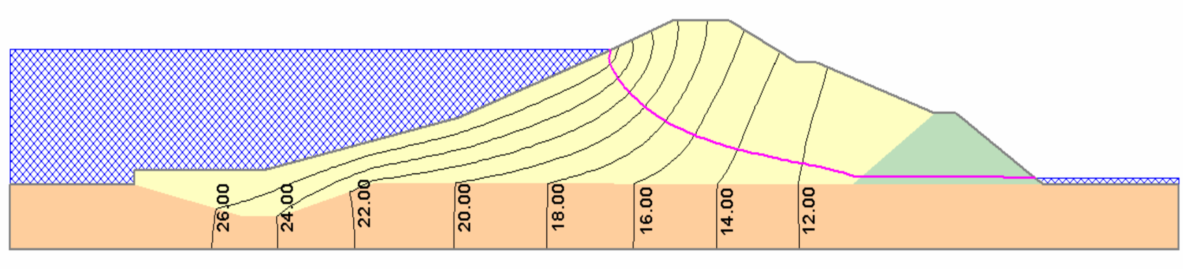


Figure 11.5 Total head contours using Slide

Note: See file Groundwater#11_2.sli

11.3 References

1. Gardner, W. (1956) “Mathematics of isothermal water conduction in unsaturated soils.” Highway Research Board Special Report 40 International Symposium on Physico-Chemical Phenomenon in Soils, Washington D.C. pp. 78-87.

2. Zhang, J, Xu Q. and Chen Z (2001) “Seepage analysis based on the unified unsaturated soil theory”, Mechanics Research Communications, **28** (1) 107-112.