THE EFFECT OF CUTOFF WALL ANGLE ON SEEPAGE UNDER DAMS

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ABSTRACT

Flow of water under concrete dams generates uplift pressure under the dam, which may cause the dam to function improperly, in addition to the exit gradient that may cause piping if exceeded a safe value.

Cutoff walls usually used to minimize the effect of flow under dams. It is required to 1)minimize the flow quantity to conserve water in the reservoir, it is also required to 2)minimize the uplift pressure under the dam to maintain stability of the dam, and it is required to 3) minimize the exit gradient to prevent quick condition to occur at the toe of the dam where piping may occur and may cause erosion of the soil.

Varying the angle of cutoff walls affects its influence on the factors aforementioned that are required to be minimized.

In this paper, the cutoff wall angle was varied from 0° to 180° using GeoStudio 2007 SEEP/W computer program, and the variations of the three factors were studied and analyzed.

The results shows that the best angle to minimize the water flow is about 60°, the best angle to minimize the uplift pressure was about 120° to 135°, and the best angle to minimize the exit gradient was about 45° to 75°.

The case where two cutoff walls were used one with angle 60°, the other with an angle 120° were investigated. The results indicated where the minimum values for all factors may be obtained.

الخلاصة

ان عملية جريان الماء تحت السدود الخرسانية تولد ضغط للمياه تحت السد، ومن الممكن لهذا الضغط ان يقلل من الاداء الصحيح للسد، اضافة الى ما يسببه انحدار الخروج من جرف للتربة في نهاية السد اذا ما زادت عن حدها المسموح به.

لذا تستخدم الجدران القاطعة للتقليل من تاثيرات جريان المياه تحت السد. حيث انه من المطلوب 1) تقليل كمية المياه التي تجري تحت السد وذلك للمحافظة على كمية المياه في الخزان امام السد، كذلك من المطلوب 2) تقليل ضغط المياه تحت السد للمحافظة على استقرارية السد، اضافة الى 3) تقليل انحدار الخروج لتفادي حصول حالة انجراف التربة في نهاية السد. ان تغيير زاوية انشاء الجدار القاطع له تاثير على العوامل التي تم ذكرها بشكل مباشر والتي من المطلوب تقليلها.

في هذا البحث، تمت دراسة تاثير تغيير زاوية الجدار القاطع من 0 حتى 180 درجة باستعمال برنامج حاسوبي متخصص (GeoStudio 2007 SEEP/W) وتم تحليل نتائج تغير الزاوية على العوامل المذكورة.

اسفرت النتائج عن تقليل جريان المياه الى اقل ما يمكن بزاوية 60 درجة وتقليل ضغط المياه اقل ما يمكن تحت السد بزاوية تتراوح بين 120 حتى 135 درجة وتقليل انحدار الخروج اقل ما يمكن بزاوية تتراوح بين 45 حتى 75 درجة.

تمت تحليل حالة وجود جدارين قاطعين الاول بزاوية 60 درجة والثاني بزاوية 120درجة. اسفرت النتائج عن الحصول على اقل قيم ممكنة للعوامل المدروسة جميعا.

Keywords: Flow under dams, optimization, cutoff walls, uplift pressure, exit gradient.

INTRODUCTION

Dams are constructed mainly to keep water in reservoirs, and to function for long times, hence the factors that may affect the functionality of these dams and may reduce it must be studied carefully and minimized to obtained a proper function of the dam.

Flow under concrete dams can create uplift pressure that could affect the dam and may cause it to fail to function properly; also the exit gradient can cause piping and quick condition at the toe of the dam, so, it is required to reduce the effect of water seepage by using cutoff walls, like slurry wall.

Slurry walls are non-structural barriers (Cutoff Walls, Slurry Trenches) that are constructed underground to impede groundwater flow. Slurry walls have been used for decades to provide cost-effective, long-term solutions for many groundwater control and groundwater remediation problems (www.geo-solutions.com, 2010)".

Seepage analysis of cutoff walls is useful in order to determine if high gradients develop at the base of the cutoff wall or on the downstream exit point.

The objective of this paper is to examine the effect of cutoff walls angle under a dam on the flow quantity, pore water pressure and the exit gradient, this will help to minimize flow quantity, the uplift forces under the dam and prevent quick condition at the exit points of the downstream flow for different angles of cutoff walls.

LITERATURE AND THEORY

The problem of seepage under dams was considered by many authors (Harr, 1962, Lambe and Whitman, 1979, Das, 2008, Craig, 2004) and many others.

In case of concrete dams, water flows under these dams. The line along which a water particle will travel is called flow line, and the line joining the points that show the same piezometric elevation called equipotential line.

A set of flow lines and equipotential lines is called a flow net; the flow lines intersect the equipotential lines at right angles. The flow and equipotential lines are usually drawn in such a way that the flow elements are approximately squares, as shown in figure 1.

A flow net is a graphical solution to the Laplace equation for two-dimensional flow for flow through a homogenous soil, it is an orthogonal network of flow lines and equipotential lines (approximately square for homogeneous, isotropic media).

$$\frac{\partial^2 H}{\partial x^2} + \frac{\partial^2 H}{\partial y^2} = 0 \quad (1)$$

There are several problems involving a concrete dam, prior to conducting an analysis, the problem to be studied must be defined in terms of:

a. Aquifer and concrete dam dimensions.
b. Coefficients of permeability of the dam and foundation soils.
c. Horizontal to vertical permeability ratios.
d. Boundary conditions (impermeable and symmetrical).
e. Exits and entrances (fixed potential areas).
f. Head versus time relationships for unsteady flow.

To solve these problems, there are approximate solutions as mentioned (Harr, 1962):

1) Graphical flow net.
2) Solution by Analogies (electrical analogue).
3) The flow tank.
4) Viscous flow models (Hele shaw model).
5) Relaxation method.
6) Method of fragments.
7) Others.

Flow nets and the method of fragments are two techniques that have long been used with limited success in furnishing seepage under hydraulic structures. The method of fragments is an approximate analytical method for the computation of flows and pressure heads for any ground-water system.

CASE STUDY

An example of flow under dam (after Craig, 2004) is taken to show the effect of cutoff wall on the flow quantity, pore water pressure, as calculated by hand.
The section through a dam is shown in Figure 2. It is required to determine the quantity of seepage under the dam and plot the distribution of uplift pressure on the base of the dam. The coefficient of permeability of the foundation soil is 2.5 × 10^{-5} m/s.
The flow net is shown in figure 2. The downstream water level is selected as datum. Between the upstream and downstream equipotentials the total head loss is 4.00 m. In the flow net there are 4.7 flow channels and 15 equipotential drops. The seepage is given by:

$$q = kh\frac{N_f}{N_d} = 2.5 \times 10^{-5} \times 4.00 \times \frac{4.7}{15}$$
$$= 3.1 \times 10^{-5}\,\text{m}^3/\text{s} \quad (\text{per m})$$

where N_f= Number of flow lines , N_d= Number of equipotential lines.

The pore water pressure is calculated at the points of intersection of the equipotentials with the base of the dam. The total head at each point is obtained from the flow net and the elevation head from the section. The calculations are shown in Table 1 and the pressure diagram is plotted in Figure 2.

This example will be used as a verifying case for the computer program Geostudio 2007 SEEP/W to study the objective of this paper and examine the effect of cutoff wall angle on the seepage under the dam.

COMPUTER PROGRAM

The computer program Geostudio 2007 SEEP/W was used as the software to examine the effect of cutoff walls on the flow, exit gradient, and pore water pressure under dam.
The same data used for the example in the case study are used here in the computer program.

Figure 3 shows the complete flownet of the example mentioned in case study with the flow lines and equipotentional lines distribution, where figure 4 shows the pore water pressure distribution under the dam.
The flow quantity is found to be 3.1231 × 10^{-5} m^3/sec, which is very close to the value obtained using hand calculations. The difference is:

$$\frac{3.1231\times10^{-5} - 3.1\times10^{-5}}{3.1\times10^{-5}} = 0.00745 = 0.745\%$$

This is considered an identical value to the one obtained in the example. The pore water pressure distribution is shown in figure 5(a) (B-C on fig. 3) to be the same as obtained from hand calculations, varying from 43 kPa under the beginning of the dam just after the cutoff wall, to the

value of 22 kPa just before the toe of the dam.
In addition, the exit gradient at the toe (A-B on fig. 3) was also obtained to be 0.36 at the toe at ground level and 0.215 at –0.8m. This is shown in figure 5 (b).
From the aforementioned results, the computer program GeoStudio 2007 SEEP/W is verified to be used for studying the effect of varying the cutoff wall angle on the flow quantity, pore water pressure, and the exit gradient.
The angle of the cutoff wall will vary from 0° to the horizontal ground level and this angle will increase in the clockwise direction (as shown in figure 6) in increments of 15° till the angle of 180° is reached. (angle 180° assumes no cutoff wall presence).

RESULTS AND DISCUSSION

The results of many runs of the computer program using various angles of cutoff wall are obtained. Starting from 0° to 180°, graphs showing total head, flownet (flow lines and equipotential lines), pore water pressure distribution, and exit gradient are shown for each case. Those results are shown in figures 7-42.
The results of flow quantities are summarized in table 2. This variation is also shown in figure 43. The flow quantity decreases as the angle increases from 0° to about 60°, after that the flow quantity increases with the increase of the angle.
A trend line can be drawn describing this relation between flow quantity and cutoff angle and could be described by equation 2:

$$y = -4\times10^{-14}x^4 + 1\times10^{-11}x^3 - 6\times10^{-10}x^2 - 4\times10^{-8}x + 3\times10^{-5} \quad (2)$$

This polynomial gave a regression value R^2 of 0.9981 which is considered very good as this equation could describe this variation. The pore water pressure under the base of the dam is also considered here in this paper; as it is important to examine this value to describe the uplift pressure exerted on the base of the dam to ensure stability of the dam. Table 3 shows the values of the pore water pressure under the base of the dam.

The data are also represented in graphical form as shown in figure 44. The pore water pressure is shown to decrease as the angle increase till the angle reaches about 120° to 135° then the pore water pressure increases with reshaping as shown in figure 44. Figure 45 is a magnification of the right end portion of figure 44, where the change on pore water pressure is shown more clearly.

Figure 46 is a magnification of the middle portion of fig. 44 where the base of the dam changes in thickness by an angle of 45°, this effect is shown clearly to affect the pore water pressure at the base of the dam, with an average value taken for an arbitrary angle (say 120°) to be:
37 – 28 = 9 kPa within about 20.5 – 19 = 1.5m
That is about 9 / 1.5 = 6 kPa / m
Compared to other portions of the graph in fig. 44 for the same angle where the reduction is about:
42.42– 38.02 = 4.4 kPa within about 28.9 – 21.48 = 7.42 m
And that is about 4.4 / 7.42 = 0.593 kPa / m
This demonstrates the big influence of the inclination of the base of the dam on the pore water pressure hence the uplift pressure.
The exit gradient is also studied at the end of the dam at two points, the first point is

at ground level (0 m), the second point is at (–0.8 m).

The data also represented graphically in figure 47 where the variation of the exit gradient is shown for the two points at the toe of the dam.

It is obvious from the graph that the value of the exit gradient for the point at –0.8 m is less compared to the exit gradient at the ground level (0 m). But both curves have approximately the same trend of variation. By that we mean that starting from angle 0°, the exit gradient decreases in value till we reach a minimum value at about 45°–75° then the exit gradient rises with the increase of the angle.

A trend line of a polynomial was found to describe this relationship for both points:

a- for point (0 m)

$$y = -6\times10^{-10}x^4 + 2\times10^{-7}x^3 - 1\times10^{-5}x^2 - 0.0001x + 0.3862 \quad (3)$$

$R^2 = 0.9953$

b- for point (–0.8 m)

$$y = -3\times10^{-10}x^4 + 1\times10^{-7}x^3 - 7\times10^{-6}x^2 - 0.0002x + 0.229 \quad (4)$$

$R^2 = 0.9967$

As shown from the aforementioned results, we conclude that the cutoff wall angle of around 60° gave the minimum flow quantity and minimum exit gradient, whereas the cutoff wall angle around 120° to 135° gave the minimum uplift pressure under the base of the dam.

According to these conclusions, an additional run of the computer program was conducted with two cutoff walls the first with an angle of 60° and the other with an angle of 120°.

The results are shown in figures 48 to 50, where figure 48 shows the total head distribution and the flownet, figure 49 shows the pore water pressure distribution, and figure 50 shows the pore water pressure under the base of the dam and the exit gradient.

Water quantity was found to be 3.089×10^{-5} m^3/sec which is very near to the minimum value obtained previously (3.06×10^{-5} m^3/sec) with difference of 0.948% only.

Pore water pressure of 41.08 kPa at the beginning of the dam was found to be even less than the value obtained previously 42.42 kPa with difference of 3.16%.

The exit gradient was found to be 0.361 and 0.215 at level 0m and -0.8m respectively, which are the same values that were obtained previously with negligible difference.

So it is concluded that using two cutoff walls gives the best results considering the three factors under study (flow quantity, pore water pressure, and exit gradient).

CONCLUSIONS AND RECOMMENDATIONS

From the results obtained previously, many conclusions are found and could be summarized as follows:

1- There is a direct relation between the angle of cutoff wall and the flow quantity of water under the dam. This relation could be described as shown in equation 2.
2- Minimum value of flow was found to occur at an angle of about 60° of cutoff wall.
3- Pore water pressure, hence uplift pressure under the dam was shown to have direct relation with the angle of cutoff wall.
4- The minimum value of pore water pressure was found to be at an angle of about 120° to 135°.
5- Exit gradient also has a direct relation with cutoff wall angle. This could be described by equations 3 and 4.

6- Minimum value of exit gradient was found to take place at an angle of about 45°–75°.

7- Using two cutoff walls with two different angles (60° and 120°) gave minimum values of the factors under study.

It is recommended that:

1- Further study of the effect of angle of cutoff wall on flow quantity, pore water pressure, and exit gradient is needed for many soil types.
2- Different geometry also should be investigated to examine the relations mentioned earlier.
3- Anisotropic condition is recommended to be investigated also.

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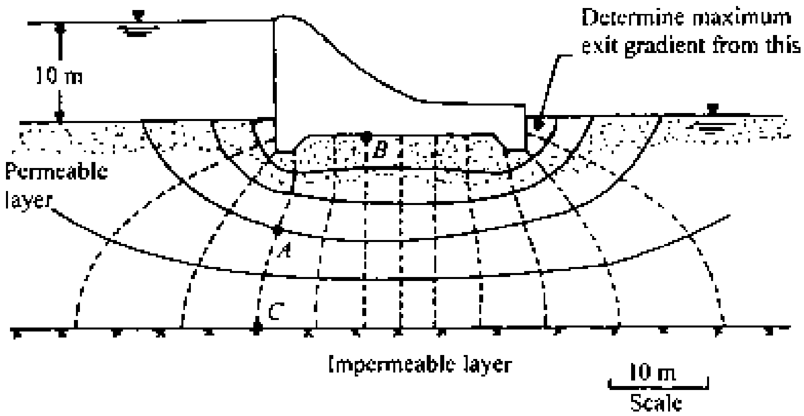


Figure 1 Typical flownet under a concrete dam

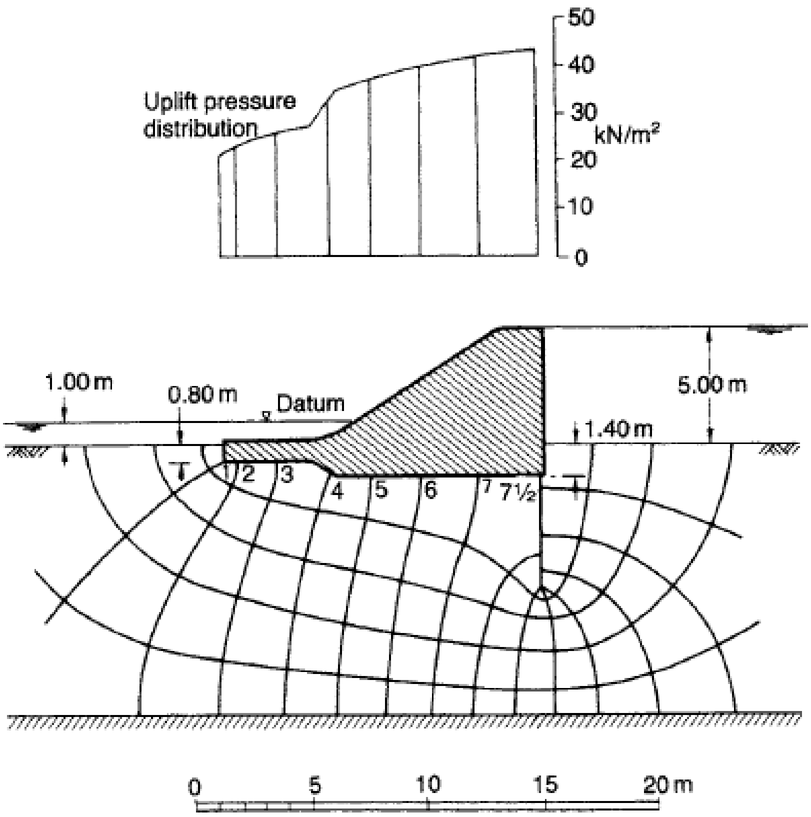


Figure 2 geometry and flow net of the example

Table 1

Point	h (m)	z (m)	$h - z$ (m)	$u = \gamma_w(h - z)$ (kN/m^2)
1	0.27	−1.80	2.07	20.3
2	0.53	−1.80	2.33	22.9
3	0.80	−1.80	2.60	25.5
4	1.07	−2.10	3.17	31.1
5	1.33	−2.40	3.73	36.6
6	1.60	−2.40	4.00	39.2
7	1.87	−2.40	4.27	41.9
$7\frac{1}{2}$	2.00	−2.40	4.40	43.1

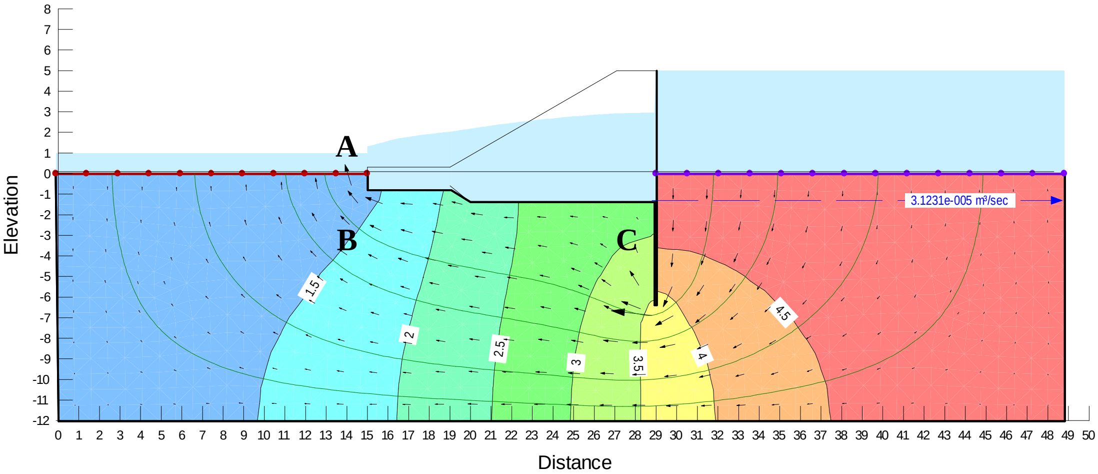


Figure 3 Flow net, flow quantity, and total head under the dam for the example

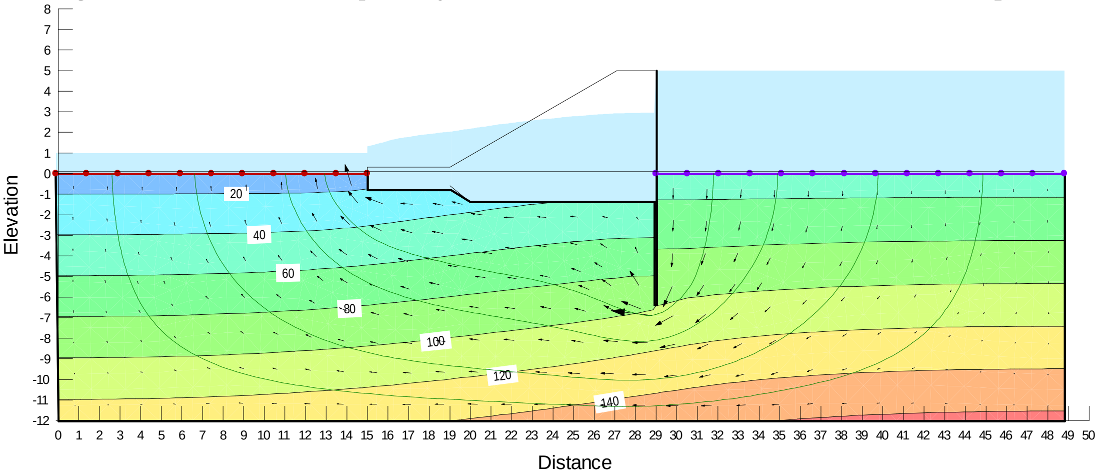
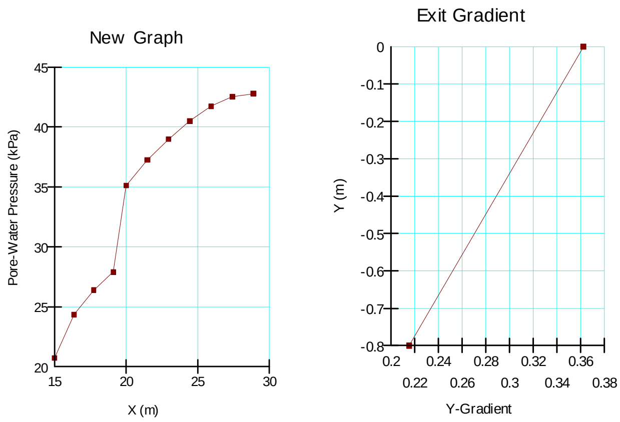


Figure 4 Pore water pressure (kN/m^2) distribution under the dam for the example



a **b**

Figure 5 a) Pore water pressure distribution (**BC**), b) Exit gradient at toe (**AB**)

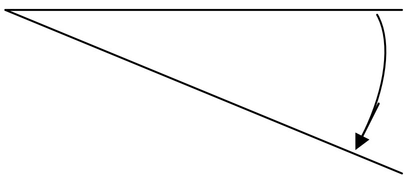


Figure 6 Positive direction for angle of cutoff wall

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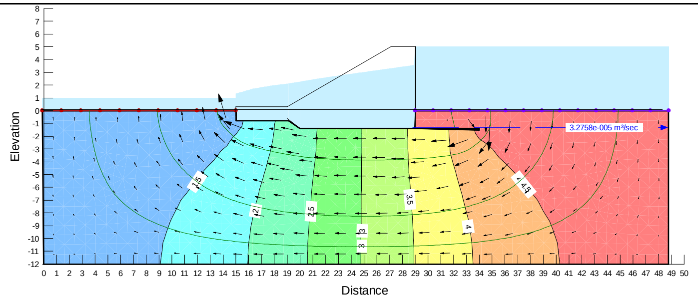
<tr><td>Case 0°</td><td>

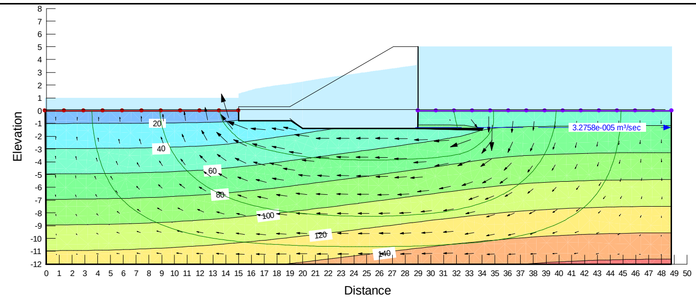
Figure 7 Flownet, flow quantity, and total head distribution for angle 0°</td><td>

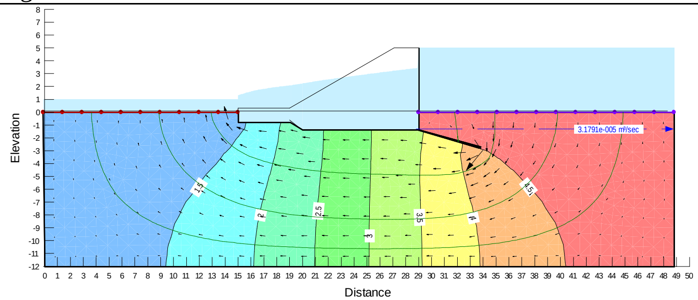
Figure 8 Pore water pressure distribution under the dam for angle 0°</td></tr>
<tr><td>Case 15°</td><td>

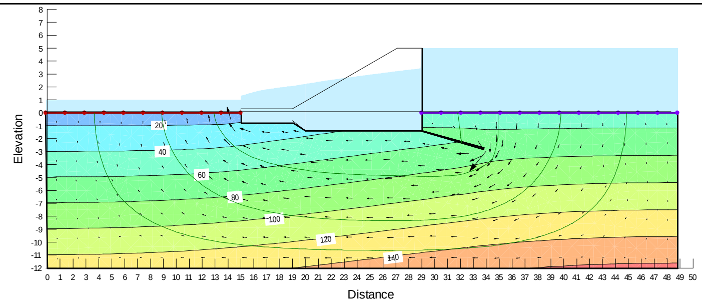
Figure 9 Flownet, flow quantity, and total head distribution for angle 15°</td><td>

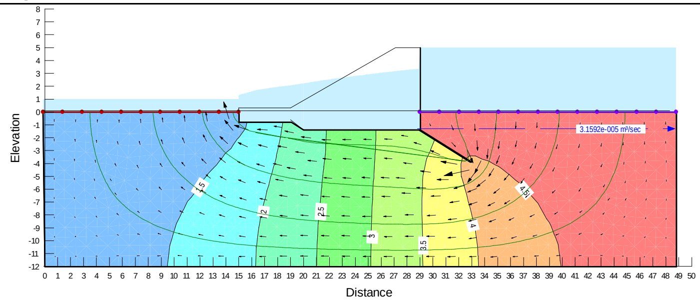
Figure 10 Pore water pressure distribution under the dam for angle 15°</td></tr>
<tr><td>Case 30°</td><td>

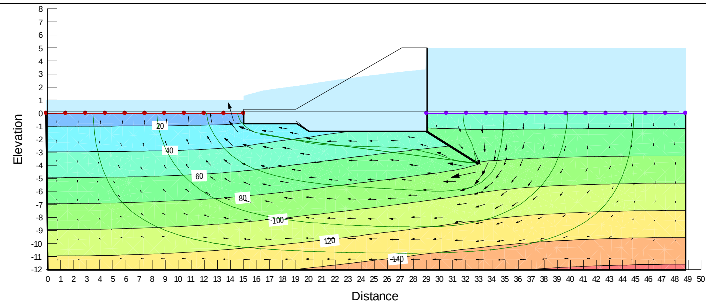
Figure 11 Flownet, flow quantity, and total head distribution for angle 30°</td><td>

Figure 12 Pore water pressure distribution under the dam for angle 30°</td></tr>
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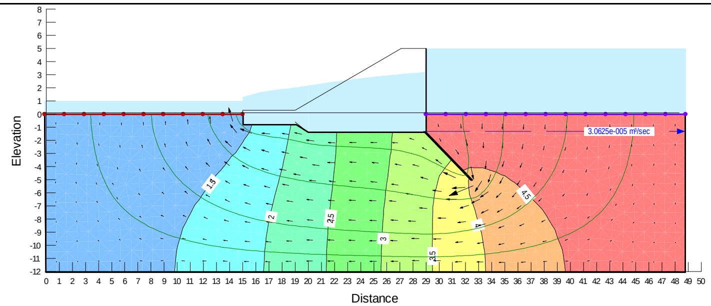
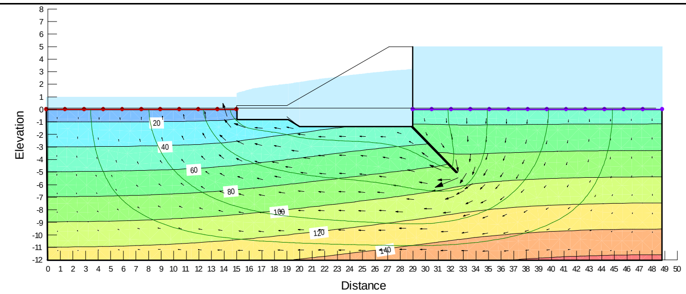
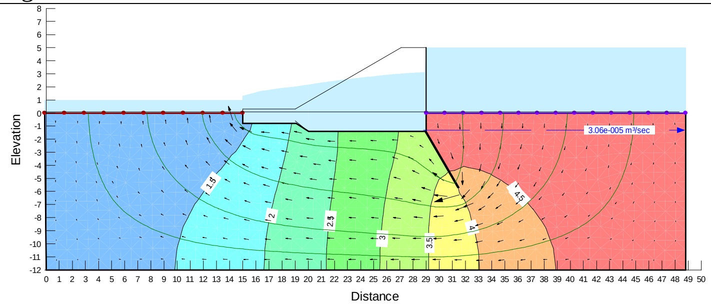
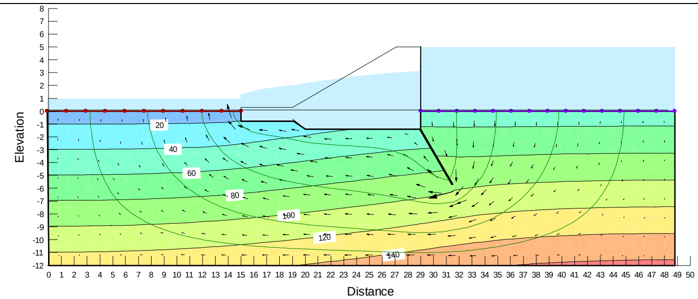
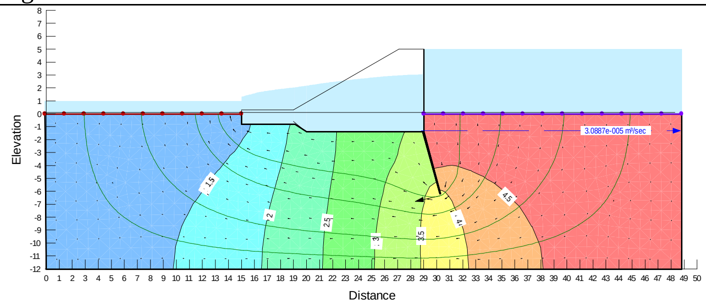
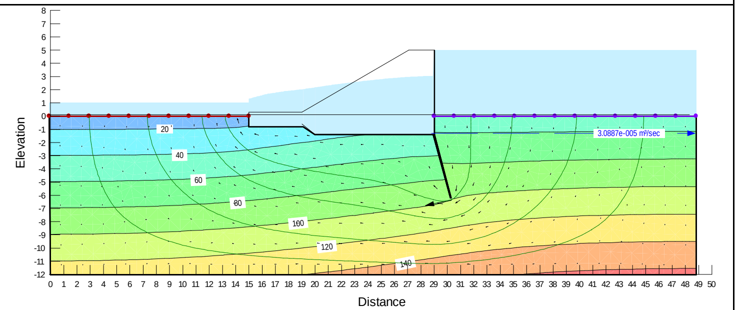
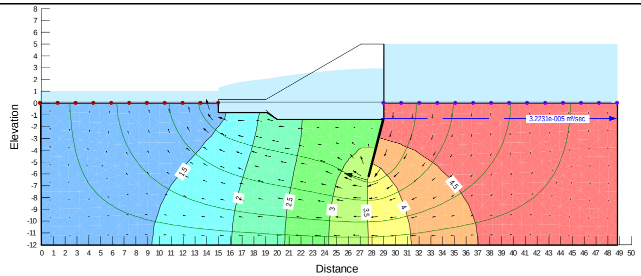
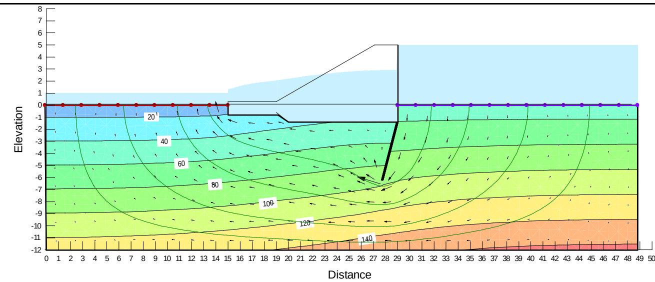
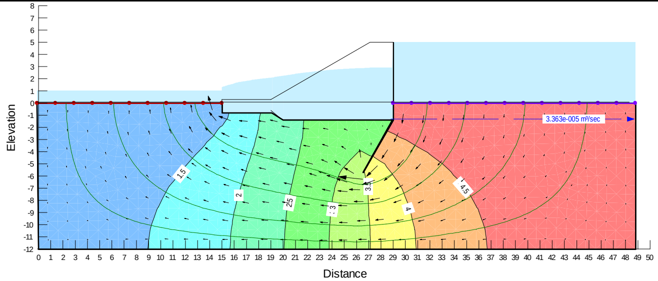
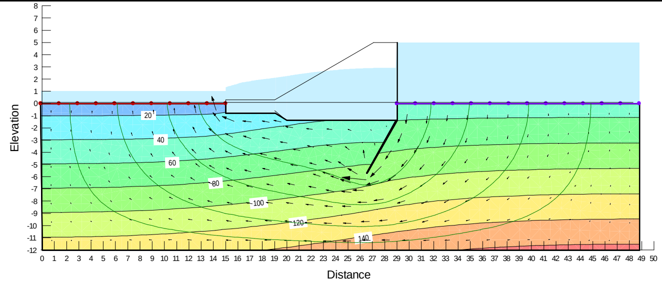
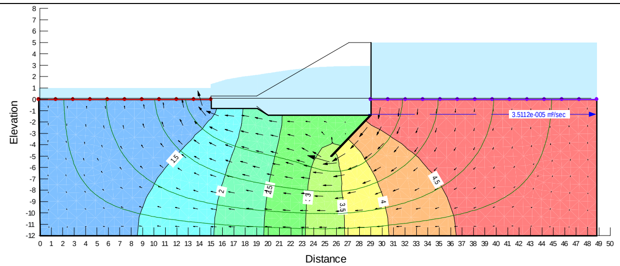
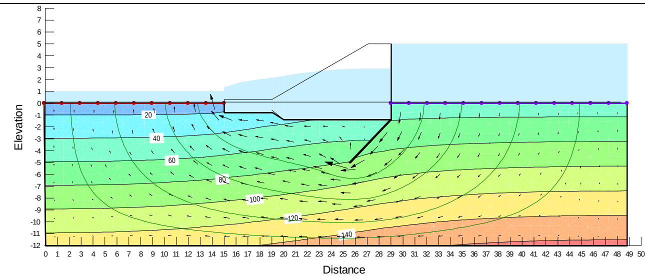
Case 45°	 Figure 13 Flownet, flow quantity, and total head distribution for angle 45°	 Figure 14 Pore water pressure distribution under the dam for angle 45°
Case 60°	 Figure 15 Flownet, flow quantity, and total head distribution for angle 60°	 Figure 16 Pore water pressure distribution under the dam for angle 60°
Case 75°	 Figure 17 Flownet, flow quantity, and total head distribution for angle 75°	 Figure 18 Pore water pressure distribution under the dam for angle 75°
Case 90°	See figure 3	See figure 4

Case 105°	 Figure 19 Flownet, flow quantity, and total head distribution for angle 105°	 Figure 20 Pore water pressure distribution under the dam for angle 105°
Case 120°	 Figure 21 Flownet, flow quantity, and total head distribution for angle 120°	 Figure 22 Pore water pressure distribution under the dam for angle 120°
Case 135°	 Figure 23 Flownet, flow quantity, and total head distribution for angle 135°	 Figure 24 Pore water pressure distribution under the dam for angle 135°

Case 150°

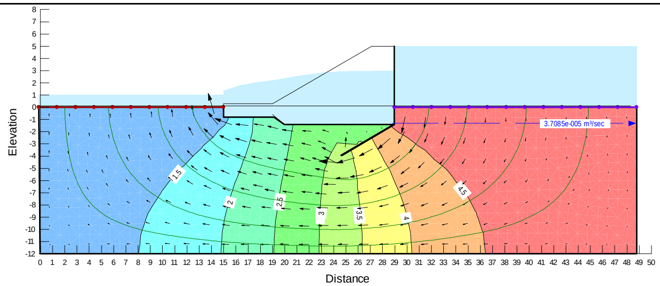


Figure 25 Flownet, flow quantity, and total head distribution for angle 150°

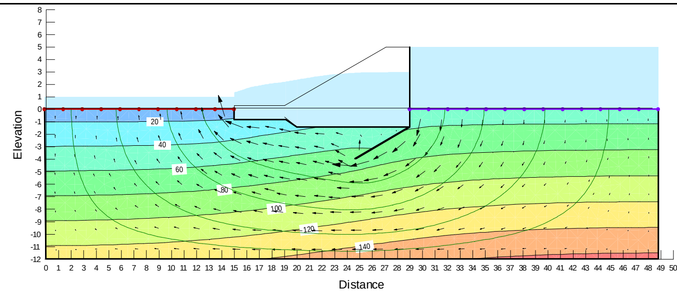


Figure 26 Pore water pressure distribution under the dam for angle 150°

Case 165°

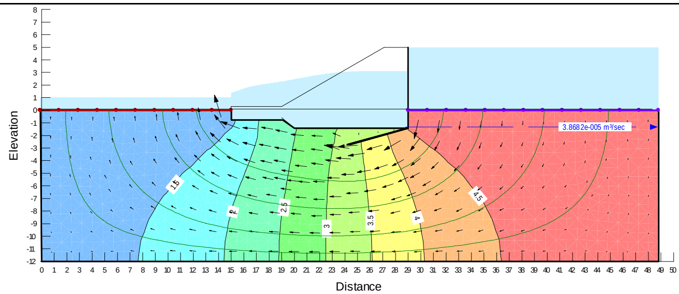


Figure 27 Flownet, flow quantity, and total head distribution for angle 165°

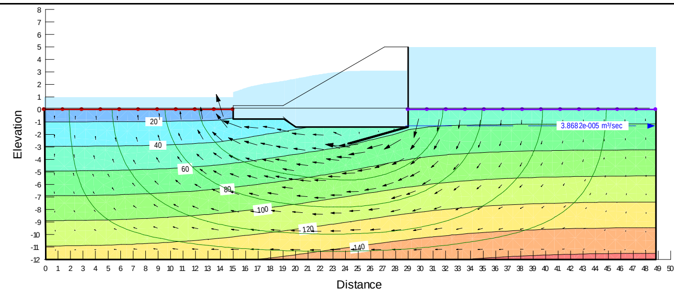


Figure 28 Pore water pressure distribution under the dam for angle 165°

Case 180°

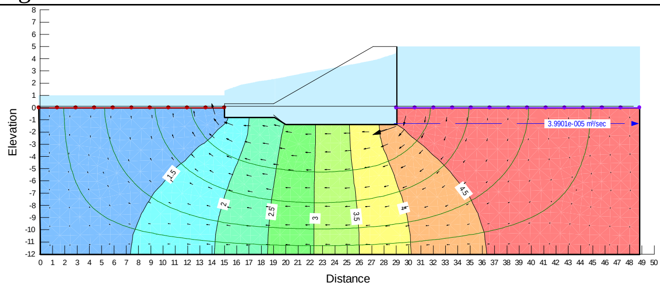


Figure 29 Flownet, flow quantity, and total head distribution for angle 180°

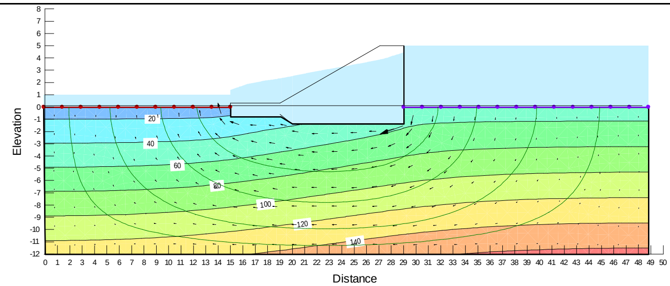
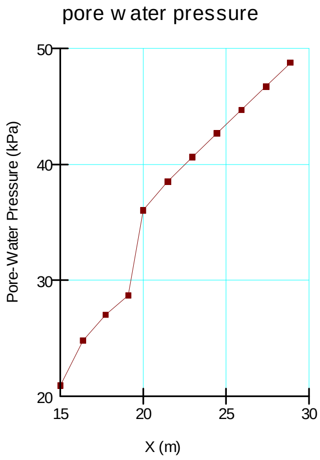
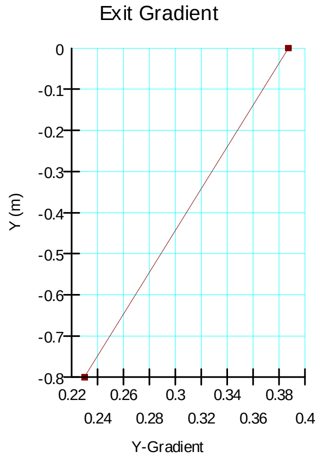


Figure 30 Pore water pressure distribution under the dam for angle 180°

Case 0°

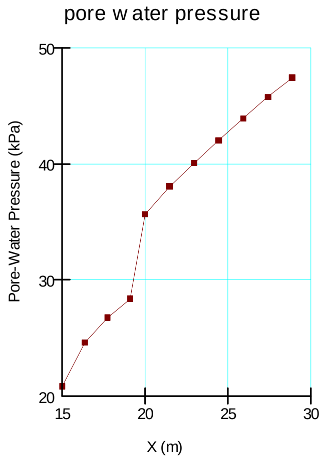


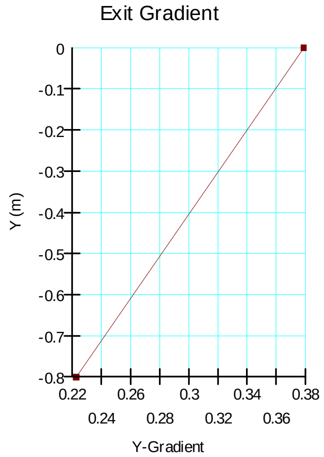


a b

Figure 31 a) Pore water pressure distribution, b) exit gradient at toe angle 0°

Case 15°

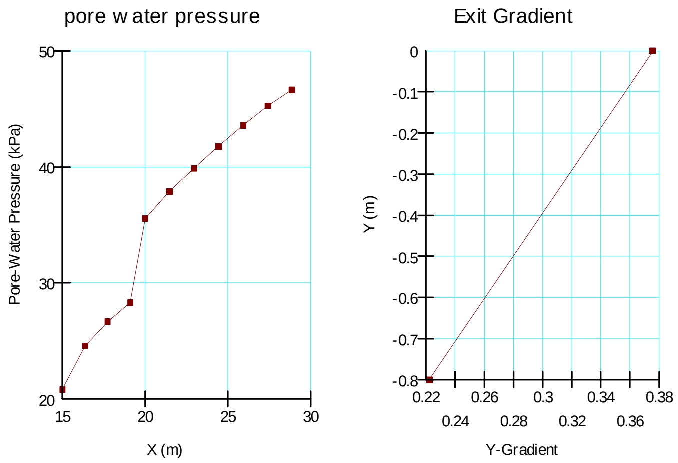




a b

Figure 32 a) Pore water pressure distribution, b) exit gradient at toe angle 15°

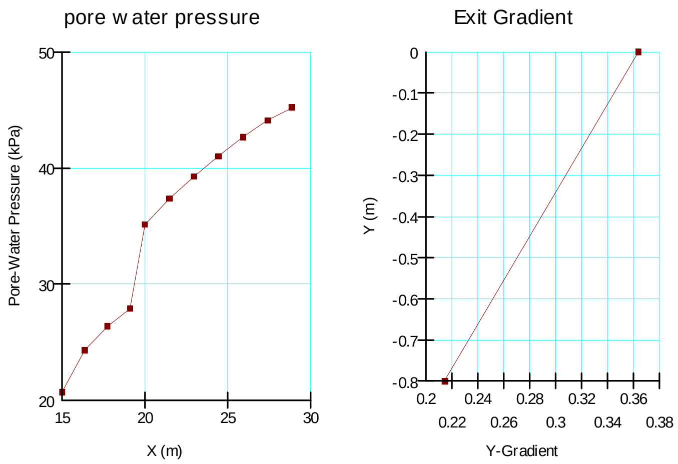
Case 30°



a b

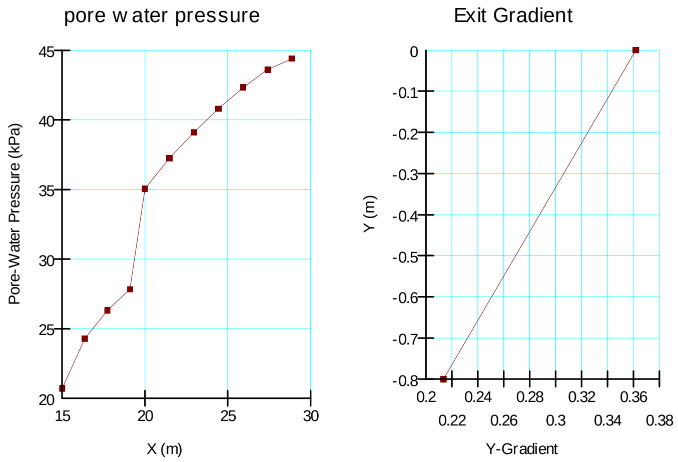
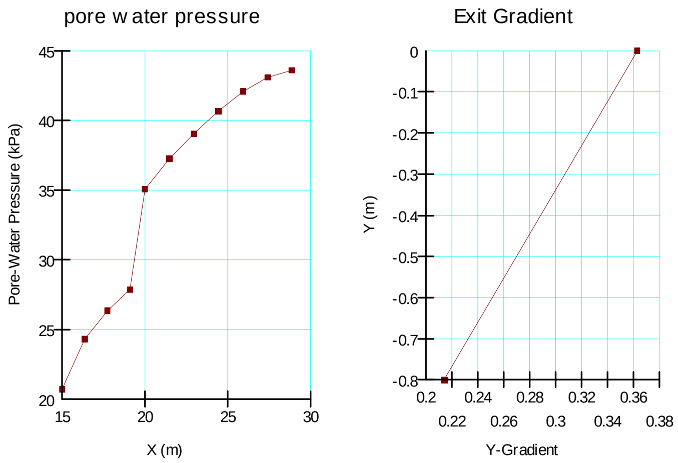
Figure 33 a) Pore water pressure distribution, b) exit gradient at toe angle 30°

Case 45°

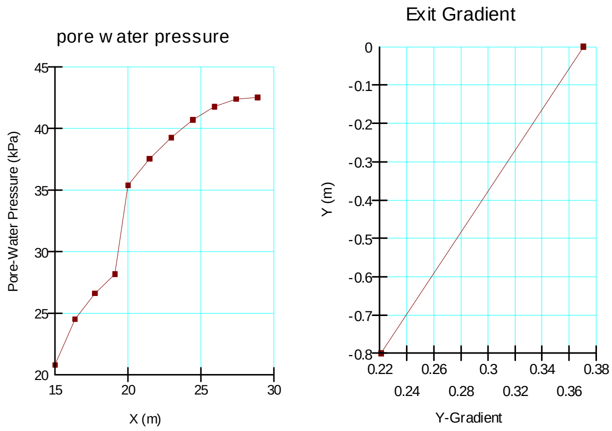


a b

Figure 34 a) Pore water pressure distribution, b) exit gradient at toe angle 45°

Case 60°	 a b Figure 35 a) Pore water pressure distribution, b) exit gradient at toe angle 60°
Case 75°	 a b Figure 36 a) Pore water pressure distribution, b) exit gradient at toe angle 75°
Case 90°	See figure 5

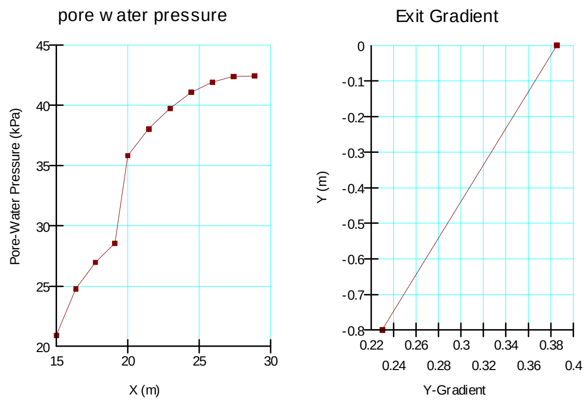
Case 105°



a b

Figure 37 a) Pore water pressure distribution, b) exit gradient at toe angle 105°

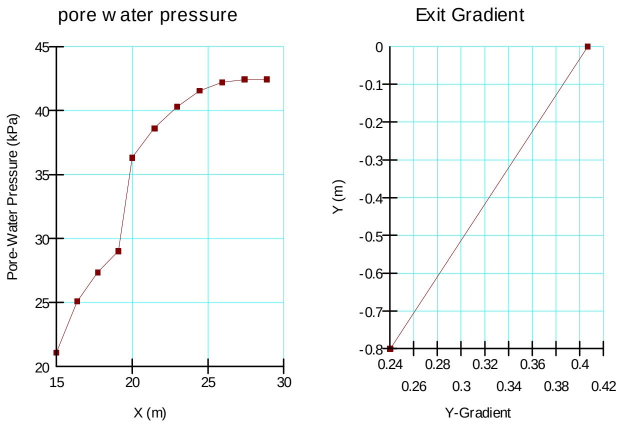
Case 120°



a b

Figure 38 a) Pore water pressure distribution, b) exit gradient at toe angle 120°

Case 135°



a b

Figure 39 a) Pore water pressure distribution, b) exit gradient at toe angle 135°

<table>
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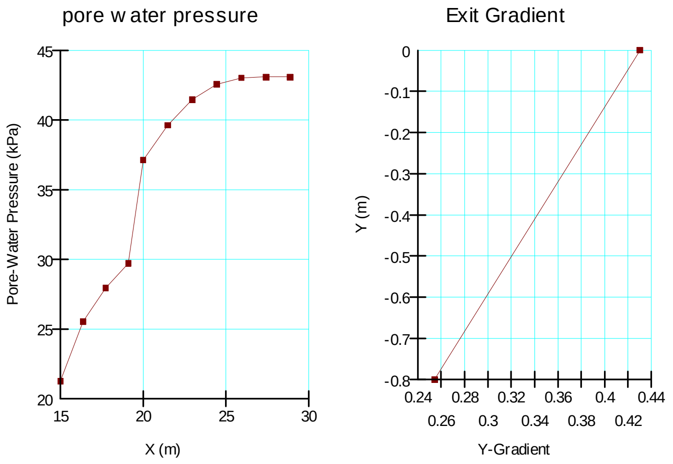

a b
Figure 40 a) Pore water pressure distribution, b) exit gradient at toe angle 150°
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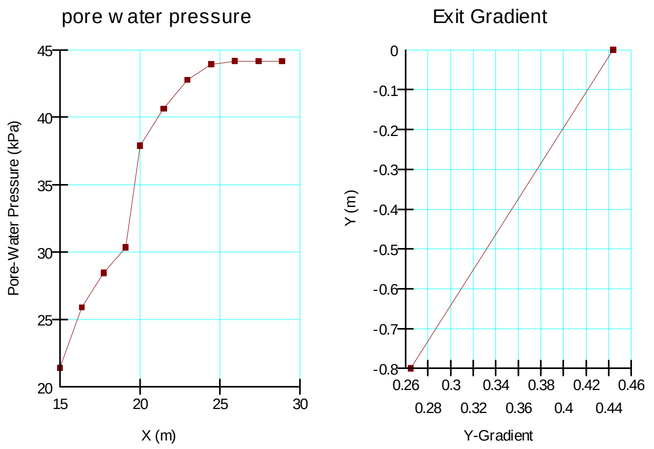
<tr><td>Case 165°</td><td>


a b
Figure 41 a) Pore water pressure distribution, b) exit gradient at toe angle 165°
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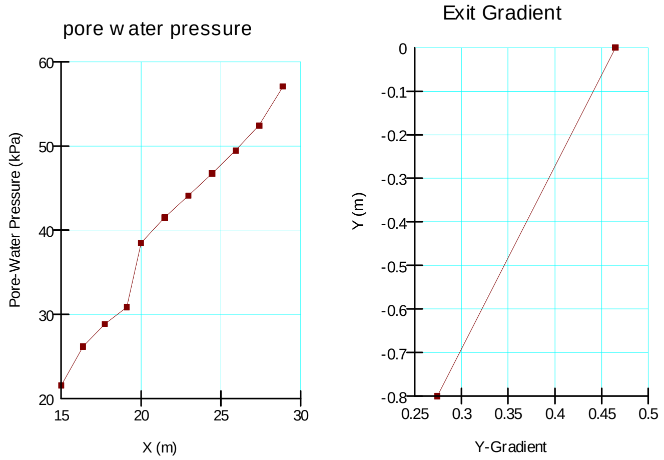
Case 180°



a b

Figure 42 a) Pore water pressure distribution, b) exit gradient at toe angle 180°

Table 2 Variation of flow quantity vs. cutoff wall angle

cutoff wall angle	Flow Quantity m^3/sec
0	3.2758E-05
15	3.1791E-05
30	3.1592E-05
45	3.0625E-05
60	3.0600E-05
75	3.0887E-05
90	3.12E-05
105	3.2231E-05
120	3.3630E-05
135	3.5112E-05
150	3.7085E-05
165	3.8682E-05
180	3.99E-05

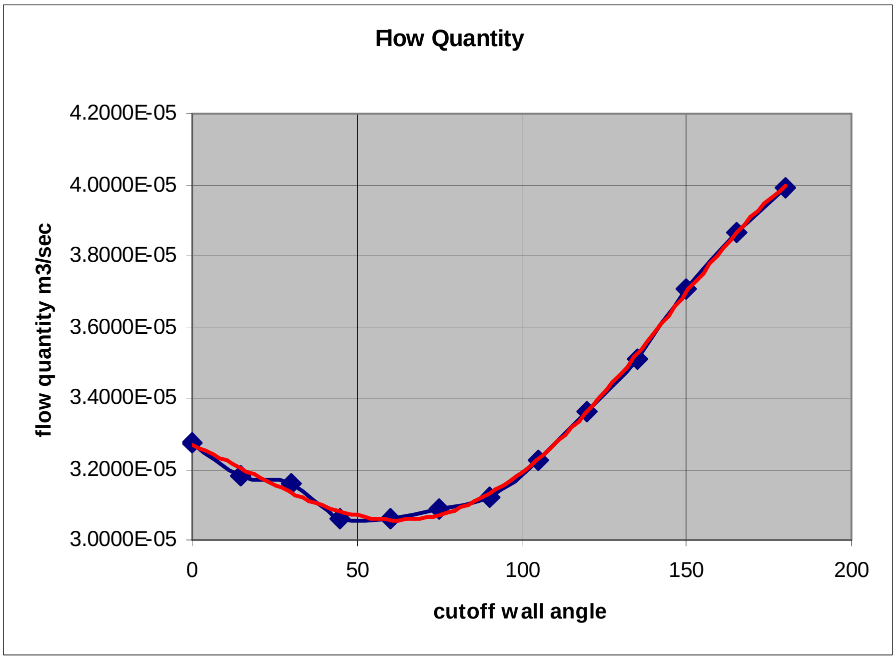


Figure 43 Variation of flow quantity vs. Cutoff wall angle

Table 3 pore water pressure under the base of the dam (kPa)

distance / angle	15	16.37	17.73	19.1	20	21.48	23	24.45	25.93	27.42	28.9
0	20.93	24.82	27.04	28.69	36.03	38.49	40.6	42.65	44.67	46.69	48.75
15	20.84	24.61	26.77	28.37	35.66	38.05	40.1	42.02	43.92	45.77	47.44
30	20.81	24.57	26.67	28.29	35.54	37.88	39.9	41.76	43.56	45.24	46.65
45	20.71	24.32	26.38	27.91	35.14	37.37	39.3	41.03	42.67	44.11	45.21
60	20.69	24.28	26.33	27.84	35.05	37.25	39.1	40.79	42.32	43.6	44.4
75	20.71	24.31	26.35	27.87	35.07	37.26	39.1	40.67	42.08	43.1	43.61
90	20.72	24.35	26.39	27.91	35.1	37.25	39	40.5	41.73	42.52	42.79
105	20.8	24.52	26.62	28.16	35.38	37.54	39.3	40.69	41.77	42.39	42.53
120	20.92	24.78	26.96	28.56	35.82	38.02	39.7	41.07	41.91	42.38	42.42
135	21.08	25.09	27.36	29.01	36.33	38.61	40.3	41.56	42.21	42.44	42.43
150	21.27	25.53	27.95	29.71	37.13	39.61	41.5	42.55	43	43.08	43.08
165	21.43	25.9	28.46	30.34	37.89	40.64	42.8	43.93	44.18	44.16	44.15
180	21.57	26.2	28.87	30.85	38.49	41.49	44.1	46.73	49.45	52.44	57.07

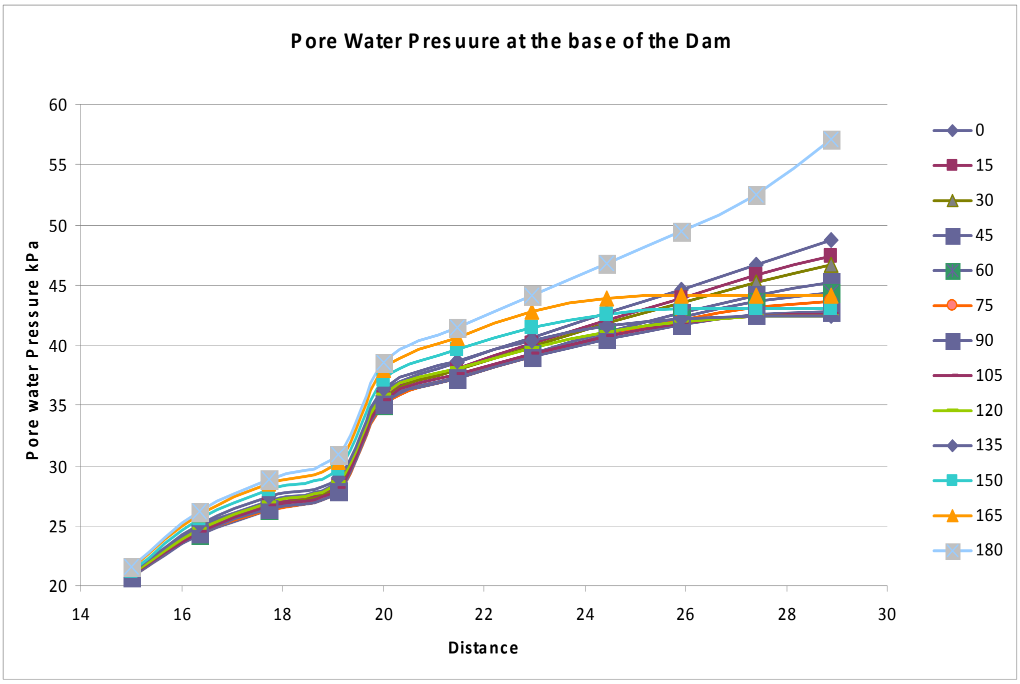


Figure 44 Variation of pore water pressure with the cutoff angle (kPa)

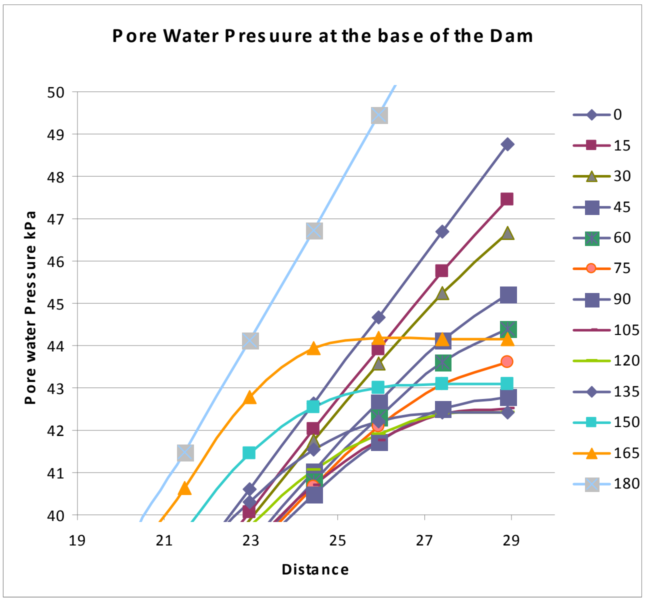


Figure 45 pore water pressure magnified end portion

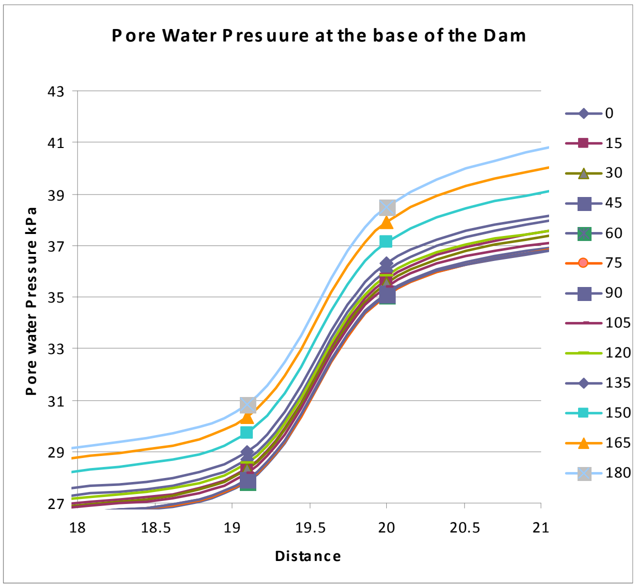


Figure 46 pore water pressure magnified middle portion

Table 4 Exit gradient vs. dam toe level

Angle / Level	0	15	30	45	60	75	90	105	120	135	150	165	180
0	0.39	0.38	0.38	0.36	0.36	0.36	0.36	0.37	0.39	0.41	0.43	0.44	0.46
-0.8	0.23	0.22	0.22	0.21	0.21	0.21	0.22	0.22	0.23	0.24	0.25	0.26	0.27

Figure 47 Graphical representation of exit gradient for the two points at dam toe

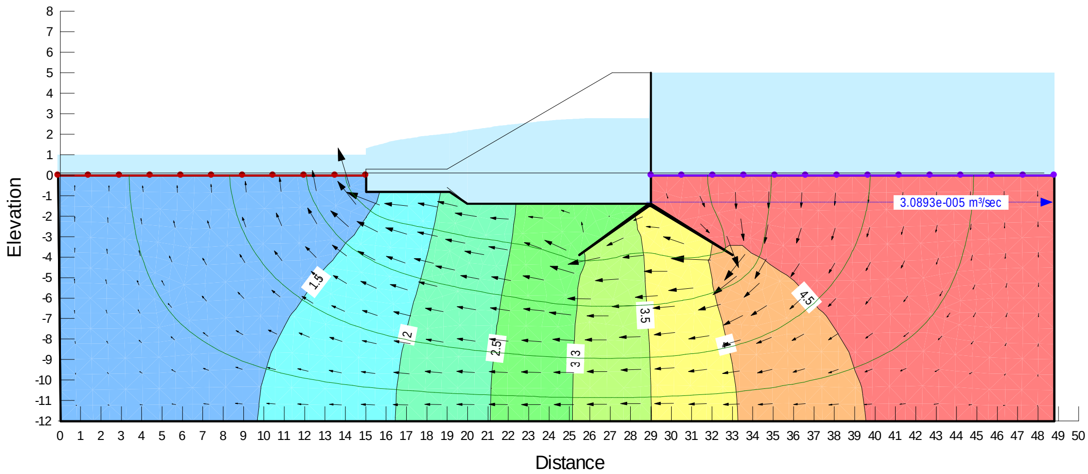


Figure 48 Flownet, flow quantity, and total head distribution (m) for angle 60° and 120°

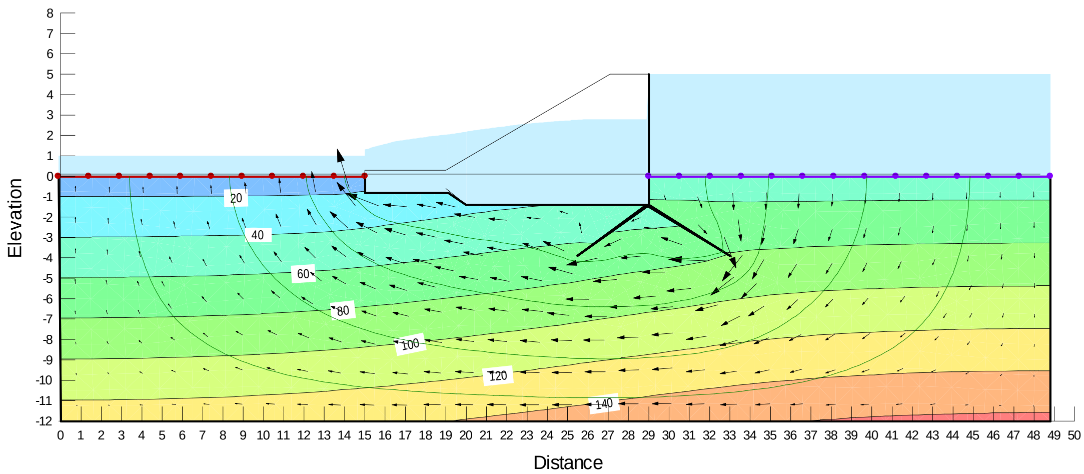
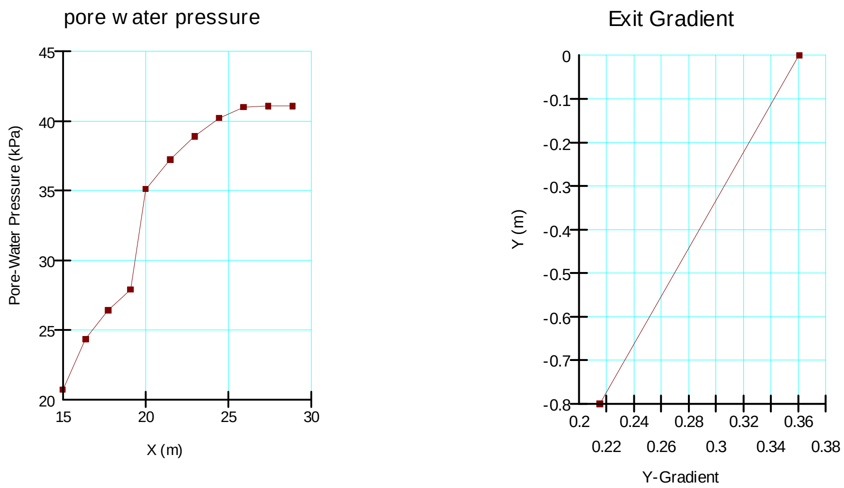


Figure 49 Pore water pressure (kN/m^2) distribution under the dam angle 60° and 120°



a b

Figure 50 a) Pore water pressure distribution, b) exit gradient at toe angle 60° and 120°