Performance of the horizontal drains in upstream shell of earth dams on the upstream slope stability during rapid drawdown conditions

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Abstract Slope stability analysis during rapid drawdown is an important consideration in the design of embankment dams. During rapid drawdown, the stabilizing effect of the water on the upstream face is lost, but the pore water pressures within the embankment may remain high. As a result, the stability of the upstream face of the dam can be much reduced. Installing horizontal drains is a very efficient and cost-effective method for reducing the pore water pressure and increasing the stability of the upstream slope. The theory of horizontal drains in the upstream shell of earth dams is well established, but there seems to be limited resources available for the design of this type of horizontal drains. Hence, this study is focused on the performance of horizontal drains in the upstream shell of the slope of earth dams on the upstream slope stability during rapid drawdown conditions. The parametric study has been conducted on the variation of horizontal drain parameters such as the number of drains, their length, and their location. In this study, ten scenarios were analyzed based on different drainage configurations and the performance of each scenario is investigated on the seepage and the upstream slope stability during rapid drawdown conditions using finite element and limit equilibrium methods. The results demonstrated that the stability of the upstream slope during rapid drawdown conditions increases by increasing the number of drains. The length of drains extending further from its intersection with the critical failure surface does not provide any significant change in the factor of safety. Finally, the study also found that installing drains in the lower region of the upstream shell of earth dams gives more stability than those installed in higher elevations.

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Introduction

When the water level at a dam drops, the stabilizing force due to the weight of the water becomes absent. If the dam material has a low permeability and the water level drops quickly, then excess pore pressures will be slow to dissipate and can reduce the stability of the slope. Hence, the upstream shell stability undermined due to the hydrostatic pressures caused by the drawdown. The soil within the dam body remains saturated and seepage commences from it towards the upstream slope. Seepage and hydrostatic pressures exert downward forces on the upstream slope. Those are adverse to the stability and create a critical condition to the upstream slope (Tran 2004).
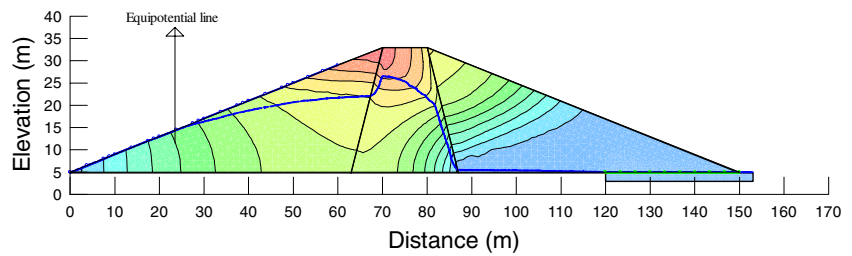
Rapid drawdown leads in most cases to slope failures. Thus, to improve the stability, the phreatic surface should be lowered. The horizontal drains method is a cost effective and widely used method to drawdown the phreatic surface for deep-seated failures. These drains dissipate the excess pore pressure and causing the equipotential lines tend to become more horizontal near the soil's surface (Figs. 1 and 2). They have a very significant effect on the stability of the upstream slope during rapid drawdown. The effectiveness of the horizontal drainage system is a function of many factors including the drain location, length, and spacing, as well as soil properties and slope geometry. Typically, effectiveness is described in terms of increase in the slope's factor of safety as compared to the factor of safety for the case without horizontal drains.

There have been a few studies (Royster 1980; Lau and Kenney 1984; Martin et al. 1994), which have described in part the many parameters controlling the horizontal drainage

design or evaluate the feasibility of using a system of horizontal drains to lower groundwater levels in hillsides (Craig and Gray 1985). Martin et al. (1994) suggested that a small number of drains installed at appropriate locations in accordance with a well-conceived conceptual groundwater model may be more effective than a large number of drains installed at uniform spacing over the slope. Rahardjo et al. (2002) examined the effectiveness of horizontal drains for slope stability for residual slopes under tropical climate. The selected study area was in a region with heavy rainfall and higher temperatures. Horizontal drains were used as a preventive measure to drain away the groundwater in such cases and improve stability. The results showed that the bottom drain as most efficient in draining out the water and maintaining the stability of the slope. Berilgen (2007) investigated the slope stability during drawdown depending on factors such as the soil permeability, drawdown rate, and drawdown ratio, considering the nonlinear material

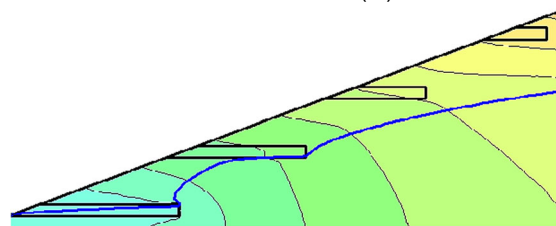**Fig. 2** Equipotential lines in case of four horizontal drains during drawdown in upstream toe
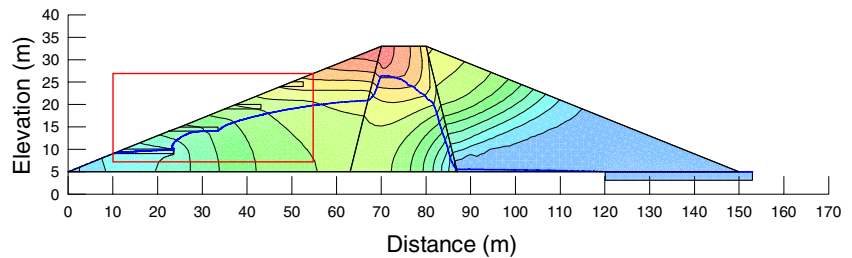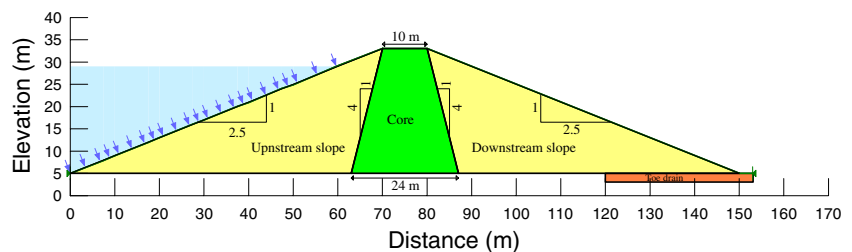

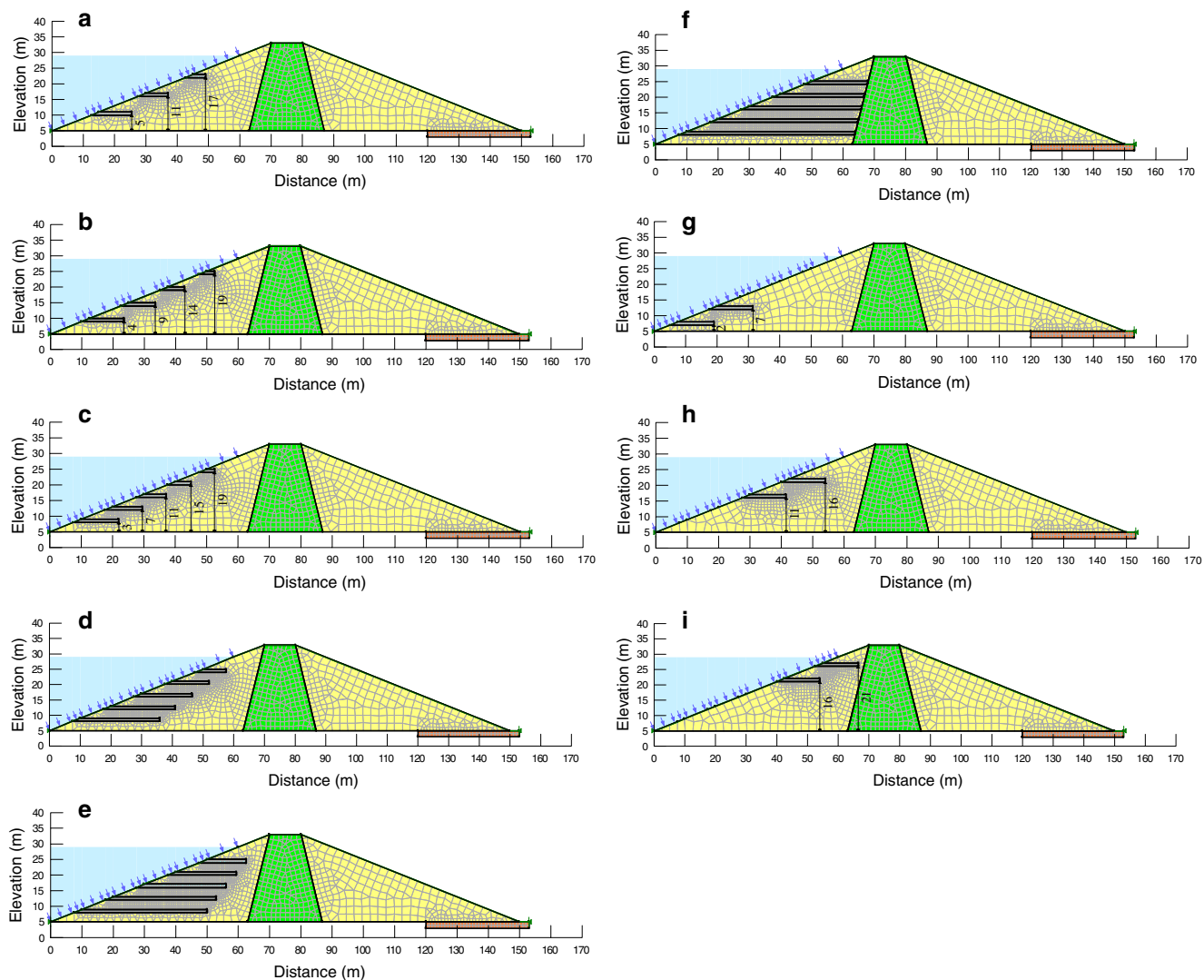**Fig. 3** Cross-section of dam model (first scenario)

Fig. 4 Different configuration of horizontal drains in upstream slope, **a** Dam with three horizontal drains in upstream slope (second scenario). **b** Dam with four horizontal drains in upstream slope (third scenario). **c** dam with five horizontal drains in upstream slope (fourth scenario). **d** Five horizontal drains dam with drain length half of horizontal length between slope surface and the core (fifth scenario),. **e** Five horizontal drains dam with drain length three quarters of

horizontal length between slope surface and the core (sixth scenario). **f** Five horizontal drains dam with drain length entire of horizontal length between slope surface and the core (seventh scenario). **g** Dam with two horizontal drains in low region of a slope (eighth scenario). **h** Dam with two horizontal drains in middle region of a slope (ninth scenario). **i** Dam with two horizontal drains in upper region of a slope (tenth scenario)

and loading conditions. According to his studies, a coupled transient seepage and deformation analyses (including consolidation), together with the stability analysis, were performed using the finite element method for submerged slopes. Nonlinear elastoplastic behavior of the slope soil was taken into account while analysis of the generation and dissipation of pore pressure was carried out.

There seems to be limited resources available for designing horizontal drains during rapid drawdown condition. This study is focused on a numerical method to investigate the performance of horizontal drains in the upstream shell of the slope of earth dams on the upstream slope stability during rapid drawdown conditions. The parametric study is

Table 1 Soil properties for rapid drawdown analyses

Parameter	Core	Shell material	Horizontal drain	Toe drain
K_x/K_y	2	2	2	1
C' (kpa)	33	1	1	1
K_x (m/days)	0.0003456	0.43	43.2	60.48
φ' (degree)	28	45	41	41
Failure criterion	Mohr–Coulomb	Mohr–Coulomb	Mohr–Coulomb	Mohr–Coulomb
γ (KN/m³)	18	21	19	19

Fig. 5 Soil–water
characteristic curve (*right*) and
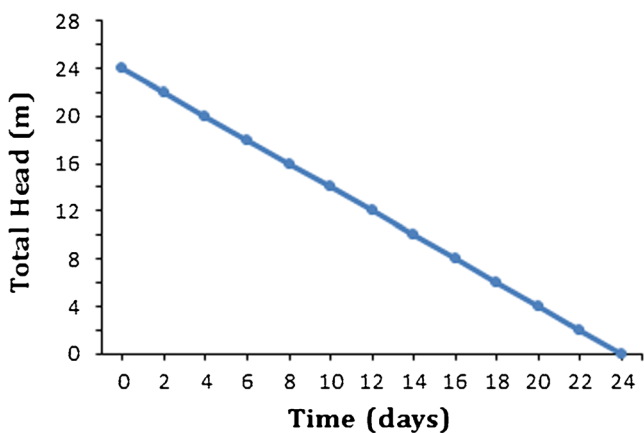permeability function (*left*) for
soil materials
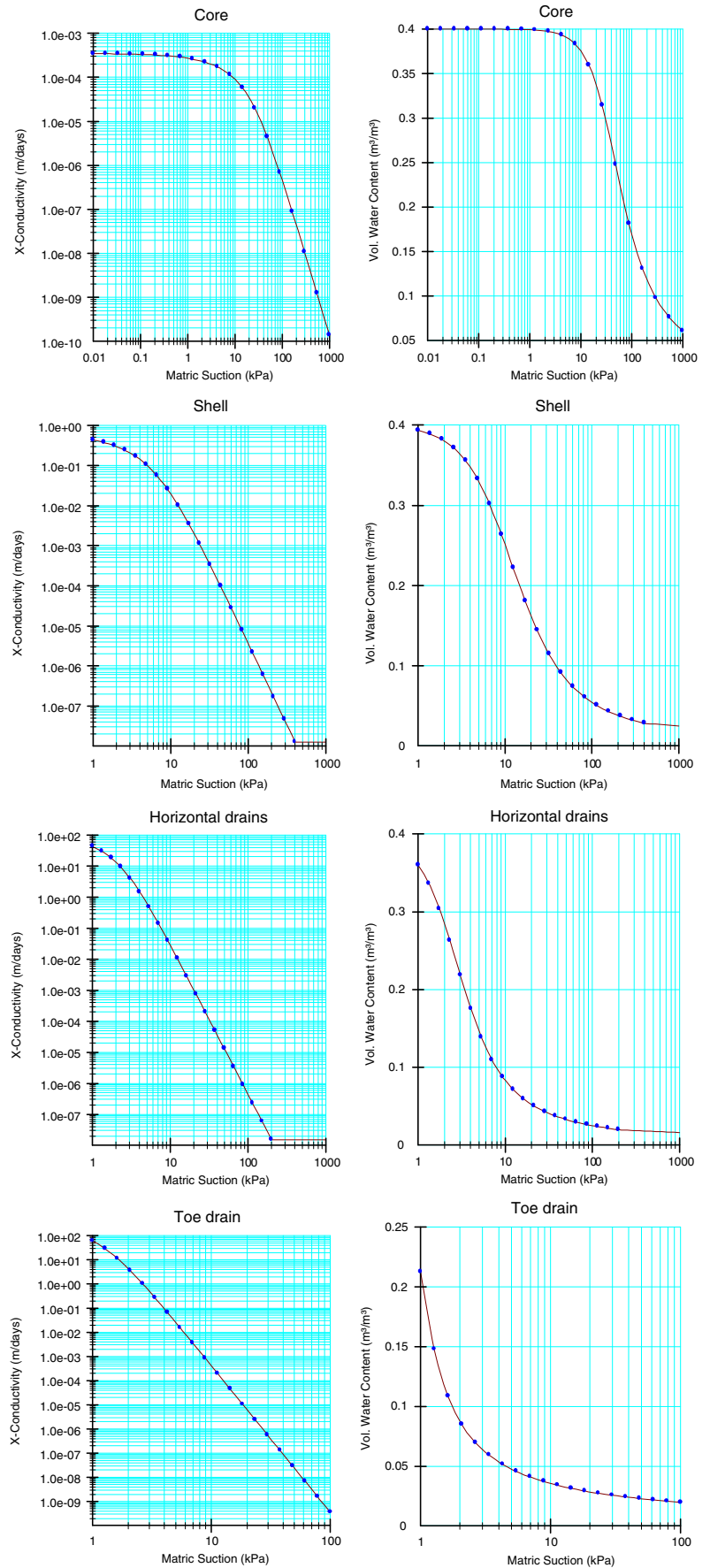
Fig. 6 Total head versus time function for reservoir drawdown

conducted on the variation of the following horizontal drain parameters; number of drains, their length, and their location.
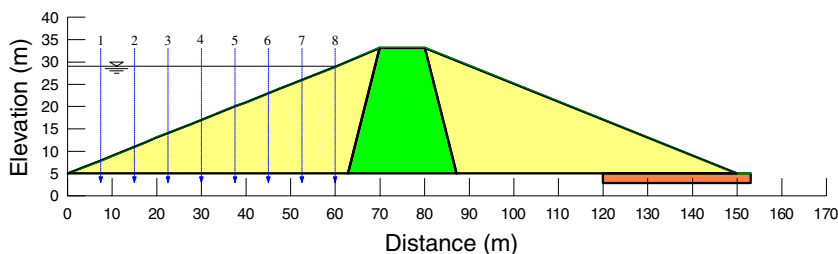
Theory of water flow in saturated and unsaturated soils

Seepage flows in saturated and unsaturated soils are governed by Darcy's law. One of the major differences between water flows in unsaturated soils and saturated soils is that the permeability coefficient is not a constant but a function of the degree of saturation or soil suction in an unsaturated soil. The governing equation for water flow through soil can be obtained by introducing Darcy's law into the mass continuity equation. The deformation of the soil skeleton is usually ignored for convenience. This can be explained by the fact that the soil deformation due to soil consolidation and settlement can effect on permeability coefficient, hence the study does not consider soil deformation and its effect on permeability coefficient. Taking the total hydraulic head h as the unknown and when the directions of the coordinate axes are the same as the directions of anisotropy of hydraulic conductivity, the general two-dimensional governing differential equation for water flow through soil is as follows:

$$\frac{\partial}{\partial \chi}\left[k_{\chi}\frac{\partial h}{\partial \chi}\right] + \frac{\partial}{\partial y}\left[k_y\frac{\partial h}{\partial y}\right] = \gamma_w \frac{\partial \theta_w}{\partial \psi}\frac{\partial h}{\partial t} \qquad (1)$$

Where k_x and k_y are the coefficients of permeability in the x and y directions, respectively; θ_w is the volumetric water content, γ_w is the unit weight of water, h is the total head, ψ is the soil suction, and t is time. According to the equation, a soil–water characteristic curve, which is a relationship between the volumetric water content and the soil suction, as well as a permeability function, must be known for transient seepage analyses (Reddi 2003).

Description of problem

In Fig. 3, a numerical model comprising a zoned earth dam with a crest height of 28 m above the ground level, a crest width of 10 m and a length of 153 m in its foundation is shown. Both upstream and downstream slopes have the inclination of 2.5 h: 1 V, which is so common in earth dams. Thickness and the length of the toe drain are 2 and 33 m in its foundation, respectively. The foundation is considered to be impervious. The maximum water table is at 24 m above the ground level and corresponds to the water surface level in the impoundment (Fig. 3).

The dam configurations and the horizontal drains location are shown in Fig. 4. Ten scenarios were analyzed based on different drainage configurations. The first scenario involved the dam configuration without drainage (Fig. 3). In the second, third, and fourth scenarios, the dam contained three, four, and five horizontal drains in upstream slope, respectively (Figs. 4a–c). It should be mentioned that the drains length of these scenarios were considered to be one quarter of the horizontal length between slope surface and the core. In the fifth, sixth, and seventh scenarios, the dam had five horizontal drains; however, the length of the drains were half, three quarters and the entire horizontal length between upstream slope's surface and the core, respectively (Figs. 4d–f). Finally, the three remaining scenarios involved the dam with two horizontal drains such that the length of the upstream drains were equal (14 m), whereas the drains were located in the lower, middle, and upper region of the slope in the dam model, respectively (Figs. 4g–i). It should be noted that the thickness of the upstream horizontal drains was 1 m. Also, all of the dam models and the soil properties for rapid drawdown analysis in this study were selected hypothetically.

Fig. 7 The sketch of the suggested eight sections on the upstream slope (first scenarios)

Fig. 8 The discharge through the upstream slope for suggested eight sections in the tenth day of drawdown (first scenarios)
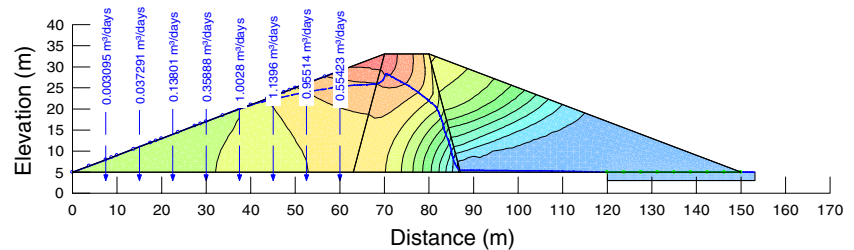
All the material parameters used in rapid drawdown analysis is according to Table 1: K_x saturated permeability coefficient in the x direction, K_y saturated permeability coefficient in the y direction, effective cohesion, φ' effective angle of internal friction, and γ wet unit weight. For unsaturated flow, it is necessary to define the hydraulic conductivity function, which describes how the hydraulic conductivity varies with change in matric suction. The fit of the hydraulic conductivity functions is highly dependent on material properties. At lower suctions, the coarse material has a higher hydraulic conductivity than the fine material, which is intuitive (Fig. 5). The materials used in this model for the core, shell, horizontal drains, and toe drain were silty clay, silty sand, sand, and gravel, respectively. Silty clay had a suction range from 0.01 to 1,000 kPa, silty sand had a suction range from 1 to 400 kPa, sand had a suction range from 1 to 200 kPa, and gravel had a suction range from 1 to 100 kPa. Also, the saturated water content was determined as 0.4 for all materials in the model of earth dam. Soil–water characteristic curve and permeability function of soils are shown in Fig. 5.

Method of analysis

The stability during rapid drawdown can be analyzed using two approaches; namely the "effective strength" approach and the "staged undrained strength" approach. The approach in this study for investigating the performance of horizontal drains in upstream shell of earth dams on the upstream slope stability during rapid drawdown is analyzed by the effective stress approach. This advanced method which analyzes drawdown from the seepage results (numerical simulation process) obtained from a SEEP/W (GEO-SLOPE 2007a)

analysis, is more accurate, since uses the exact pore water pressures in the soil during the drawdown process, as opposed to simply computing the pore water pressure from the vertical distance between the phreatic line and the base of the slice. The software (SEEP/W) is based on the finite element method. In order to reach this goal, the analyses were done in four stages.

First, it was assumed that the maximum water level is at 24 m above the ground level whereas a steady state seepage analysis was then performed for all different drainage scenarios. Using the steady state seepage analyses, pore water pressure could thus be obtained in any region of dam. These pore water pressures would then be used as initial conditions in the rapid drawdown analyses.

In the second stage, the rapid drawdown was simulated by means of hydraulic functions. The water level in the reservoir was lowered into 12 steps. The maximum water level lowered equally, is 2 m for each step which the drawdown level for even days (2nd, 4th … 24th days) were modeled in this research. It should be noted that, due to the reduction of water level at the upstream slope, the boundary condition for the slope below water level was not considered constant total head. In this study, three boundary conditions were considered in the analysis of rapid drawdown. First, the pressure head on the toe drain was defined as zero. Next, the total head in the upstream slope boundary was considered to be 24 m. Finally, the reservoir drawdown was determined as a function of time such that the rate of drawdown was 1 m/day (Fig. 6).

In the third stage, eight sections in the upstream region of the dam 7.50 m long were considered for determining the discharge of flux through the upstream slope boundary, shown schematically in Fig. 7. The discharge through each section was then analyzed for the first seven scenarios. It should be noted that after analyzing the rapid drawdown for

Fig. 9 The flow vectors in the dam materials in the 10th day of drawdown (first scenarios)
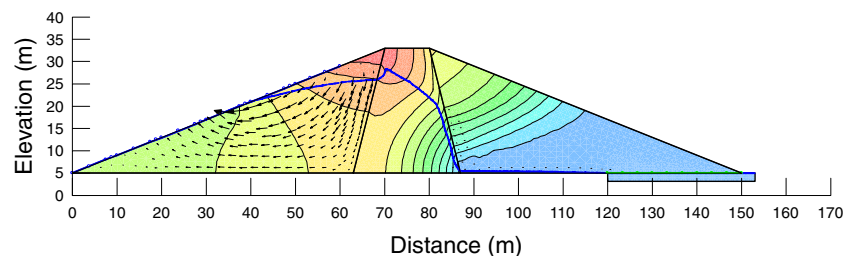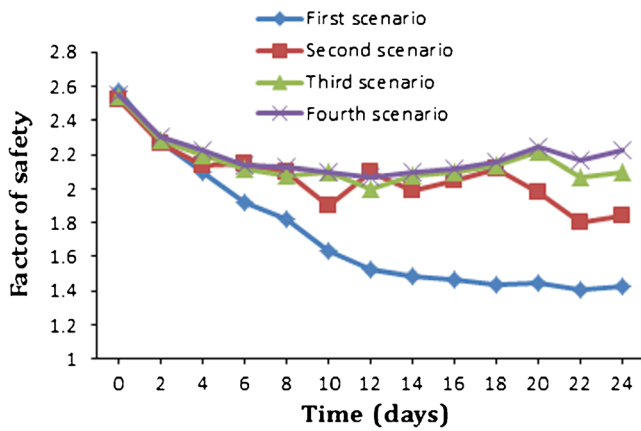
Fig. 10 Minimum factor of safety versus time (scenarios 1–4)

Fig. 12 Minimum factor of safety versus time (scenarios 8–10)

the first seven scenarios, the discharge through each section was calculated whereas the average was considered as the approximate discharge through the upstream slope boundary (Fig. 8).

For the final stage, the limit equilibrium method according to Spencer (1967) presented by computer program SLOPE/W (GEO-SLOPE 2007b) was applied to determine the potential slip surface and to calculate the factor of safety of the upstream slope. The failure area was determined and divided into 1,456 of sections. The slope stability analysis was utilized to assess the performance of drains in improving the upstream slope stability during rapid drawdown. The equilibrium of each section was considered to determine a factor of safety for the determined slip surface, considering the equilibrium of the whole mass. The potential slip surface and factor of safety were iteratively determined until a critical slip surface and minimum factor of safety were found. The shear strength of soil was described using the Mohr–Coulomb failure criterion and a factor of safety was calculated for each scenario at every time step by importing the pore water pressure head data into SLOPE/W.
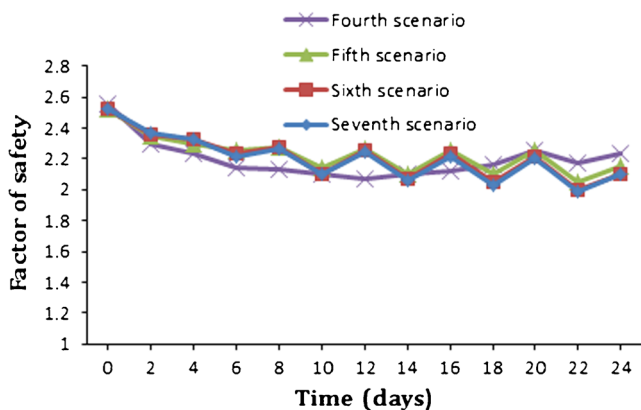
Discussion of results

As the water level in the reservoir drops, the flow vectors in the dam materials tend to move to the upstream slope as shown in Fig. 9. The potential slip surface or failure mechanism, occur in the upstream slope. The explanation of this fact is that when the water level drops rapidly within the reservoir the stabilizing effect of water on the upstream slope are disappeared, while the pore pressures need more time to dissipate. Therefore, high pore pressures are created in the earth dam towards the reservoir and as a result a slip surface may emerge and develop at the upstream slope.

In this study, the stability of the upstream slope during rapid drawdown was analyzed for 1 m/day rate of drawdown as shown in Figs. 10, 11, and 12. It can be seen that in the first scenario, the factor of safety decreases continuously during the rapid drawdown. The average value of the safety factor for the second, third, and fourth scenarios increased up to 28, 35, and 38 % compared to the first scenario while the value of safety factor in the last day of rapid drawdown for the second, third, and fourth scenarios increased up to 29, 47, and 56 %
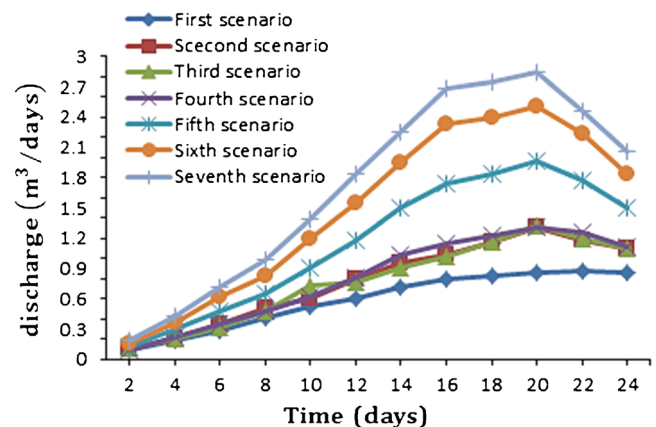

Fig. 11 Minimum factor of safety versus time (scenarios 4–7)

Fig. 13 Approximate discharge through the upstream slope for the first seven scenarios during rapid drawdown conditions

compared to the first scenario. In the fifth, sixth, and seventh scenarios, the average value of safety factor differed very slightly from the fourth scenario (approximately 3 %). In other words, extending the length of drains longer than its intersection with the critical failure surface was found not to increase in factor of safety.

In the next three scenarios, the study was performed to investigate the significance of the drains location within the shell of the upstream slope of earth dams. From the results of the upstream slope stability analyses, shown in Fig. 12, it can be seen that in the eighth, ninth, and tenth scenarios, the lowest value of safety factor was obtained 1.7, 1.46, and 1.44, respectively. In addition, the average value of the safety factor in the eighth, ninth, and tenth scenarios, increased up to 22, 14, and 6 % compared to the first scenario. The general trend in Fig. 12 shows that drains were the least beneficial when located in the upper region of the upstream slope and the most beneficial when located at the lower of the upstream slope. Therefore, the bottom drains are most efficient in draining out the water and maintaining the stability of the upstream slope.

Seepage outflow during rapid drawdown increases, due to the existence of upstream slope shell horizontal drains in earth dams for the first seven scenarios as shown in Fig. 13. The study found that the seepage outflow increases significantly when the length of horizontal drains was extended (e.g., fifth, sixth, and seventh scenarios with respect to the fourth scenario). This can explain the fact that, internal erosion, which is one of the major reasons for earth dam failure, is caused by increased seepage flow due to loss of fines. This undesirable effect of upstream slope horizontal drains should be taken into consideration in design of earth dams. The study also found that the seepage outflow changes very slightly when the number of horizontal drains was increased (e.g., third and fourth scenarios with respect to the second scenario).

Conclusion

The performance of horizontal drains has been studied for a homogeneous unsaturated slope (upstream shell). The main results of this study can be summarized into six aspects:

1. The simulation of an earth dam with and without drainage systems in its upstream slope indicates that in all scenarios discussed the installation of drains resulted in the reduction of the pore-water pressures and increased stability against sliding.

2. The stability of the upstream slope during rapid drawdown conditions increases by increasing the number of horizontal drains.

3. The length of the drains extending further from its intersection with the critical failure surface does not provide any significant change in the factor of safety.

4. The study also found that installing drains in the lower region of the upstream shell of earth dams gives more stability than those installed in higher elevations.

5. The seepage outflow during rapid drawdown conditions increases by extending the length of horizontal drains.

6. Finally, the seepage outflow during rapid drawdown conditions changes very slightly when the number of horizontal drains was increased.

The study ignored fractures, cracks, and vegetation of the slope; however, such effects may be included in a future analysis. Also the dam model used in this study was hypothetical and recommended in the future analysis, the upstream slope stability during rapid drawdown condition conducted on the real dam.

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