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Numerical Investigation of the Embankment Dam Safety during Rapid Drawdown Conditions Using Horizontal Drains

Sahar Al-Khyat *, **May Samir Saleh**, **Hayder A. Hasan**, **Zuhair Abd Hacheem**
Water Resources Engineering Department, College of Engineering, Mustansiriyah University, Baghdad, Iraq.

Keywords:
Factor of safety; Finite elements; Geostudio; Slope stability; Upstream slope failure.

Highlights:

- *Stability of upstream slope with horizontal drains during rapid drawdown.*
- *Horizontal drain performance was considered using Geostudio.*
- *Factors influencing the slope stability were investigated.*

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*Corresponding author:
Sahar Al-Khyat
Water Resources Engineering Department, College of Engineering, Mustansiriyah University, Baghdad, Iraq.

Abstract: Rapid drawdown loading condition is a critical state that can cause failure of the upstream slope in earthen dams. Applying upstream horizontal drains has been a prevalent solution to prevent such potential failure. However, existing literature tends to focus on the drains' geometric and material properties, neglecting the impact of the drawdown rate and geotechnical properties of the dam on the upstream drainage systems' effectiveness. The present research employs a Finite Element Method, utilizing GeoStudio software, to comprehensively assess the performance of upstream horizontal drains in enhancing slope stability of a homogeneous embankment during rapid drawdown scenarios under varied rates of drawdown and dam properties. The stability analysis results indicated that the factors of safety of the upstream slope at a drawdown rate of 1 m/d and a permeability rate of 10^{-2} m/d satisfy the minimum safety limits. Notably, introducing upstream drains substantially increased the factors of safety, particularly in scenarios involving faster drawdown rates and slower permeability rates. It was found that the required number of horizontal drains for ensuring the stability of the upstream slope primarily depended on drawdown and permeability rates. However, the presence of upstream drains increased seepage through the upstream face and dam bodies.

تحري عددي في سلامة السد أثناء ظروف السحب السريع باستخدام المصارف الأفقية

سحر الخياط، مي سمير صالح، حيدر عباس حسن، زهير عبد حاجم
قسم هندسة الموارد المائية/ كلية هندسة / الجامعة المستنصرية/ بغداد – العراق.

الخلاصة
يعد تحميل السحب السريع حالة حرجة يمكن أن تتسبب في فشل المنحدر العلوي للسدود الترابية. استخدام المبازل الأفقية في المنحدر العلوي يعتبر حلاً سائدًا لمنع هذا الفشل المحتمل. ومع ذلك، تميل الأدبيات الحالية إلى التركيز على ابعاد المبازل وخصائصها الهندسية، مع إهمال تأثير معدل السحب والخصائص الجيوتقنية للسد على فعالية نظام التصريف في المنبع. يستخدم هذا البحث نظرية العناصر المحدودة، باستخدام برنامج GeoStudio، للتقييم الشامل لأداء المبازل الأفقية في المنحدر العلوي في تعزيز استقرار المنحدر لسد ترابي متجانس أثناء سيناريوهات الانسحاب السريع في ظل معدلات مختلفة من السحب السريع وخصائص التربة الهندسية للسد. بينت نتائج تحليل الاستقرار إلى أن عوامل سلامة المنحدر العلوي بمعدل سحب قدره ١ متر/يوم ومعدل نفاذية قدره ١٠-٢ متر/يوم تفي بحدود الأمان الدنيا. والجدير بالذكر أن اضافة المبازل الافقية زاد بشكل كبير من عوامل السلامة، لا سيما في السيناريوهات التي تنطوي على معدلات سحب أسرع ومعدلات نفاذية أبطأ. كذلك وضحت النتائج أن العدد المطلوب من المصارف الأفقية لضمان استقرار المنحدر العلوي يعتمد في المقام الأول على معدلات التخفيض ومعامل النفاذية للتربة. ومع ذلك، أدى وجود مبازل في المنحدر العلوي إلى زيادة كمية التسريب خلال كل من المنحدر العلوي وأجسام وجسم السد.

الكلمات الدالة: معامل الأمان، نظرية العناصر المحدودة، برنامج GeoStudio, استقرارية الميل، فشل المنحدر العلوي.

1.INTRODUCTION

1.1.Overview

Embankment dams are earthen structures normally made from earth-fill materials. It is a self-resisting kind of structure that is able to resist sliding and overturning through its own sheer weight. As a rule, such dams are constructed by laying and compacting a range of soil compositions: gravel, sand, clay, and so on [1]. Dams are engineered for certain uses, namely water supply, irrigation, flood control, and generating electricity and power. It generally classifies the earth dams' failure situation into hydraulic, seepage, and structural failures [2]. From the number of operational scenarios mentioned in the available literature, the rapid drawdown is identified as the most severe to cause upstream slope failures [3, 4]. The accelerating drop in the reservoir water level undermines the slope's stabilizing impact of the hydrostatic pressure upstream. However, the slope's pore pressures are unable to drop quickly enough. As a result, the embankment creates a significant pressure gradient towards the reservoir, which may cause a slip surface to arise at the upstream slope. Extreme flooding events represent an example of the rapid drawdown condition [5, 6].

1.2.Literature Review

During rapid drawdown conditions, the stability of the upstream slope is primarily influenced by the drawdown ratio and rate, the hydraulic conductivity of the soil, and drainage facilities. When the water level after the drop is almost one-third the height of the embankment, the safety factor for upstream slope stability significantly decreases [7, 8]. Similar findings were provided by Tran [9] using the Dau Tieng Dam as a case study. The study evaluated the effect of the drawdown ratio (L/H), where L is the water depth after the drawdown, and H is the height of the dam. It was found that the value of the safety factor declined by almost 34% at the drawdown level of H/3 and by almost 43% at full emptying, indicating that the safety factor critically decreased even prior to the reservoir being completely drained. One of the most important factors that control the stability of earth-fill dams is the soil characteristics. According to Al-Nedawi and Al-Hadidi [10], an earth dam's stability is greatly influenced by the material properties employed in its construction. Utepov et al. [11] explored how varying permeability rates affect Lugoda dam stability in Tanzania under various scenarios of rapid drawdown. The study identified 10^{-6} m/s as the critical value of the hydraulic conductivity for the dam material, beyond which dam failure occurs at a drawdown rate of 1 m per day. The horizontal drains technique is a prevalent way to draw down the phreatic surface for increasing upstream slope stability. The drainage ability of the horizontal drains to discharge excess pore pressure produces horizontal equipotential lines near the soil surface. The drains' position, length, spacing, soil characteristics, and slope geometry affect the horizontal drainage efficiency system. Effectiveness is often measured by the increased value in the safety factor of slopes compared to the scenario without horizontal drains. A few studies [12–14] assessed the feasibility of employing horizontal drains to stabilize the upstream slopes or partially detailed the multiple factors influencing the design of the horizontal drains. According to Martin et al. [14], installing a small number of drains in the right places could be more efficient than placing a large number spaced evenly throughout the slope. In a tropical climate, Rahardjo et al. [15] investigated the efficiency of the horizontal drain in residual slope stability. The region where the study site was chosen experienced high temperatures and significant rains. In such situations, groundwater was drained away as a precautionary step to increase stability. The bottom drain was the most effective at removing water and preserving the slope's stability. Moharrami et al. [16] partially investigated some factors influencing the horizontal drains' performance on slope stability. The studied factors were the drains' number, length, and location. The findings showed that during rapid drawdown conditions, adding more horizontal drains improved the upstream slope stability, while no appreciable change in the factor of safety was found as the drains' length increased away from their intersection with the critical failure surface. The study also revealed that placing drains lower on the upstream side of embankment dams offered more stability. Using a computer-assisted program, the earth dam's operation and stability can be examined. It is an inexpensive and fast procedure, and the results can be communicated quickly to the parties involved. Regarding what concerns an embankment dam, seepage, and slope stability are often used with GeoStudio. It is a program providing a set of connected numerical modeling software, realized through SEEP/W for the simulation of seepage and through SLOPE/W for accomplishing slope stability. For example, Hasani et al. [17] conducted a safety analysis of an earthen dam structure using a sub-product Slope/W of a software package, namely GEOSTUDIO. The Bishop and Janbu, Ordinary method of slides and Morgenstern methods considered by determining the minimum factor from all these analyses as the safety factor for slope stability. Arshad and Baber [18] conducted an effective seepage analysis of an earth dam using the finite element-based program SEEP/W. From the results of seepage analysis, one could see the model application in the confirmation of the ability to represent field behavior. At each and every point in the flow net, the program can estimate several flow net parameters of interest that include seepage discharge, exit gradient, seepage velocity, pore pressure, and lifting pressure [10]. The long-term stability of earth dams mainly depends on the shape, material properties, and applied pressures [19]. Thus, it is inferred that under such quick drawdown conditions, the above-cited parameters' response should control the upstream slope. In this regard, proper evaluation of quick drawdown cases for seepage and slope stability of an earth-fill dam can be extremely important [20]. Previous studies focused only on the effects of the horizontal drain geometry or other factors separately investigated for this numerical study, where attempts have been made to investigate all other configured factors that could influence, by all means, the stability of the upstream slope during rapid drawdown. The number, location, spacing of the horizontal drains, drawdown rate, and permeability of the dam material were all varied in this parametric research. The study findings could deepen the understanding of different design factors' roles, making it easier to build more reliable and effective methods for enhancing the stability of earthen dams.

2.PROBLEM STATEMENT AND BOUNDARY CONDITIONS

Finite Element Modeling was employed for simulating the problem statement and boundary conditions. The study is limited to analyzing the upstream slope stability of a hypothetical homogenous embankment dam, as shown in Fig. 1, during rapid drawdown conditions using horizontal drains. The model was verified with a case study of the Pilarcitos Dam, a homogeneous embankment in California, which experienced slope failure in 1969 due to rapid drawdown in water levels [21]. The verification results showed that the factor of safety obtained using GeoStudio was 0.885. The absolute percent difference is 7.93% based on the reported safety factor value of 0.82 by [21], which is within the acceptable accuracy. The dam geometry was checked according to the Benchmark safety regulation criteria of the United States Army of Corps Engineers (USACE) [22] and the British Dam Society [23], as given in Table 1, and considered to be acceptable. The toe drain dimensions were 1 m and 15 m. The maximum water table was 10 m above the ground level, representing the highest water level. Horizontal drains of 0.5 m thickness and having a length equal to a quarter of the distance between the dam center and upstream shell were added to the homogeneous embankment dam. Table 2 provides the soil properties of the embankment dam shell, horizontal drains, and toe drain. The embankment dam's generated mesh and boundary conditions are shown in Figs. 2 (a, b, c). A mesh refinement study is performed to assess the sensitivity of the results to changes in mesh size. Starting with a coarse mesh of 1 m and gradually increasing the number of elements by a mesh size of 0.5 m and 0.25 m. The mesh sensitivity results showed that the maximum standard deviation in the obtained safety factors for all the dam cases was 0.0031. Therefore, a mesh size of 0.5 m was chosen as it reasonably represents the problem domain. In the analysis of rapid drawdown, four boundary conditions were considered. The downstream toe drain was considered a zero head. The total head at the boundary of the upstream slope was assigned to 10 m. The rate of reservoir drawdown was calculated as a function of time such that it was varied between 1, 2, and 3 m/day. Finally, the potential seepage face boundary at the upstream along the slope face and dam crest.

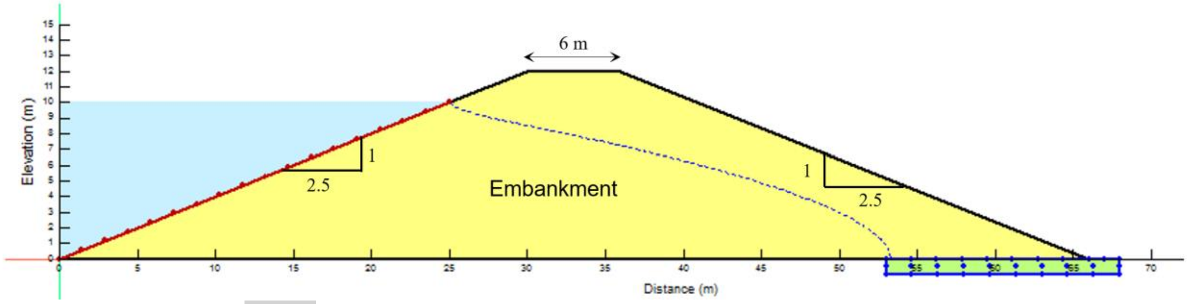


Fig. 1 Cross-Section of Homogenous Embankment Model.

Table 1 Dam Safety Against Safety Regulation Criteria.

Parameter	Homogenous Dam	BDS, 1994 safety limits	USACE safety limits	Dam safety
Upstream slope	1:2.5	1:2.5	1V:2H to 1V:4H	Acceptable
Downstream slope	1:2.5	1:2.5	1V:2H to 1V:2.5H	Acceptable
Crest width	6 m	≥ 2 m	6-12 m	Acceptable
Freeboard	2 m	≥ 1.5 m	≥ 1.5 m	Acceptable

Table 2 Soil Properties of the Dam Sections.

Parameter	Embankment dam	Horizontal drain	Toe drain
Cohesion, C (kPa)	5	1	0
Angle of internal friction, φ (degree)	25	30	35
Density, ɣ (kN/m³)	20	20	20
Coefficient of permeability, k (m/d)	10^{-2}	10	1
Saturated volumetric water content, θ_s	0.4	0.3	0.2
Suction range, ψ (kPa)	0.01-1000	1-400	1-100

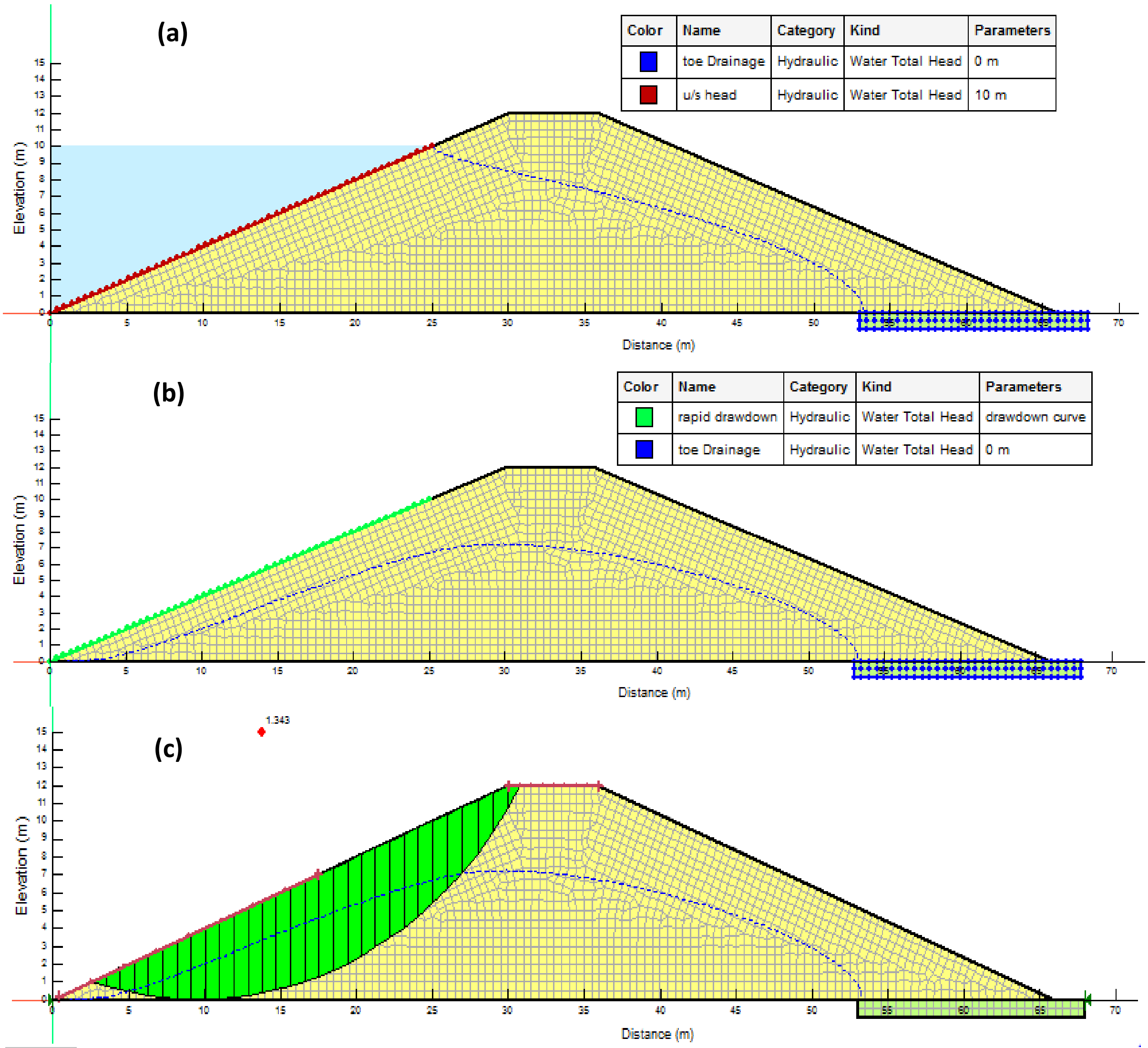


Fig. 2 Generated Mesh with Boundary Conditions of the Embankment Model (a) During Steady-State Analysis, (b) During Rapid Drawdown Analysis, and (c) During Stability Analysis.

3.FINITE ELEMENT FORMULATION

For two-dimensional seepage, the general governing differential equation utilized for modeling the SEEP/W is given in Eq. (1).

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial H}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial H}{\partial y}\right)+Q=\frac{\partial\theta}{\partial t} \qquad (1)$$

where H is the total head, Q is the flow rate, and θ is the volumetric water content. The hydraulic conductivity in the x and y directions is represented by the variables k_x and k_x, respectively. A safety factor is defined as the amount by which the soil mass must be brought into a condition of limiting balance along a selected slip surface, reducing the soil shear strength. The shear strength in terms of effective stress is defined in Eq. (2).

$$S=c'+(\sigma_n-u)tan\emptyset' \qquad (2)$$

where S stands for shear strength, c' stands for soil cohesion, $\emptyset'$ stands for the friction angle, σ_n stands for total normal stress, and u stands for pore water pressure. As part of the stability study, a slip surface is run through the earth's mass and split into vertical slices. The slip surface can be linear, circular, or any other shape, with a series of straight lines forming its shape. The safety factors against failure based on the theory of limit equilibrium of horizontal force and moments can be computed using two independent equations, Eqs. (3) and (4).

$$F_f=\frac{\sum(c'\beta\cos\alpha+(N-u\beta)\tan\phi'\cos\alpha)}{\sum N\sin\alpha+\sum kW-\sum D\cos\omega\mp\sum A} \qquad (3)$$

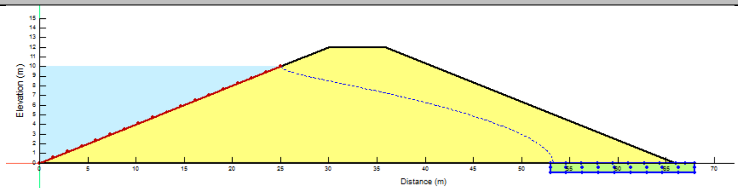
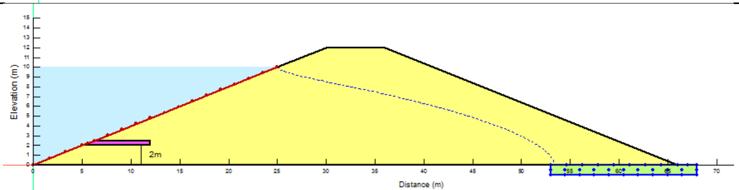
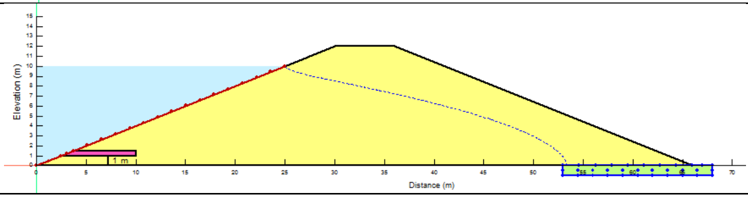
$$F_m=\frac{\sum(c'\beta R+(N-u\beta)R\tan\emptyset')}{\sum W_x-\sum N_f+\sum kWe\mp\sum Dd\mp\sum Aa} \qquad (4)$$

where β, α, and ω are the length of the slice base, the angle formed by the tangent to each slice base center, and the load angle from the horizontal, respectively. W is the slice weight, N is the normal force on the base of the slice, D is an external load, kW is the horizontal seismic load, and R is the radius for a circular slip surface. x and e are the horizontal and vertical distances, respectively, from the centerline of each slice to the center of rotation, d is the vertical distance from a point load to the center of rotation, a is the vertical distance from the resultant external water force to the center of rotation, and A is the resultant external water forces. Spencer [24] developed the concept of employing two equations in safety calculations. The two safety equation elements (force and momentum) were solved by SLOPE/W. Every technique for slicing utilized can be seen as an instance of the General Limit Equilibrium solution. The formulation and solution for General Limit Equilibrium can be used to replicate the majority of commonly used slice methods. Slice techniques can be classified according to the assumptions made about the forces between the slices and the conditions of static equilibrium met. In the Spencer method used in this study, static equilibrium is utilized for the horizontal al, vertical forces, and moments assuming constant slope for calculating resultant inter-slice forces.

4.MODELLING CASE SCENARIOS

Table 3 displays the placement of the horizontal drain and the embankment configurations. In total, thirteen dam cases were examined using various drainage layouts. The parametric study considered the effect of drawdown rate and geotechnical characteristics of the dam material, as given in Table 4, along with the number, vertical spacing, and location of the horizontal drains provided in Table 3.

Table 3 Modeling Dam Cases.

Cases	No. of drains	Location	Spacing	Embankment condition
0	0	-	-	
1	1	Bottom	2 m	
1a	1	Bottom	1 m	

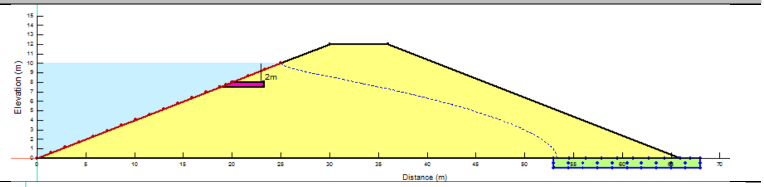
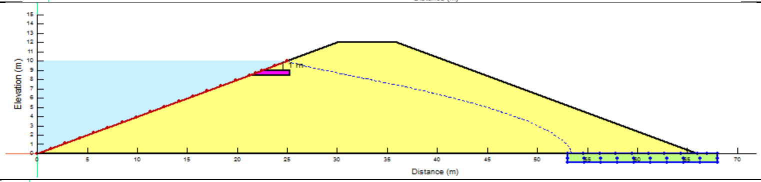
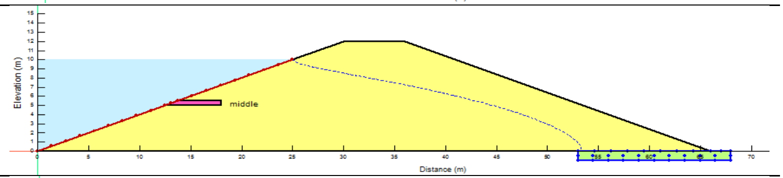
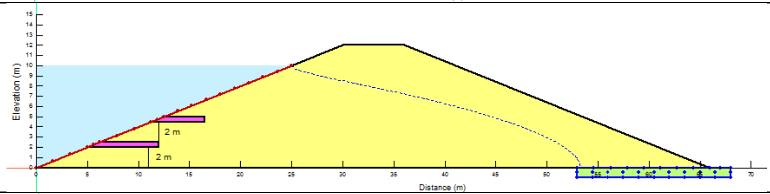
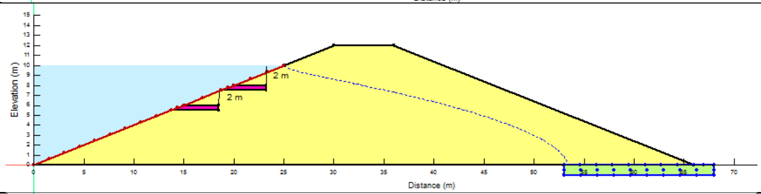
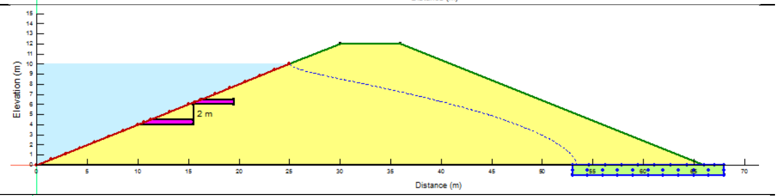
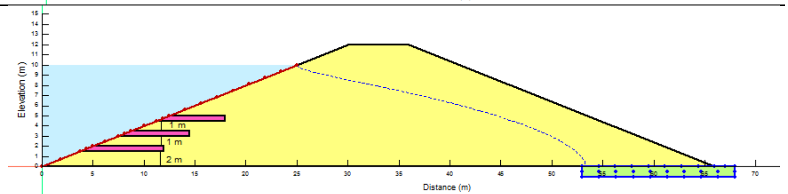
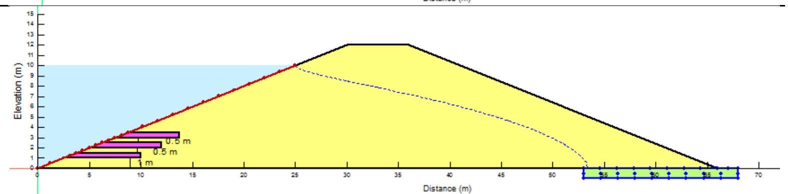
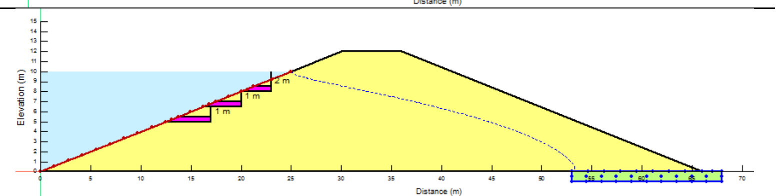
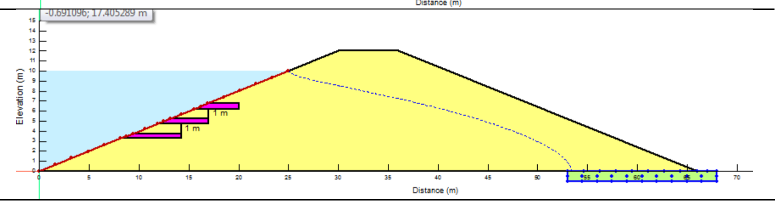
Cases	No. of drains	Location	Spacing	Embankment condition
2	1	Top	2 m	
2a	1	Top	1 m	
3	1	Middle	4.75 m	
4	2	Bottom	2 m	
5	2	Top	2 m	
6	2	Middle	2 m	
7	3	Bottom	1 m	
7a	3	Bottom	0.5 m	
8	3	Top	1 m	
9	3	Middle	1 m	

Table 4 Variables Studied.

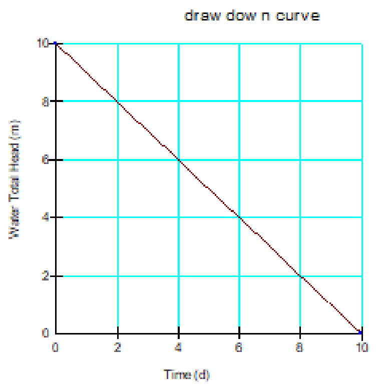
Variables	**Values**		
Drawdown rate, R (m/d)*	1	2	3
Permeability coefficient $K_{embankement}$ (m/d)*	10^{-2}	10^{-3}	10^{-4}
Cohesion, $C_{embankement}$ (kPa)	5	10	20
Friction angle, $Ø_{embankement}$ (°)	15	25	35

5.METHOD OF ANALYSIS

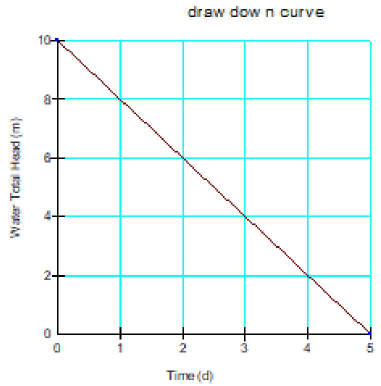
The stability analysis of a typical earth dam was simulated in the present work using GeoStudio computer code (GEO-Slope, 2018) [25]. It examined the dam and its stability mechanism using the SEEP/W and SLOPE/W sub-programs in the product. A numerical model that utilizes the finite element method is the SEEP/W software. The actual physical process of water moving through a particle medium can be numerically simulated. The program discusses the basic steady-state and transient flow laws and demonstrates how these laws are represented numerically. The SLOPE/W software employs various techniques to evaluate the factor of safety of slopes.

Using SEEP/W coupled with SLOPE/W, stability during drawdown was analyzed. The input data were the dam geometry and its material properties. The following steps were followed:

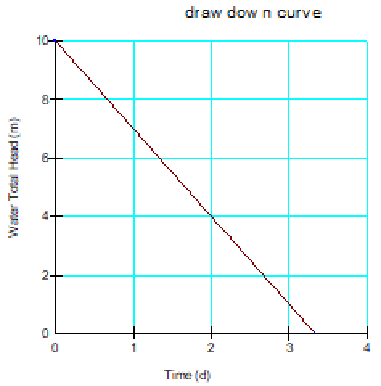
1- SEEP/W initial condition: A steady-state seepage study was conducted after assuming that the water level was 10 m above ground level.
2- SEEP/W transient analysis for rapid drawdown: The reservoir's water level was rapidly lowered by applying various drawdown rates of 1, 2, and 3 m/day, as shown in Figs. 3 (a, b, c), respectively.
3- Upstream stability after rapid drawdown using SLOPE/W: The potential slip surface was calculated using Spencer's (1967) limit equilibrium approach [24]. The Mohr-Coulomb failure criterion was used to describe the shear strength of the dam material, and the upstream slope safety factor was computed.



(a) R = 1 m/d



(b) R = 2 m/d



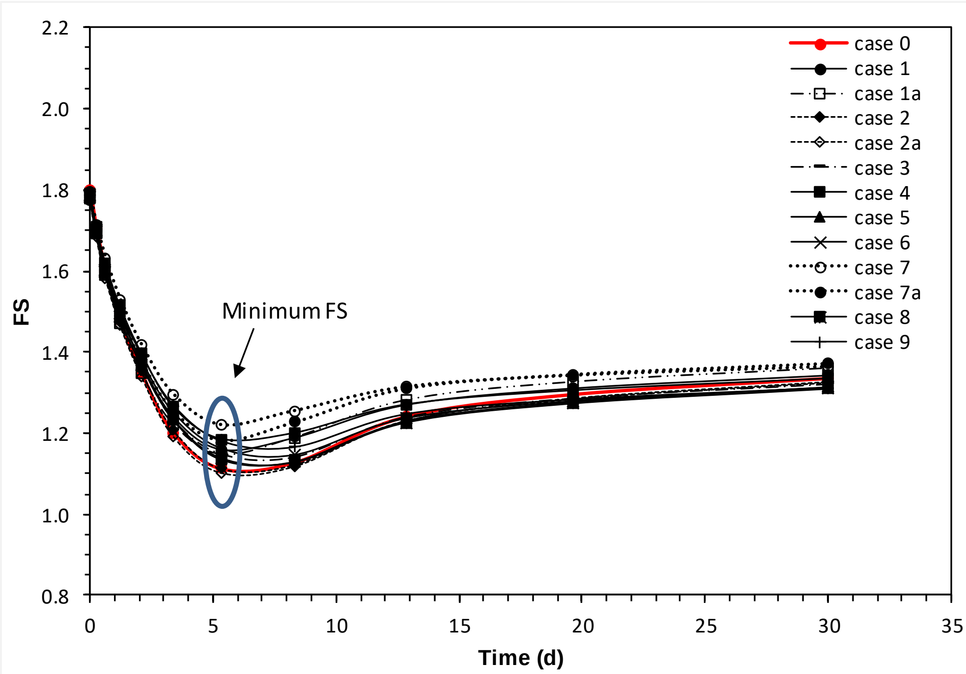
(c) R = 3 m/d

Fig. 3 Rapid Drawdown Curve Function at Different Rates (R) of (a) 1 m/d, (b) 2 m/d, and (c) 3 m/d.

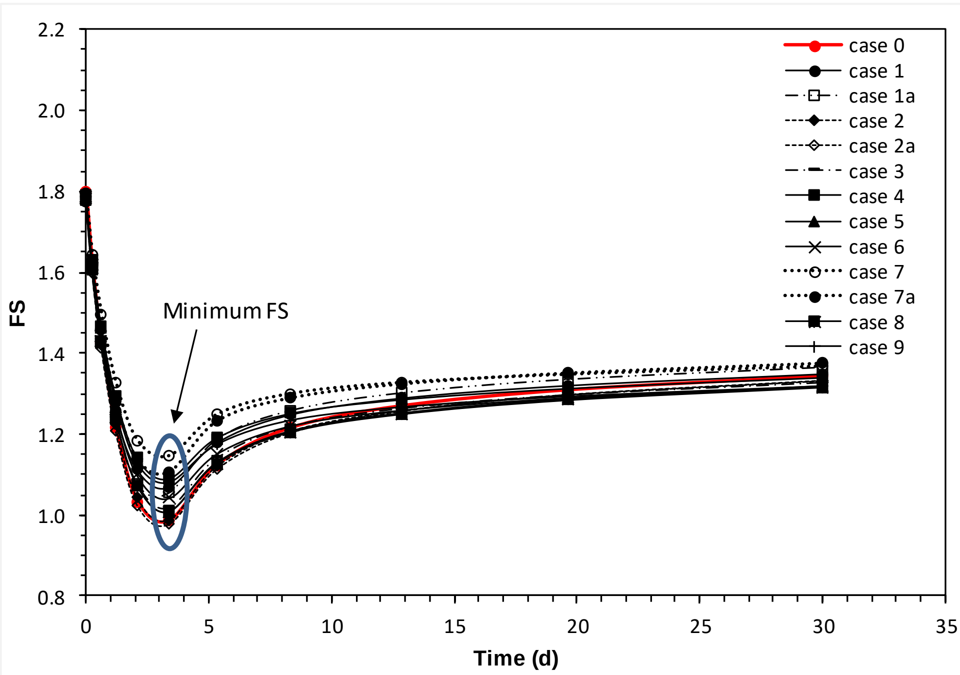
6.RESULTS

6.1.Effect of Drawdown Rate

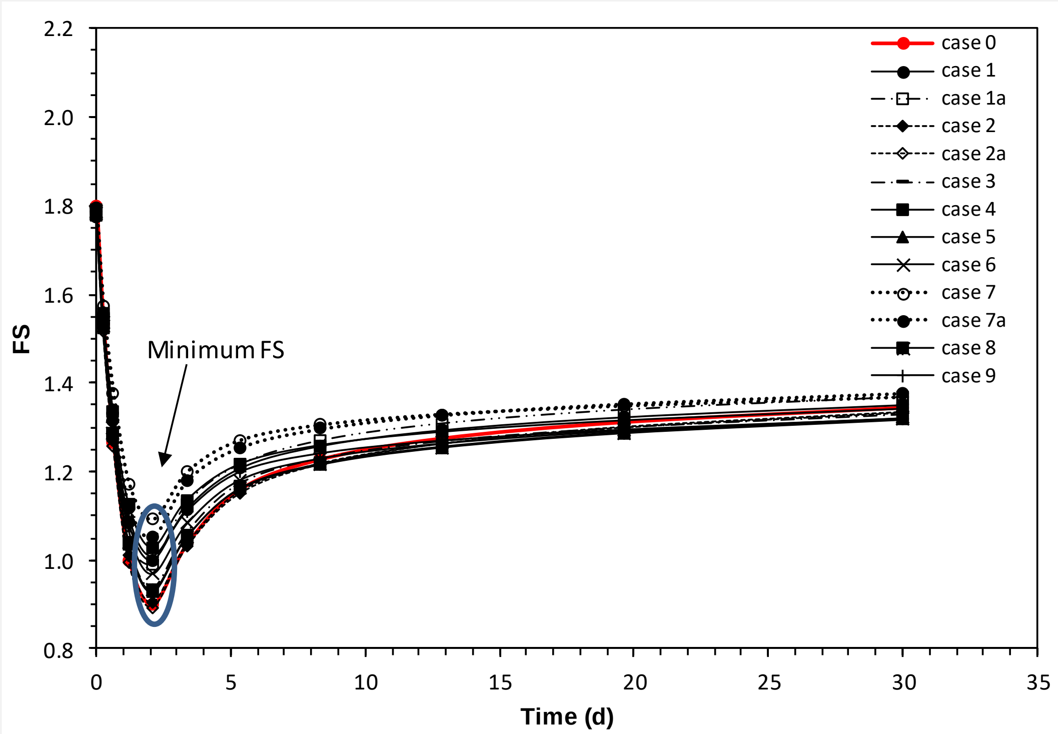
Figures 4 (a, b, c) present the slope stability analysis results in terms of the changes in the factor of safety with time for the homogenous embankment dam cases under rapid drawdown at 1, 2, and 3 m per day, respectively. For all dam cases, the factor of safety (FS) initially decreased after the reservoir drawdown up to minimum values. Such reduction resulted from the slow dissipation of the pore water pressure after the drawdown. As the pore water pressures in the embankment kept dropping, the FS gradually started to restore stability. The factor of safety value attained a nearly constant value of about 1.3 for the 30 days of analysis. Minimum FS values were reached after a few days of the rapid drawdown and before the complete emptying of the dam reservoir. It was also observed that as the time elapsed after commencing the drawdown at higher rates, the reduction in the safety factors was faster. Figure 5 presents the variation in the pore water pressure versus time discussed above as evidence of the changes that occurred when the reservoir was emptied under a sudden drawdown of 2 m/d rates at critical points 1 to 4. The results indicated that the pore water pressure decreased with time, especially after the start of the drawdown. A similar trend was obtained by [26]. It should be noted that the discussion of the results considers the minimum factor of safety as it represents the least value attained in response to the rapid drawdown condition, which might critically influence dam safety. The potential risk of a dam failure occurs when the FS is less than 1 [27]. Figures 6 (a, b, c) illustrate the minimum factor of safety values obtained for all the dam configurations considered in the present study at 1, 2, and 3 drawdown rates, respectively. The results revealed that the dam without horizontal drains was safe ($FS \geq 1$) at a 1 m/d drawdown rate. It can be, however, observed that faster drawdown of the reservoir subjected the embankment to a potential failure as the FS was below 1, revealing further that for such dam properties, the drawdown rate should not be more than 1 m per day. Otherwise, stability improvement of the upstream slope is needed. The present study found that to ensure slope stability at 2 m/d drawdown, at least one upstream drain placed at the bottom is needed, while a minimum of 2 bottom drains would be sufficient at 3 m/d.



(a)

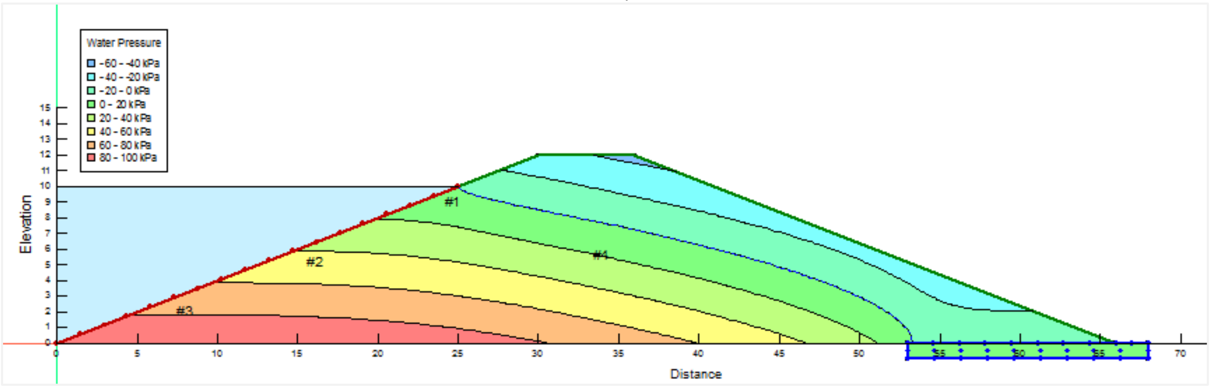


(b)



(c)

Fig. 4 Safety Factors Variation with Time after Rapid Drawdown Rates of (a) 1 m/d, (b) 2 m/d, and (c) 3 m/d.



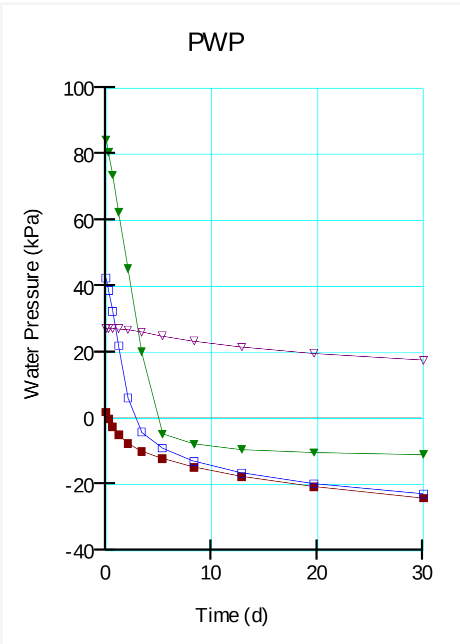
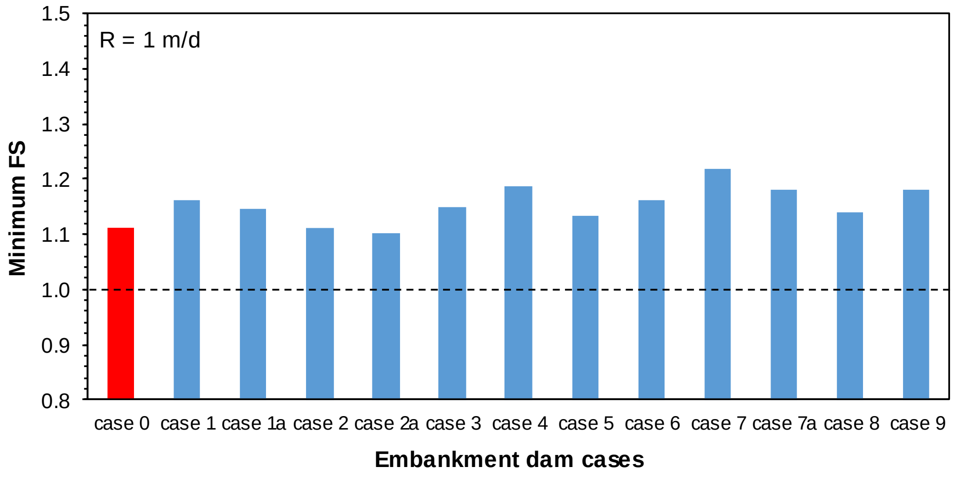
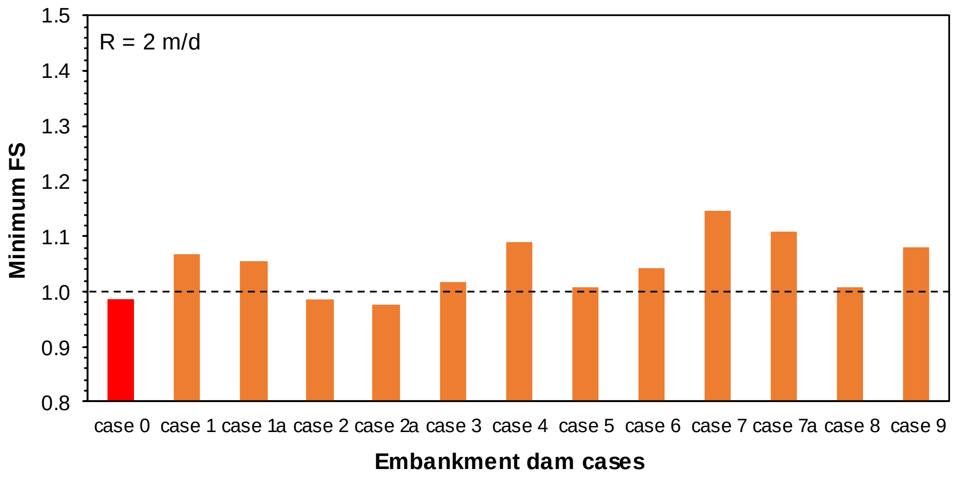


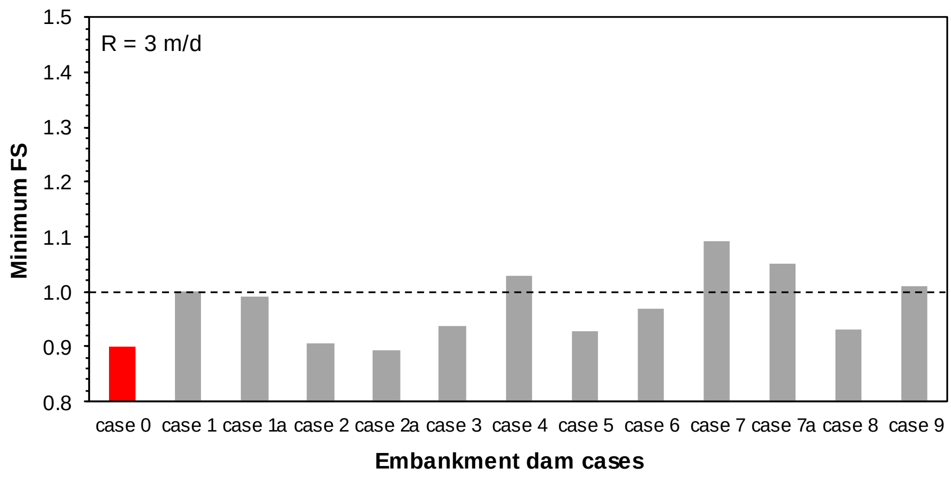
Fig. 5 Pore-Water Pressure Changes with Time during R = 2 m/d at points 1 to 4.



(a)



(b)



(c)

Fig. 6 Minimum Values of the Safety Factors for Different Dam Configurations at Drawdown Rates of (a) 1 m/d, (b) 2 m/d, and (c) 3 m/d.

Although the dam body subjected to rapid drawdown of 1 m per day was stable, installing horizontal drains increased the stability further. At a 1 m/d drawdown rate (Fig. 6(a)), the greater number of horizontal drains produced higher safety factor values. The best performance in terms of slope stability was noticed in case 7 when the dam was enhanced with three drains located at the bottom with a spacing of 1 m. At a 2 m/d rate of drawdown (Fig. 6 (b)), a solution offered to increase the dam safety was installing horizontal drains. The drains applied on the embankment's upstream side considerably increased the dam safety except for cases 2 and 2a (1 drain at the top with a spacing of 2 and 1 m, respectively). By increasing the number of drains, slopes became more stable. Compared to the dam without drains (case 0), the highest increases in the minimum safety factor values in the case of adding one, two, and three drains were by 7%, 9%, and 15%, respectively. At a 3 m/d drawdown rate (Fig. 6(c)), installing one or two drains in the upstream slope of earth dams had no or little (case 4) effect on the slope stability. Three drains added at the bottom of the upstream slope showed a better response in transferring the dam from unsafe to safe by about a 9% improvement. Such results suggest that more drains should be applied to further improve safety.

6.1.1.Effect of Drain Location

Figure 7 presents the effect of drain location on the dam's stability. The results showed that the optimum location for a horizontal drain was at the bottom of the upstream slope. The slope stability analysis results at other drawdown rates (i.e., 2 and 3 m/d) further support that bottom drains were the most effective at allowing water drainage and preserving the slope stability. However, they were not included to prevent repetition. A similar finding was also reported by [15, 16].

6.1.2.Effect of Spacing between Drains

Reducing the space between the horizontal drains from 1 m (case 7) to 0.5 m (case 7a) inversely impacted the dam safety by a reduction of 5% in the safety factor when the reservoir rapidly drained at 3 m/d. This observation can be attributed to the amount of water discharged from the surrounding area of the drains, as evidenced by the measured rate of flow shown in Figs. 8 (a, b, c) for comparison, water flux in case 7 and case 7a, respectively. Similar observation was also achieved for 1 and 2 rates of drawdown.

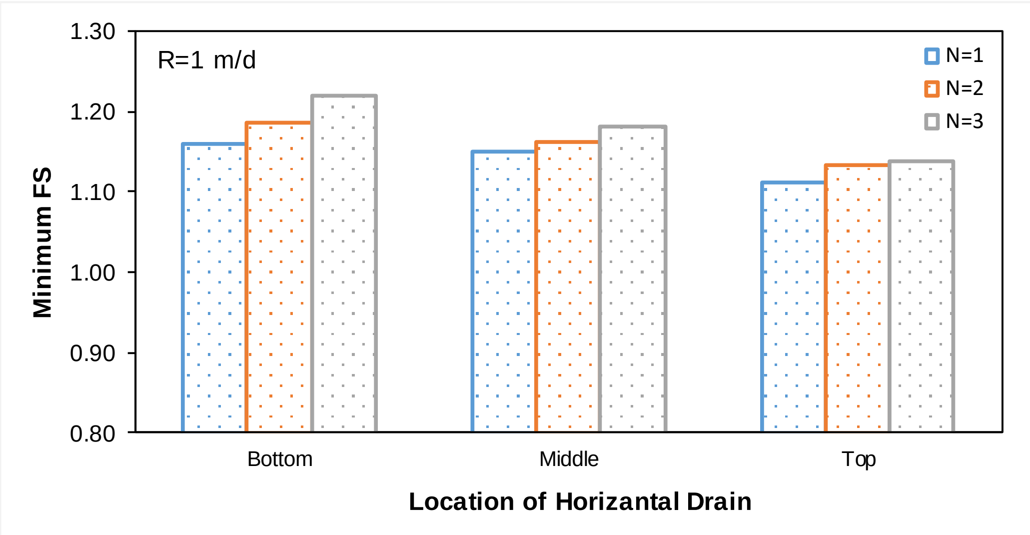
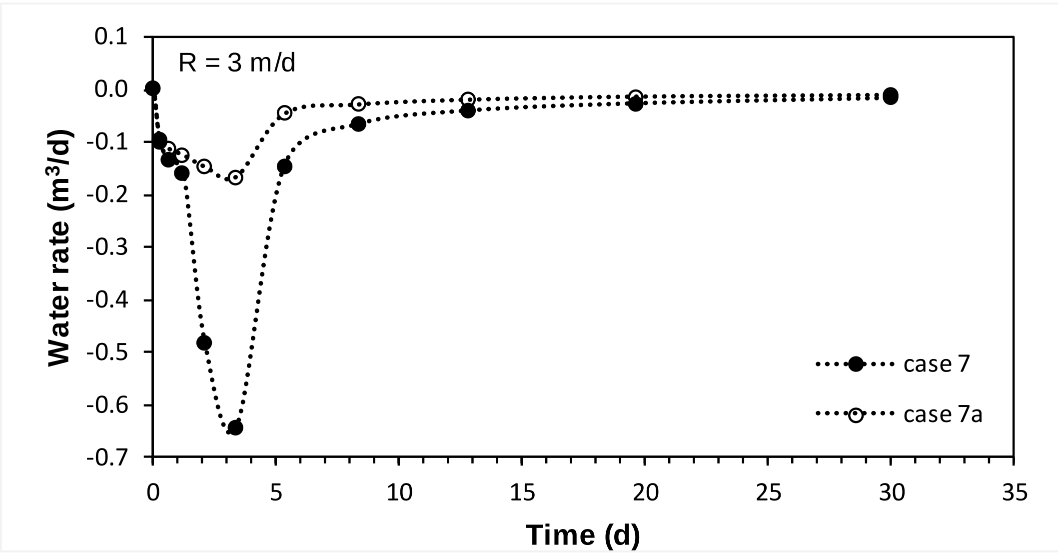
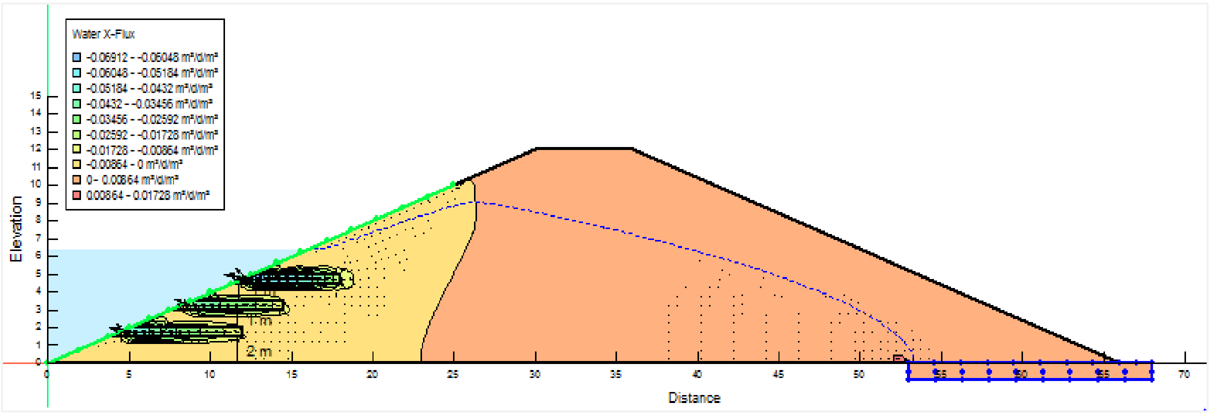


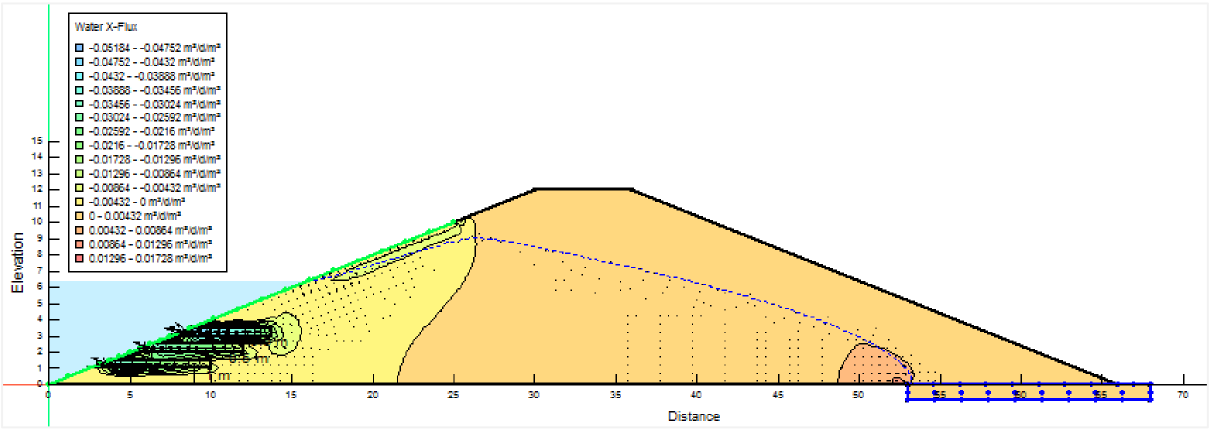
Fig. 7 Effect of the Horizontal Drain Location on the Dam Safety.



(a)



(b)



(c)

Fig. 8 Seepage Through the Upstream Drains (a) Water Flow Rate with Time for Cases 7 and 7a, (b) Water Flux for Case 7, and (c) Water Flux for Case 7a.

The performance of the installed horizontal drains was also evaluated in terms of the percentage of improvement in the safety factor, as given in Eq. (5). Figure 9 shows the percentage increase in FS versus the dam cases. Generally, horizontal drains in the upstream slope improved the dam's safety. The results of the slope stability assessment indicated that dam case 7 (3 drains at the bottom) produced the best-case scenario in the FS compared to the other cases. By increasing the number of horizontal drains, the safety factor increased by a maximum value of about 20%.

$$FS\ (percentage\ of\ improvement\ \%) = \frac{FS_{dam\ with\ horizontal\ drain} - FS_{reference\ dam}}{FS_{reference\ dam}} \times 100 \qquad (5)$$

where reference dam represents a dam without horizontal drain.

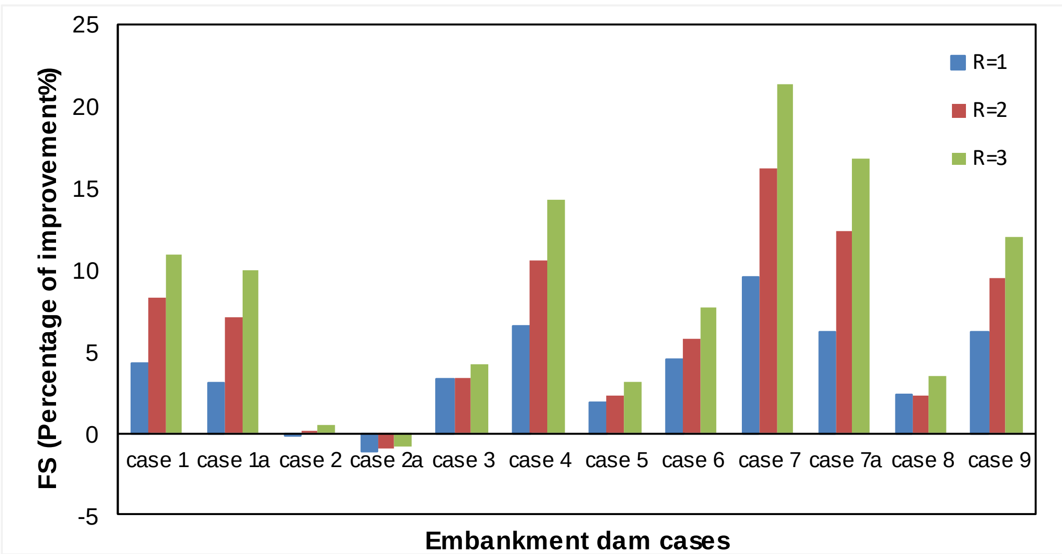


Fig. 9 Improvement in Safety Factors for Different Dam Configurations at Various Drawdown Rates.

6.2.Effect of Permeability of Embankments

Figure 10 illustrates a comparison of the safety factor values obtained for different saturated embankment permeability; namely, k= (0.01, 0.001., and 0.0001) m/d, corresponding to a considerably partially draining material and an impervious shell (generally a mix of clay, silt, sand, and gravel), considering a constant drawdown rate of 1 m/d for all cases. The results were analyzed for case 7, which previously evidenced the best performance regarding the safety factor against slope failure. Installing three horizontal drains in the bottom of the upstream shell of the dam one meter apart from each other increased the safety further. However, for the cases of low dam permeability, the embankments were unsafe ($FS < 1$). Thus, the applied drawdown was not allowed for these kinds of soils. From Figs. 10 and 11, it can be noticed that for the impervious shell (k= 0.001 and 0.0001) m/d, the improvement of the safety factor was more considerable than that for partially draining materials (k= 0.01) m/d, which may be attributed to the fact that providing horizontal drains to the embankment of impervious material helps raise the seepage rate out of the dam, thus becoming more beneficial than being in well-drained materials. By considering the less vertical distance between horizontal drains (case 7a), the upstream slope stability improved, especially for the case with k=0.0001 m/d, in which the safety factor slightly increased (Fig. 13). On the other hand, the case with k=0.001 m/d showed no improvement in safety factor (Fig. 12). Although, both cases where unsafe, however, this finding is practically interesting and need further analysis to provide insight of how to decide the value of the vertical distance between drains considering the value of embankment permeability to gain optimum use of these drains.

6.3 Effect of strength parameters

Figures 14 (a , b) show the changes in the minimal factor of safety for some dam cases in response to changes in the shear strength properties of the embankment at a 1 m/d drawdown rate. Increasing the cohesion parameter from 5 kPa to 20 kPa produced a more stable embankment with an improvement of about 59% in the safety factor (Fig. 14(a)). Using upstream drains further enhanced the stability by increasing values of the safety factor with an increased number of drains. Similarly, varying the friction angle to higher values increased the safety factor linearly. The improvement percentage in the safety factor obtained at a 35° friction angle was about 106% over that obtained from 15°. Notably, the horizontal drains improved slope stability at a higher friction angle of 35°, as shown in Fig. 14 (b).

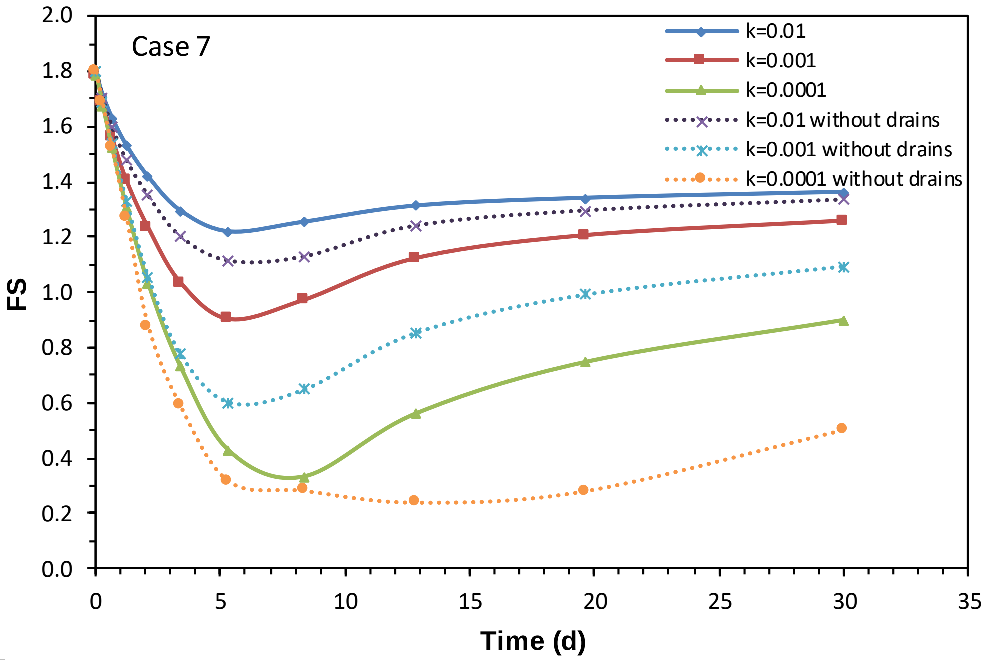


Fig. 10 Safety Factors Variation with Elapsed Time After Rapid Drawdown Rates of R= 1 m/d for Different Embankment Permeability for (Case 7).

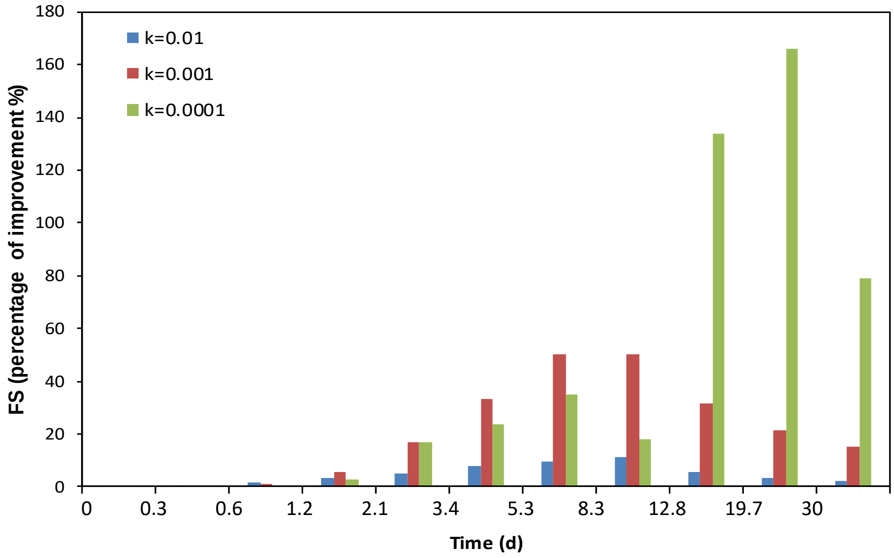


Fig 11 Improvement in Safety Factors for Different Embankment Permeability for (Case 7) with R=1 m/d.

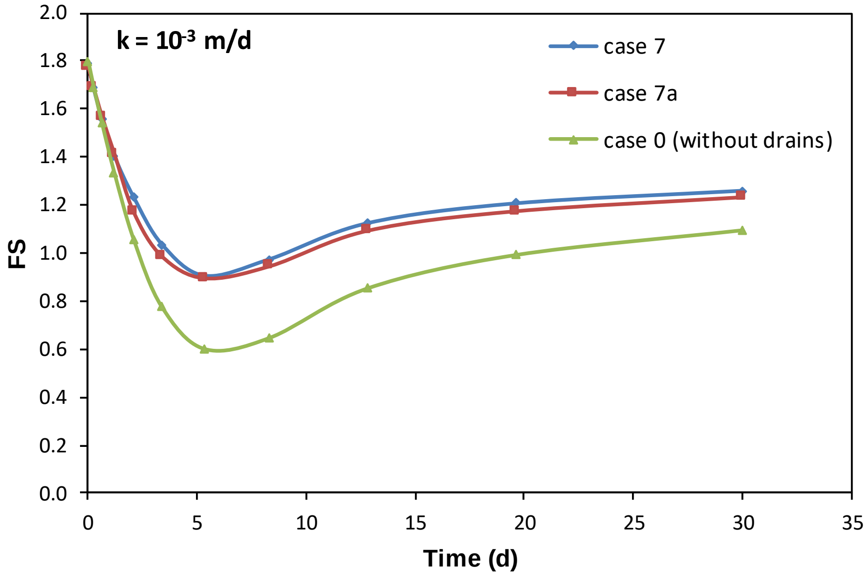


Fig. 12 Comparison of Safety Factors Variation with Elapsed Time After Rapid Drawdown Rates of R= 1 m/d for Cases 7 and 7a with $K_{embankment}$=0.001 m/d.

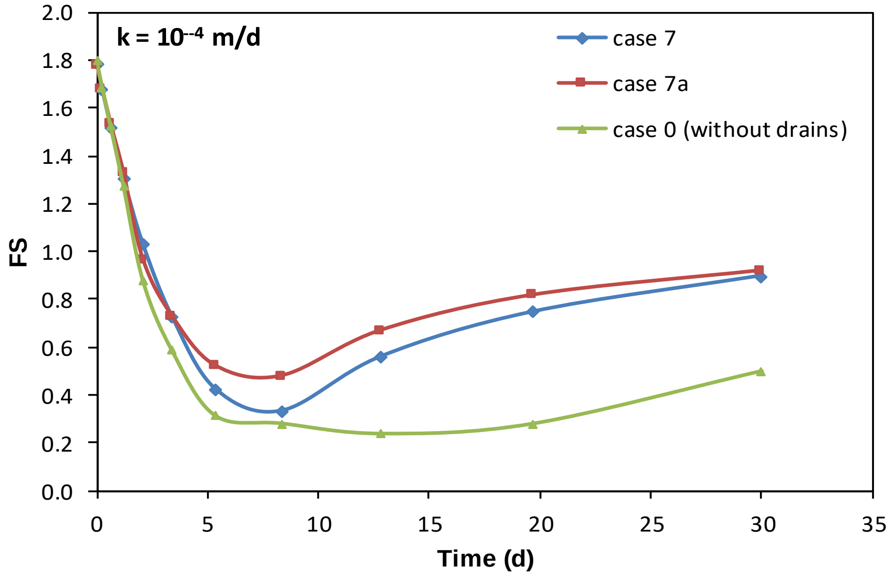
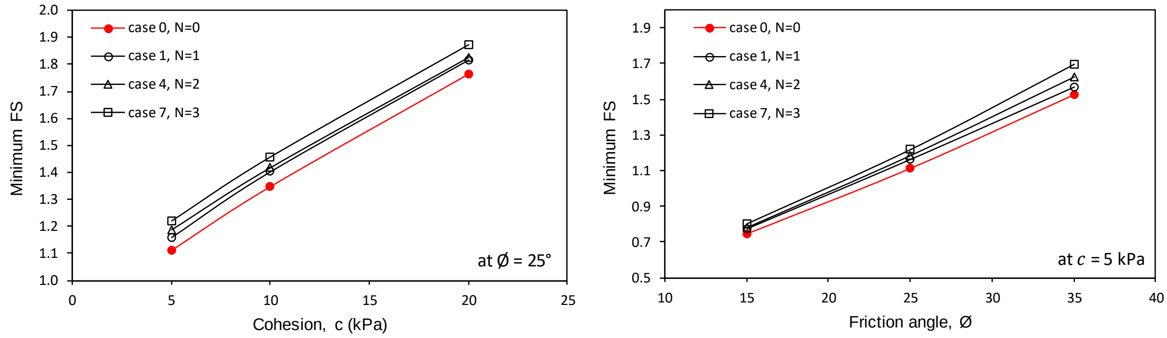


Fig. 13 Comparison of Safety Factors Variation with Elapsed Time After Rapid Drawdown Rates of R= 1 m/d for Cases 7 and 7a with $K_{embankment}$=0.0001 m/d.



(a) **(b)**

Fig. 14 Variation in Minimal Safety Factors with Strength Properties, (a) Cohesion and (b) Friction Angle.

6.4.Seepage

Figure 15 presents the seepage rate out of the dam through the upstream shell during the rapid drawdown of 1 m/d. It was found that the upstream seepage outflow increased when horizontal drains were installed. Generally, with each increase in the number of horizontal drains, the maximum seepage was raised by about 0.1 m^3/d. The peak seepage rate was recorded in dam case 7 (3 drains at the bottom 1 m apart) with a 1.95 increment ratio compared to the dam with no horizontal drains (case 0). Note that the maximum discharge in each dam case occurred after a certain elapsed time since applying the rapid drawdown, which differs from other cases, and this can be related to the number and location of the drains. Figure 16 displays the amount of seepage through the dam for a long-term condition (10 years). The transient analysis revealed that seepage increments of 0.02%, 0.16%, and 0.41% occurred with applying one, two, and three horizontal drains, respectively. This observation indicates that horizontal drains minorly affected seepage through the dam, even in the long-term scenario.

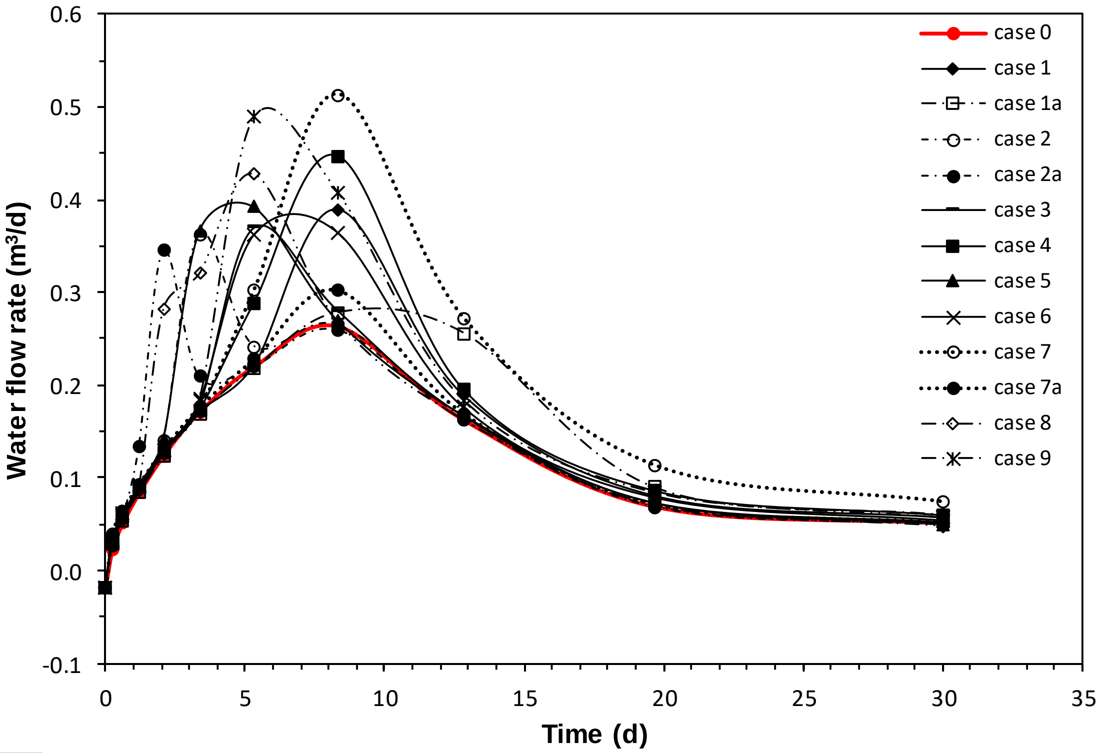


Fig. 15 Changes in Flow Rate through the Upstream Slope with Time for all Dam Cases at R= 1 m/d.

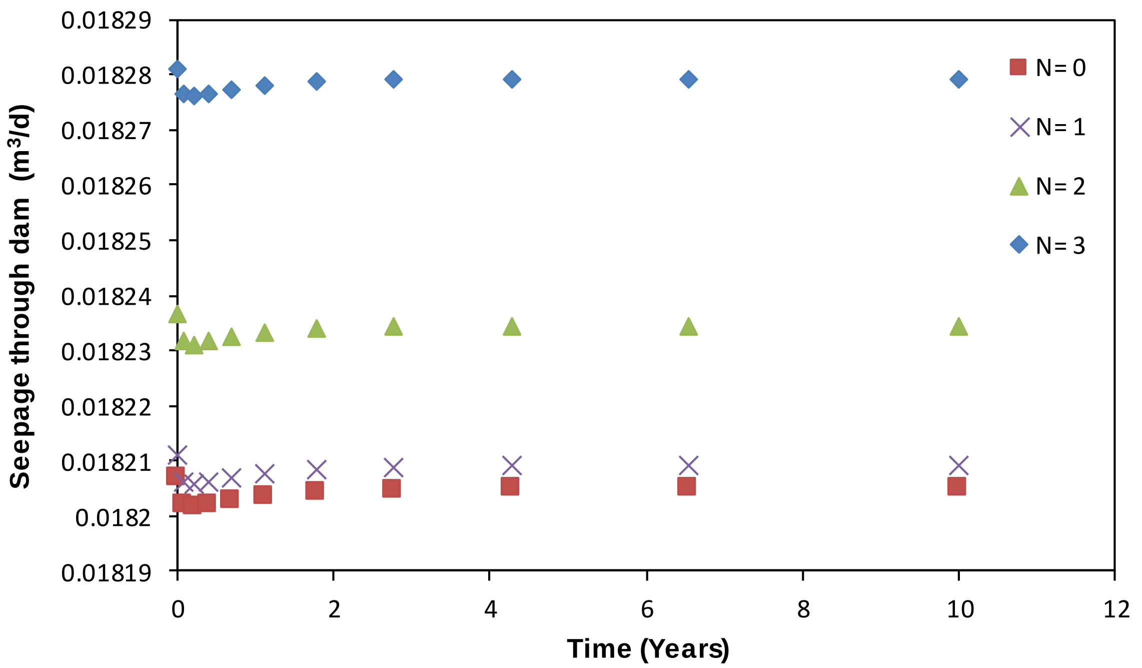


Fig. 16 Discharge Through Dam Bodies for Long Term Conditions at Varied Number of Drains.

6.CONCLUSION

Numerical stability analyses are conducted for the upstream slope of a homogenous embankment dam during sudden drawdown conditions via a Finite Element-based program named GeoStudio. The potential effect of drawdown rate and material characteristics on the stability performance of the embankment enhanced with horizontal drains and subjected to rapid drawdown conditions was investigated. The following outcomes were drawn from this study:

1- For the embankment permeability of 10^{-2} m/d subjected to a drawdown rate of 1 m/d, the safety factors were more than the minimum allowable value of 1. Thus, drains are not needed in the upstream slope. However, for the drawdown rate of 2 m/d, at least one horizontal drain should be present to achieve the minimum permissible safety factor, and two horizontal drains were required for a drawdown rate of 3 m/d.

2- Three drains at the bottom portion of the embankment with a vertical spacing of 1 m significantly influenced the upstream slope's safety factor during the rapid drawdown.

3- The minimal safety factor values increased by 9% and 15%, respectively, when two and three drains were added for the drawdown rate of 2 m/d and by 9% for the drawdown rate of 3 m/d.

4- In the case of low embankment permeability, the presence of three horizontal drains improved the factor of safety by up to 50% and 158 % for 10^{-3} m/d and 10^{-4} m/d permeability, respectively, at the drawdown rate of 1 m/d. As a result, the relative importance of the horizontal drains depends on the soil conditions. Although the cases used in this part of the analysis are unsafe, this finding is practically interesting and needs further analysis.

5- The study further supports the dependency of slope stability on the combined factors of drawdown rate and soil properties of embankments. Therefore, these phenomena need to be properly examined and considered during the design phase of an embankment dam.

6- Horizontal drains increased seepage from the upstream and through the dam. The rise in the flow rate was proportional to the number of installed drains.

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NOMENCLATURE

L/H	Drawdown ratio
L	Water depth after the drawdown, m
H	Height of the dam, m
R	Rapid drawdown rate, m/d
C	Cohesion, kPa
φ	Angle of internal friction, degree
γ	Density, kN/m³
k	Coefficient of permeability, m/d
θ_s	Saturated volumetric water content
ψ	Suction, kPa
FS	Factor of safety
N	Number of horizontal drains

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