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THE POTENTIAL EFFECTS CAUSED BY LONG-TERM WATER LEVEL CHANGES ON EMBANKMENT SLOPE STABILITY UNDER RAPID DRAWDOWN

Abstract. *The stability of embankment dams can be affected by many factors including the extent of long-term steady-state water level. Unfortunately, analysis of such a problem in-situ cannot be easily achieved due to time constraints and the complexity of the influencing factors. This study investigated the potential influence of changes in long-term water level on slope stability of an embankment when subjected to a rapid drawdown using numerical modeling. Three different water levels were investigated (10m, 8m, and 6m). To avoid variability and capture the effect of the long-term water level, the geometry of the reservoir was kept constant.*

Keywords: *numerical modeling, slope stability, embankment, water level, factor of safety.*

Introduction

Dams are structures built across a stream, a river, or an estuary to either detain or retain water. Earth-fill dams, also well known as embankment dams are among the many other types of dams in the world that are constructed by compacting successive layers of the earth [1]. Normally, earth-fill dams are built with the most impervious materials to form a core and place more permeable substances on the upstream and downstream faces [2,3]. Among many other purposes, dams are constructed to supply water for human consumption such as drinking, irrigating, or for use in industrial production processes [4]. However, disasters due to large dams are a concern in many countries, due to the significantly high economic and social consequences associated with the failures [5]. There are already many cases of dam failures in the world, such as the San Luis Dam upstream slope failure in 1981 in California, USA [6].

Normally, engineers try their best to apply different techniques as a way assuring that the risk of a slope failure is relatively low when designing an earth-fill dam [7, 8]. However, the regulations and standards differ from country to country, which means are highly dependent on the region where the dam is located. It has been observed that it is always important to recalculate the associated risk even in a low-risk situation because the standards and regulations, as well as the dam and catchment characteristics, may change with time affecting the category of the previously calculated risk [9].

Failure of an earth-fill dam can be highly influenced by the soil material properties and loading conditions [10, 11]. The maximum initial water level in an earth-fill dam that has established a long-term steady-state can pose a significant threat to its slope stability if the dam has to be drawn rapidly. A steady state in a reservoir is reached when an earth embankment has fairly retained constant water surface elevation for a long period [12]. Also, during this period the seepage and pore water pressure conditions within the embankment have the potential to reach a steady state.

In general, seepage pressures can also be written as Seepage force (*J*), which is the force applied by the flowing water to the soil structure. As it is well-known that force is equal to pressure multiplied by area. Therefore, seepage force is equal to seepage pressure multiplied by the area of the soil sample (A) [13].

$$J = iL\gamma_w A \tag{1}$$

But seepage force is usually expressed as force per unit volume (j).

$$j = \frac{iL\gamma_w A}{AL} = i\gamma_w \tag{2}$$

where: I – Hydraulic gradient; L – Length of the soil sample; γ_w – Unit weight of water.

The long-term reservoir operating water level can be defined as the height of water maintained in the reservoir for a long period that also establishes a long-term steady-state in the reservoir [14]. Many factors may lead to long-term water level fluctuations in dams including climatic land use/land surface cover changes that affect the hydrological pattern of a catchment with time [15,16]. When the water in the reservoir is drawn rapidly the long-term steady-state pore-water pressures developed within the embankment remain relatively high while the stabilizing effect due to the reservoir's weight along the upstream side of the embankment is removed leading to instability of the upstream face of the embankment [17]. However, the information about the potential response of an earth-fill dam when subjected to a rapid drawdown concerning different long-term water levels is still scarce. Therefore, investigation of a dam response to different maximum water levels subjected to a rapid drawdown is of great importance. SEEP/W and SLOPE/W units of the GeoStudio can be used to analyze such a scenario [18–20].

In this study, the potential effect of the initial maximum water level on the slope stability of an earth-fill dam is investigated. The numerical simulation in this study is achieved using the combination of SEEP/W and SLOPE/W sub-units of the GeoStudio software. SEEP/W is used for the seepage analysis while the SLOPE/W is used for slope stability analysis. Generally, three different maximum water levels (10m, 8m, and 6m) for a 65m high embankment are used to investigate the problem. To avoid variability and capture the effect of the initial maximum water level, the geometry of the reservoir is kept constant in all three study sessions.

Materials and methods

General description of the numerical simulation. To investigate the influence of a rapid drawdown on the slopes, FEM analyses were performed for three different cases as determined by the initial maximum water levels (Table 1). The modeling process in this study was achieved using the GeoStudio software packages (GeoStudio 2018 R2 v9.1.1.16749). Mainly SEEP/W and SLOPE/W sub-units were used for the seepage analysis and slope stability analysis respectively.

Table 1 – General cases of the investigation

Study	Maximum water level (m)	Freeboard (m)
Case I	10	3
Case II	8	5
Case III	6	7

Embankment geometry. The geometry of the embankment was kept constant in all three main investigations while changing initial maximum water levels in the reservoir. The embankment width was approximately 59 m wide at the base and 7 m at the top and 13 m high (Figure 1). Also, the embankment was provided with a toe drain to prevent water from exiting along the downstream slope face. The heads in the reservoir before drawdown were 10 m, 8 m, and 6 m.

To simulate the toe drain, a zero-pressure head boundary condition was applied to the toe drain region. The results from steady-state Parent Analysis were used as the initial conditions for the Instantaneous drawdown, and the 5-day drawdown.

The top width is an important parameter when designing an earthen dam and is a function of its height. Normally, the minimum top width should be designed in such a way that it can provide a safe percolation gradient at full reservoir operating conditions. In this study, the maximum water level in the reservoir was 10 m making the minimum required top width of the embankment being 5.6, where 7 m were adopted for the crest width. Equation 1 provides a summary of the formula used in the estimation of the minimum top width of the study embankment.

$$W = 1.65(H + 1.5)^{\frac{1}{2}} \quad (3)$$

where: W – Top width of the dam, m; H – Height of the dam, m.

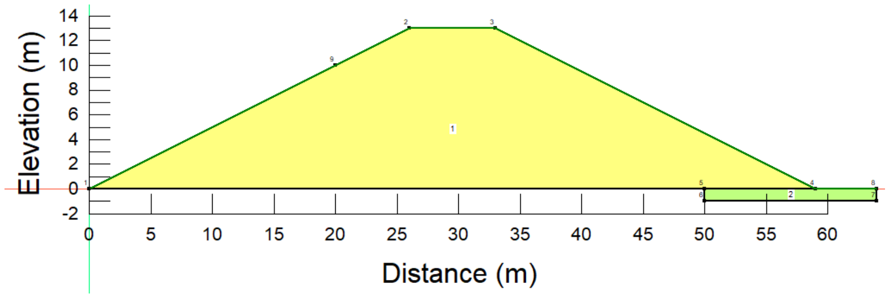


Figure 1 – General embankment geometry used in the numerical modeling [author's material]

Seepage analysis. The SEEP/W water transfer analysis was used to evaluate changing pore-water pressure conditions after the reservoir has been drained. It was in the interest of this study to investigate the worst case where the reservoir is drained instantaneously. However, more realistically, the reservoir was drained over 5 days (Figure 2). In the simulation of drawdown behavior of a slope, initially, a transient seepage analysis is performed to obtain seepage-induced pore pressures and free groundwater surface for different drawdown rates and at various drawdown ratios. In these analyses, two different slope heights, and two isotropic hydraulic conductivity values were considered. To model variation of water level during the drawdown, linearly variable groundwater heads with time were specified as the boundary condition in the transient seepage analysis. The calculated groundwater flow parameters (hydraulic heads, pore pressures, flow rates, etc.) were later used in the deformation analysis.

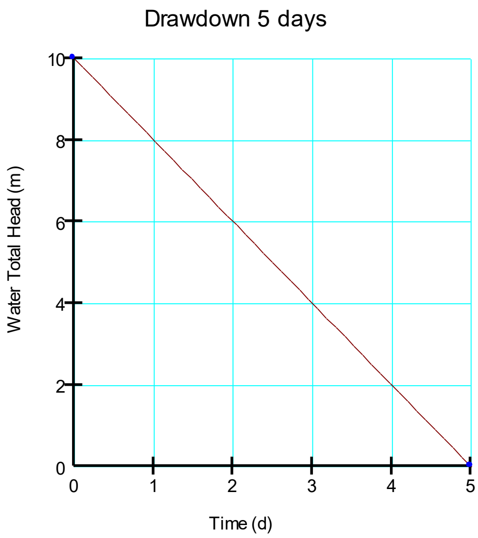


Figure 2 – Water total head function [author's material]

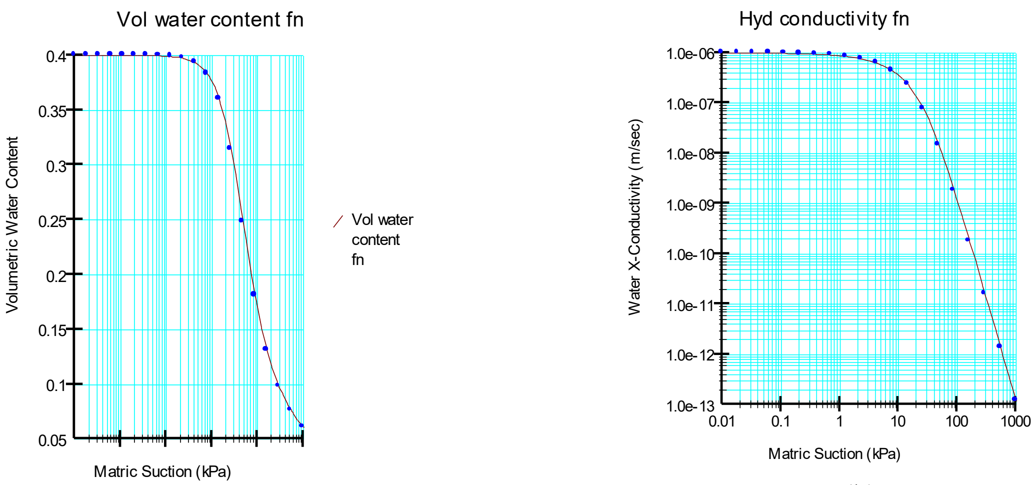
Slope stability analysis. The stability analysis was performed using the SLOPE/W unit of the GeoStudio with the help of the Spencer method. In the slope stability analysis, it is termed that, if the forces that resist the embankment movement are greater than those driving the movement, then the embankment slope is considered stable. Normally, a factor of safety (FS) is an important parameter when analyzing slope stability and is calculated by dividing the resistance by the driving forces. In this case, a factor of safety greater than 1 suggests that the slope is stable. The Spencer method used in this study allows for unconstrained slip plains and in that matter can determine the FS along any slip surface. In the literature, it has been observed that the rigid equilibrium and unconstrained slip surface result in more precise safety factors than the other methods [21].

Soil material characteristics. The embankment investigated in this study is assumed to be homogeneous in terms of soil characteristics. Also, the soil material properties for the embankment were kept constant for all three study sessions to avoid any variability in the results that are not influenced by the differences in initial maximum water levels. Table 2 provides a summary of the main soil material properties used in this study. Soil samples were investigated for parameters such as saturated water content, coefficient of compressibility, saturated conductivity, residual water content, soil unit weight, cohesion, internal friction angle, Young's modulus as well as Poisson's ratio as important inputs to the model.

Table 2 – Soil properties

Soil material properties	Symbol	Unit	Value
Saturated water content	θ_s	%	43
Coefficient of volume compressibility	M_v	m^2/kN	2×10^{-4}
Saturated conductivity	K_{sat}	m/s	1×10^{-6}
Residual water content	θ_r	%	5.5
Soil unit weight	γ	kN/m^3	20
Cohesion	c'	kN/m^2	5
Internal friction angle	$\emptyset'$	degrees	25

Under saturated/unsaturated scenarios, the volumetric water content and hydraulic conductivity functions were important inputs defining the soil characteristics in the model (Figure 3). This was achieved using built-in functions that required only fundamental information such as saturated hydraulic conductivity, water content, and coefficient of volume compressibility.



(a) (b)

Figure 3 – Functions: a) Volumetric water content;
b) Hydraulic conductivity function [author's material]

Results and discussion

Seepage analysis. Seepage analysis was conducted for the steady-state, instantaneous, and 5 days drawdowns for all three water levels and the pore-water pressures from the seepage analysis were then used as inputs to the slope stability analyses.

Seepage analysis results from 10 m water level. The long-term steady-state analysis was successfully performed. Figure 4a shows the long-term, steady-state conditions established in the reservoir from the 10m long-term water level, while Figure 4b and Figure 4c show phreatic lines after the instantaneous and 5 days drawdown respectively. It can be observed that the design of the embankment allows for most of the seepage water to be collected in the toe drain downstream. From the piezometric lines, it can be observed that, after the two rapid drawdown scenarios (instantaneous and 5 days), water stored within the embankment gradually drains from areas of high pore-water pressure [22]. This means the position of the piezometric line changes overtime during the drawdown process as shown in Figure 4, with the seepage face also reducing as the water goes down. It is of significant necessity that seepage through the embankment is controlled and safely carried away to prevent instability of the downstream slope [23]. Therefore, the phreatic line should not intersect the downstream slope and the design should be in such a way that the line is a distance greater than capillary rise below the downstream sloping face to eliminate the chances of the sloughing or piping [24].

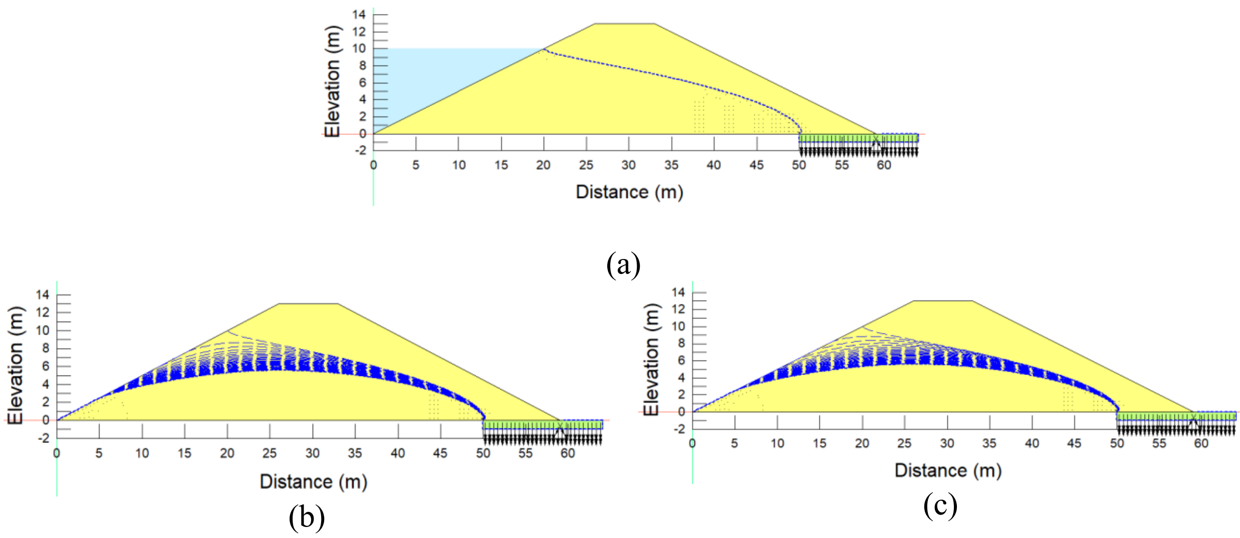
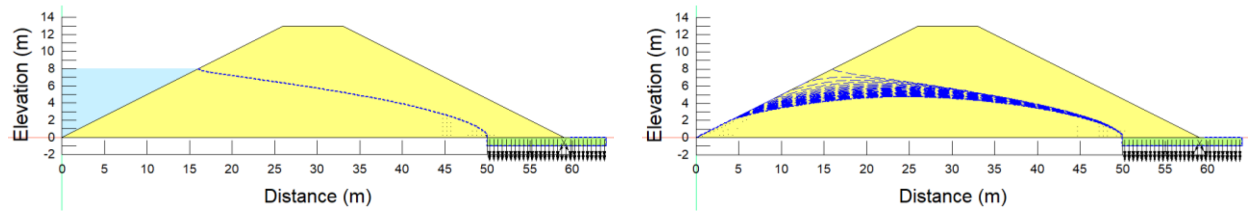


Figure 4 – Seepage results under 10 m water level:
a) Long-term steady-state; b) Instantaneous drawdown; c) 5 days drawdown [author's material]

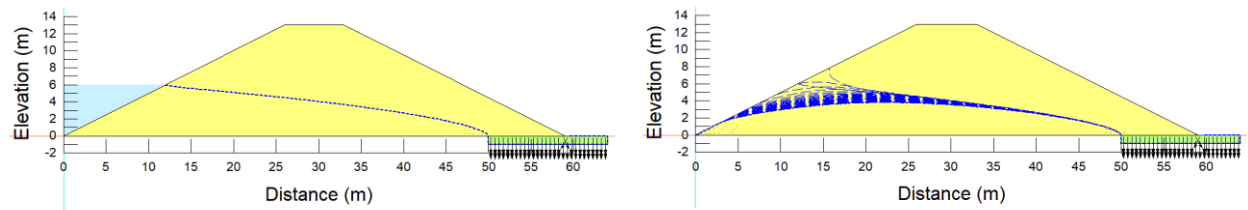
Seepage analysis results from 8m water level. The water level in the reservoir was then reduced to 8m and then subjected to the long-term steady-state before drawdown. The level of the piezometric line from the steady-state analysis starts from the maximum reservoir level (8 m) towards the toe drain downstream. As for the 10 m water level, it can be observed from the piezometric lines that, the water stored in the embankment gradually drained from areas of high pore-water pressure and the seepage face decreased with time following the rapid drawdown scenarios (Figure 5).



(a) (b)

Figure 5 – Seepage results under 8m water level:
a) Long-term steady-state; b) 5 days drawdown [author's material]

Seepage analysis results from 6m water level. Then the water level in the reservoir was further reduced to 6m and the long-term steady-state was established. In this case, the maximum water level was almost half of the embankment height. A similar phenomenon as observed from the 10 m and 8m water levels in terms of piezometric lines and size of the seepage face can be seen in Figure 6. The level of the piezometric line from the steady-state analysis starts from the maximum reservoir level towards the toe drain downstream. While from the 5 days drawdown, 30 different piezometric were drawn out of 30 days of the analysis duration from the upstream face to the toe drain downstream. The lines are more scattered at the upstream face and more concentrated as they move towards the toes drain. The scattering of the piezometric lines on the upstream face is more evident within the 5 days of the rapid drawdown and more compacted as the water has been completely drawn from the reservoir.

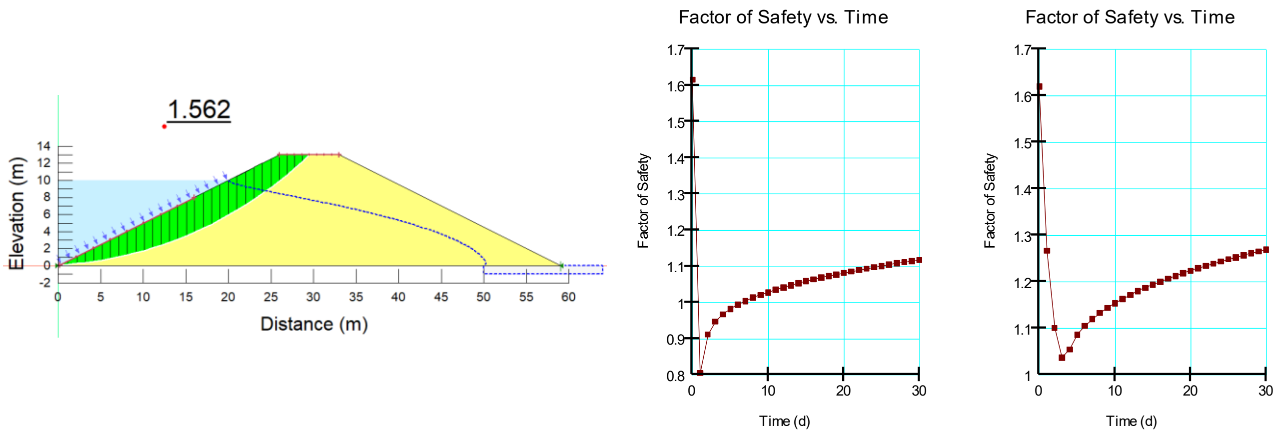


(a) (b)

Figure 6 – Seepage results under 6m water level:
a) Long-term steady-state; b) 5 days drawdown [author's material]

Slope stability. The slope stability analysis was accomplished using The Draw Slip Surface command in SLOPE/W. Where the plots of Factor of Safety versus time were created given the rapid drawdown scenarios as shown in Figures 7-9.

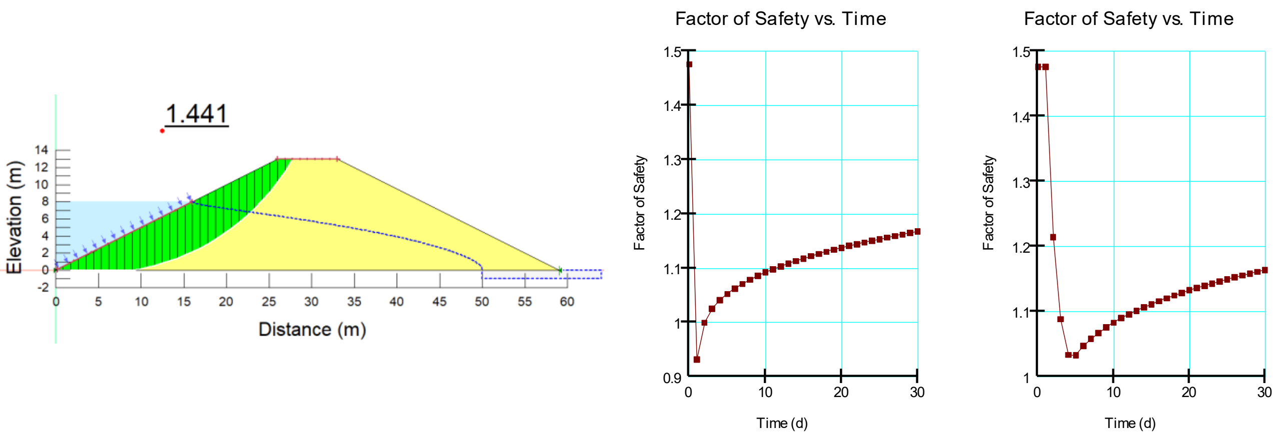
Slope stability analysis results from 10m water level. From Figure 7 it can be observed that a factor of safety of 1.562 was achieved from the steady-state slope stability analysis, which is above the minimum value recommended by different regulatory agencies [25,26]. However, the values of factor of safety are observed to drop below 1.0 immediately following the instantaneous (Figure 7b) drawdown. Within the first day of the instantaneous drawdown, the factor of safety dropped to approximately 0.8, while the lowest factor of safety value of approximately 1.04 was achieved during the fourth day of the 5 days drawdown rate. In the literature [27,28], it has been observed that the rapid drawdown scenarios are considered to be extremely dangerous when it comes to embankment dams, in which the higher the rate of drawdown the higher the risk of failure. Moreover, it can also be observed that the factor of safety values from both instantaneous and 5 days drawdowns tend to recover over time as a result of the dissipation of the excess pore-water pressure within the embankment.



(a) (b) (c)

Figure 7 – Slope stability results for 10 m water level:
a) Long-term steady-state; b) Instantaneous drawdown; c) 5 days drawdown[author's material]

Slope stability analysis results from 8m water level. After subjecting the same embankment to an 8 m water level, the steady-state factor of safety reduced to 1.441 (Figure 8) from 1.562 achieved from the 10 m water level. The reduction in the factor of safety is equivalent to 7.75%. Within one day following the instantaneous drawdown, the factor of safety dropped to approximately 0.93 and it can be observed that the factor of safety started recovering the second day after the instantaneous drawdown. Also, from the 5 days drawdown, even though the factor of safety values kept on decreasing within the first five days, they were still above 1.0 and started recovering from the 6^{th} day. However, the recovery from both instantaneous and 5 days drawdown is more of a gradual process and seems to be more gradual as time goes by.



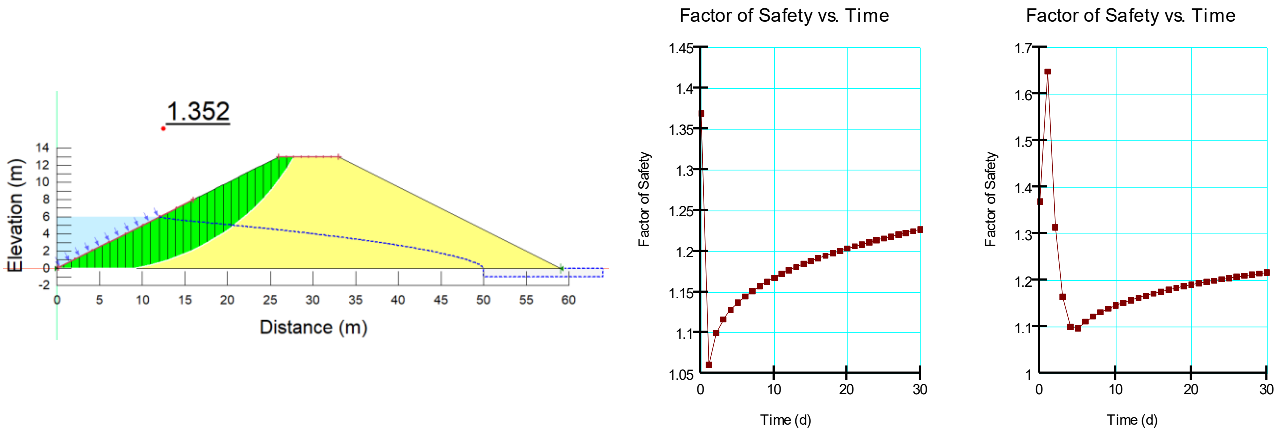
(a) (b) (c)

Figure 8 – Slope stability results for 8 m water level:
a) Long-term steady-state; b) Instantaneous drawdown; c) 5 days drawdown [author's material]

Slope stability analysis results from 6m water level. Also, after subjecting the same embankment to a 6m water level, the steady-state factor of safety reduced further to 1.352, which is equivalent to a 6.18% reduction from the 8m and 13.44% from 10 m water level steady-state factors of safety. The phenomenon agrees with what is found in the literature; according to Eduardo E. Alonso and Núria M. Pinyol [29], a drawdown may be a critical factor in the stability of slopes not only for those that are initially fully submerged but also for those partially submerged.

However, something interesting from Figure 9 is that, unlike the 10 m and 8 m water levels, the 6m water level never observed the factor of safety dropping below 1.0 for both instantaneous and 5 days drawdowns. But the trend of decrease and recovery of the factor of safety was more similar to the ones of 10 and 8 m. The general phenomenon suggests that the significant risk of a drawdown scenario is within the drawdown timeframe and the recovery in terms of the factor of safety starts immediately as the drawdown process ends. Another important note from Figure 9 is that the factor of safety value drops faster with a high drawdown rate and the trend of the factor of safety recovery is faster with instantaneous drawdown than the 5 days drawdown. This is another indication that the extent of pore-water pressure dissipation is highly affected by the rate at which the reservoir is drawdown.

In general, all the phenomena can be highly linked to the effects of water level reductions, in which they reduce the stabilizing external hydrostatic pressure due to the unloading effect of removing water, as well as modification of the internal pore water pressure [30].



(a) (c) (b)

Figure 9 – Slope stability results for 6m water level:
a) Long-term steady-state; b) Instantaneous drawdown; c) 5 days drawdown [author's material]

From Table 3 it can be observed that the changes in long-term operating water level had a significant impact on the minimum and maximum values of factor safety. The highest maximum factor of safety value is observed from the 6m water level under 5 days drawdown rate. While the lowest maximum value of the factor of safety is observed from the 8m water level under both instantaneous and 5 days drawdown rates.

Also, from Table 3.1, it is observed that the lowest minimum factor of safety value was achieved from the combination of 10m water level and instantaneous drawdown scenario. While the highest minimum factor of safety value was observed from the combination of 6m water level and 5 days drawdown rate. From the 5 days drawdown rate, both minimum and maximum factor of safety values decreased when the water level in the reservoir was reduced from 10m to 8m and then increased when the water level was reduced further to 6 m.

While for the instantaneous drawdown scenario, the minimum values of the factor of safety were observed to be increasing with the decrease in water levels, but the maximum values were observed to be linearly decreasing with the decrease in water levels. The phenomenon suggests that the relationship between water level and the factor safety may be highly unpredictable at some point and thorough investigation is of great importance when designing earth-fill dams.

Table 3 – Different drawdown modes with their minimum and maximum values of factor of safety

Water level	Drawdown mode	Factor of safety	
		Minimum	Maximum
6m	Instantaneous	1.061	1.369
	5 days drawdown	1.097	1.648
8m	Instantaneous	0.932	1.476
	5 days drawdown	1.033	1.476
10m	Instantaneous	0.806	1.616
	5 days drawdown	1.037	1.620

Conclusions

The potential influence of changes in long-term water level on slope stability of an embankment under rapid drawdown conditions with the help of numerical modeling, has been investigated. Three different long-term water levels (10, 8, and 6 m) were taken into consideration. From the analysis results it was observed that, as the long-term operating water level changes, the factor of safety values are also affected. The values of steady-state factor of safety were observed to be decreasing with the reduction in water level, in which the steady-state factor of safety reduced by approximately 13.44 % when the water level was reduced from 10 m to 6 m for a 13 m high embankment. While the upstream slope was observed to gain more stability with the decrease in the long-term water level subjected to the rapid drawdown scenarios. The results in this study revealed further that, an embankment freeboard may have a significant impact on the steady-state factor of safety. The minimum and maximum values of the factor of safety were also affected by the changes in the long-term operating water levels with the highest maximum factor of safety value observed from the 6m water level under 5 days drawdown rate and the lowest minimum factor of safety value was achieved from the combination of 10 m water level and instantaneous drawdown scenario. It should also be noted that an instantaneous drawdown scenario is a conservative approach for assessing embankment slope stability when a reservoir is being drawdown, and it was a representation of the worst drawdown scenario.

Acknowledgments

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ЖЫЛДАМ ШӨГУ КЕЗІНДЕ ЖАҒАЛАУ БЕТКЕЙІНІҢ ТҰРАҚТЫЛЫҒЫ ҮШІН СУ ДЕҢГЕЙІНІҢ ҰЗАҚ МЕРЗІМДІ ӨЗГЕРУІНЕН ТУЫНДАҒАН ЫҚТИМАЛ САЛДАРЛАР

Андатпа. *Бөгеттердің тұрақтылығына көптеген факторлар әсер етуі мүмкін, оның ішінде судың ұзақ мерзімді деңгейі. Өкінішке орай, мұндай проблеманы жергілікті жерде* *талдау уақыттың жетіспеуі мен әсер етуші факторлардың күрделілігіне байланысты оңай жүзеге асырыла алмайды. Бұл зерттеу сандық модельдеуді қолдана отырып, жылдам түсу кезінде судың ұзақ мерзімді деңгейінің өзгеруінің жағалау беткейінің тұрақтылығына ықтимал әсерін зерттеді. Судың үш түрлі деңгейі зерттелді (10 м, 8 м және 6 м). Өзгергіштікке жол бермеу және судың ұзақ мерзімді деңгейінің әсерін ескеру үшін су қоймасының геометриясы тұрақты болып қалды.*

Түйін сөздер: *сандық модельдеу, көлбеу тұрақтылық, жағалау, су деңгейі, қауіпсіздік коэффициенті.*

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ПОТЕНЦИАЛЬНЫЕ ЭФФЕКТЫ, ВЫЗВАННЫЕ ДОЛГОСРОЧНЫМИ ИЗМЕНЕНИЯМИ УРОВНЯ ВОДЫ, НА УСТОЙЧИВОСТЬ ОТКОСОВ НАСЫПИ ПРИ БЫСТРОМ ПОНИЖЕНИИ УРОВНЯ ВОДЫ

Аннотация. *На устойчивость насыпных плотин могут влиять многие факторы, включая степень долговременного установившегося уровня воды. К сожалению, анализ такой проблемы на поле не может быть легко осуществлен из-за временных ограничений и сложности влияющих факторов. В данном исследовании с помощью численного моделирования изучалось потенциальное влияние изменений долговременного уровня воды на устойчивость откоса насыпи при быстром понижении уровня воды. Были исследованы три различных уровня воды (10 м, 8 м и 6 м). Чтобы избежать изменчивости и отразить влияние долгосрочного уровня воды, геометрия водохранилища оставалась постоянной.*

Ключевые слова: *численное моделирование, устойчивость откосов, насыпь, уровень воды, коэффициент безопасности.*