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Heterogeneous embankment dam under rapid drawdown

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Abstract. Loading conditions are among the significant determinants of the stability of embankment dams: they need to be carefully investigated during the design phase of the dam construction. Unfortunately, it is almost impossible to investigate the combination of these parameters in-situ. In the current work, the influence of rapid drawdown loading conditions on the stability of the embankment dam was investigated with the help of numerical modeling for a case of the Aktobe dam in Kazakhstan. The seepage analyses were carried out concurrently with slope stability analyses. Mainly, five different drawdown cases were investigated, which are: steady-state, instantaneous drawdown, 5-days drawdown, 10-days drawdown, and 1m per day drawdown rate. In terms of flow type, both steady-state and transient flow conditions were investigated. In general, when the embankment was subjected to the 1 m per day drawdown rate a minimum factor of safety value of 1.486 was retrieved from computations. The factor of safety value is equivalent to a 3.7 % increase from the 10 days drawdown rate, 8.3 % from the 5 days drawdown rate and 48.6 % from the instantaneous drawdown.

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1. Introduction

Embankment dams are artificial barriers constructed to retain or detain water for either permanent storage or release at a controlled rate, which have been in existence for millenia. It is believed that embankment dams date back to Ancient Egypt, India, and China [1]. Embankment dams are also famous in urban catchments, where they are used as flood control structures.

Embankment dams are considered to be the most economical type of dams, a phenomenon that is highly attributed to the fact that, the filling materials can be retrieved at the dam site with little or no processing before their application [2]. However, these dams are always challenged by the potential slope failure. The slope stability of an embankment dam is highly dependent on the material characteristics, slope steepness, and nature of loading [3].

The location and geometry of these dams are highly dependent on the results from feasibility studies that have to check geological issues, hydrological conditions, nature of the terrain as well as seismic factors; without forgetting the availability of the construction materials [4]. In most cases whether an embankment dam or concrete dam will be constructed is highly dependent on the size of the valley; whereby, concrete dams are always preferable in narrow valleys while embankment or earth-fill dams are preferable in wider valleys with problematic foundation soil [5].

In terms of material characteristics; an embankment dam is normally created by the placement and compaction of a complex semi-plastic mound. This mound can have various compositions of earth-fill materials including: sand, clay, gravel, or rock. Gravels are among the materials used in the construction of embankment dams characterized by high hydraulic (k) conductivities also known as permeability rates ranging from 1 to 100 cm/s. For instance, the Hazen equation has for long been used to estimate hydraulic conductivity in cm/s based on semi-empirical correlations with effective grain size (D_{10}) as summarized in Equation 1 [6].

$$k = C \times D_{10}^2, \tag{1}$$

where, D_{10} represents the grain size in mm which is equivalent to 10 percent passing on the gradation curve for the soil, while the constant C varies from 0.4 to 1.2, with an average typical value being 1 [7]. Some other researchers have also tried to relate *k* to the D_{15} size for uniform filter sands as summarized in Equation 2 [8].

$$k = C \times D_{15}^2. \tag{2}$$

In terms of slope, it is always recommended to use shallow slopes such as 3 units horizontal to 1 unit vertical. For upstream slopes, the ratio is 4 units horizontal to 1 unit vertical, and for downstream slopes, 2.5 units horizontal to 1 unit vertical, especially for homogeneous or modified-homogeneous small dams constructed of fine-grained soils [9]. In terms of loading conditions several parameters have to be always taken into consideration when designing embankment, which are: end of construction, steady seepage, seismic forces, and most importantly rapid drawdown (from spillway elevation to the crest of the lowest gated or ungated outlet).

Despite the potential usefulness of these dams, slope failure has been always a significant concern [10]. A failure of such a dam likely leads to unmanageable catastrophic consequences. Loss of human lives, damage to domestic and wild life, loss of properties, and environmental degradation are among the potential results of the embankment dam slope failure. The slope failure process starts with seepage flow on the downstream slope of an embankment dam and is a primary indication of the migration of fine particles in the dam [11].

Unfortunately, another major issue of concern with embankment dams that has currently emerged is the potential of embankment failure under rapid drawdown scenarios [12]. Normally, an embankment dam is subjected to a fairly long-time constant elevation of water surface, which is also known as the long-term steady-state: the flow of water within the embankment (seepage) during the long-term reservoir level has likely reached a steady-state making the dam relatively stable. However, in some cases, the reservoir has to be drained rapidly either intentionally or due to the system failure upstream, including the impacts of land use/land cover change [13]. In such a case, the pore-water pressures developed within the embankment from the long-term steady-state conditions may remain relatively high, whereby the removal of water also removes the stabilizing effect of the reservoir's weight along the upstream side of the embankment and the embankment eventually fails [14–15]. However, the mode of failure due to the rapid drawdown conditions differs from one case to another. Therefore, the potential response of an embankment dam with a relatively low permeability material zone in the upstream face under rapid drawdown conditions is yet to be discovered.

There are already many cases of embankment dam failure, including the following examples. The Belci dam in Romania failed in 1991, and the embankment with a clay core was constructed in 1962 [16]. The Tous dam embankment dam in Valencia, Spain, failed due to overtopping in 1982 with an estimated damage of approximately 400 million USD [17]. The Upper Taum Sauk embankment dam failed on December, 14th 2005, in Missouri, the United States of America; the construction of the dam started in 1960 and ended in 1962, while it was put into operation in 1963 [18]. The Teton Dam located within the Teton River catchment in Madison County, southeast Idaho in the United States of America, faced a total failure in 1976 and is among the most famous case studies in terms of dam failure [19–22]. The Baldwin Hills 71 m high with a crest length of 198 m which was designed as a homogeneous embankment dam faced a failure in 1963 [23]. These are only some of the many cases of dam failures. With these cases, it is beyond reasonable doubt that the stability of embankment dams remains one of the most significant concerns for Civil and Geotechnical Engineers.

In this study, the influence of rapid drawdown loading conditions on the stability of the embankment dam is investigated with the help of numerical modeling for the case of the Aktobe dam in Kazakhstan.

2. Materials and Methods

2.1. Case study description

The Aktobe dam is located approximately 10 km from the Aktobe City center in Western Kazakhstan; latitude: 50°12'23.26"N and longitude: 57°18'36.18"E. The reservoir with a volume of approximately 245 million m^3 was put into operation in 1988. The Aktobe region is known to be among the largest regions in terms of area coverage in Kazakhstan with an approximate area of 300,629 km^2 occupying approximately 11 percent of the entire country.

Several rivers are decorating the Aktobe region including the Kargaly river which discharges its water into another river (Ilek River). One of the tributaries of the Ilek (left tributary) passes through the center of the Aktobe region. Sazdy River is another important river that passes within the city; whereby, large entertainment centers, shopping malls, and other social buildings are located along the river banks.

In terms of climatic conditions, the Aktobe region is characterized by a humid continental climate with significantly high seasonal variation levels in terms of temperature. The region is also characterized by harsh winters like many other parts of the country with temperatures dropping as low as –48 °C; whereas, the daily average minimum temperature is −16 °C. Also, the Aktobe region is characterized by hot summers with the temperature reaching 43 °C; whereas, the average maximum temperature is 30 °C. However, is also worth pointing out that, the levels of weather changes are extremely high in the region in spring and autumn, especially during the windiest days of March. Moreover, the rainy seasons are generally during early spring and a bit of late autumn (the period when winter starts); characterized by heavy snows during the winter. On average, the annual precipitation in the Aktobe region is approximately 330 mm.

Like many other parts of Kazakhstan, the geological condition in the Aktobe region is characterized by significantly extensive basement rocks resulting from the Precambrian and relatively high widespread Paleozoic rocks. Based on some studies it has been observed that the groundwater of some parts of the region is characterized by high concentration levels of petroleum products [24].

2.2. Embankment geometry and modeling process

In this study, finite element method analyses were used to evaluate the potential influence of rapid drawdown loading conditions on slope stability of an earth-fill dam for the case of the Aktobe dam. The general modeling process is characterized by two main types of analyses, namely; seepage analysis and slope stability analysis. The seepage analysis was executed using the SEEP/W unit of the GeoStudio, while the slope stability was executed using the SLOPE/W of the GeoStudio 2018 R2 (version 9.1.1.14749). Mainly, five different drawdown cases were used, namely; steady-state, instantaneous drawdown, 5-day drawdown, 10-day drawdown, and 1 m per day drawdown rate. It is also worth noting that, the seepage analyses were carried out concurrently with slope stability analyses. The Aktobe dam embankment is characterized by a maximum water depth of 18.5 m, with an embankment height of 22.7 m (Fig. 1). The embankment is mainly divided into five different zones based on material properties (discussed in the materials properties section).

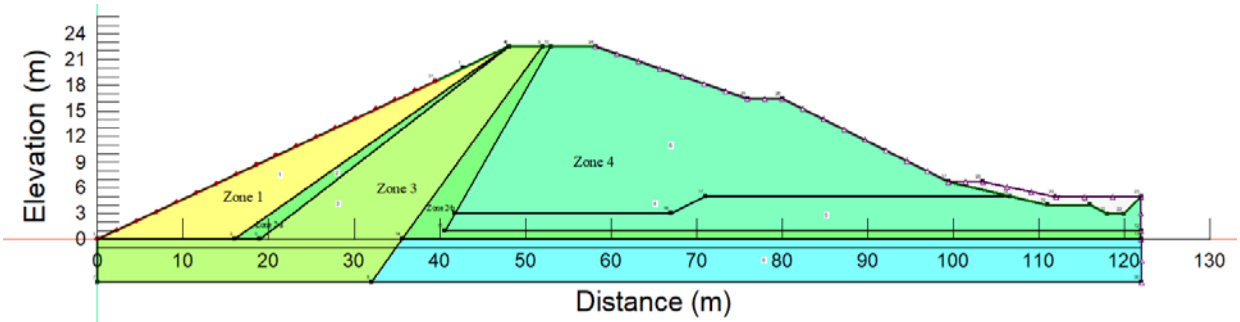


Figure 1. Embankment geometry.

2.3. Seepage analysis

In the seepage analysis, it was important to establish a long-term steady-state using the Steady-state type of analysis before subjecting the embankment to the transient analysis. In that matter, the developed long-term steady conditions were used to feed pore-water pressures to the transient seepage analyses through the “parent” approach. This was an important step or process because, from prolonged develop a steady-state condition of seepage that has to be taken into consideration during the numerical modeling [25].

However, as previously mentioned, the numerical modeling process consisted of several drawdown rates (instantaneous, 5 days drawdown, 10 days drawdown, and 1 m per day drawdown rate) and isotropic hydraulic conductivity values. To model the transient flow through varying water levels as the reservoir was being drained, linear functions were specified as a boundary condition on the upstream face of the embankment. It is also worth highlighting that, the transient flow analyses received pore-water pressures from seepage analyses. Fig. 2 presents the summary of the drawdown boundary conditions for the 5 days drawdown, 10 days drawdown, and 1 m per day drawdown rates.

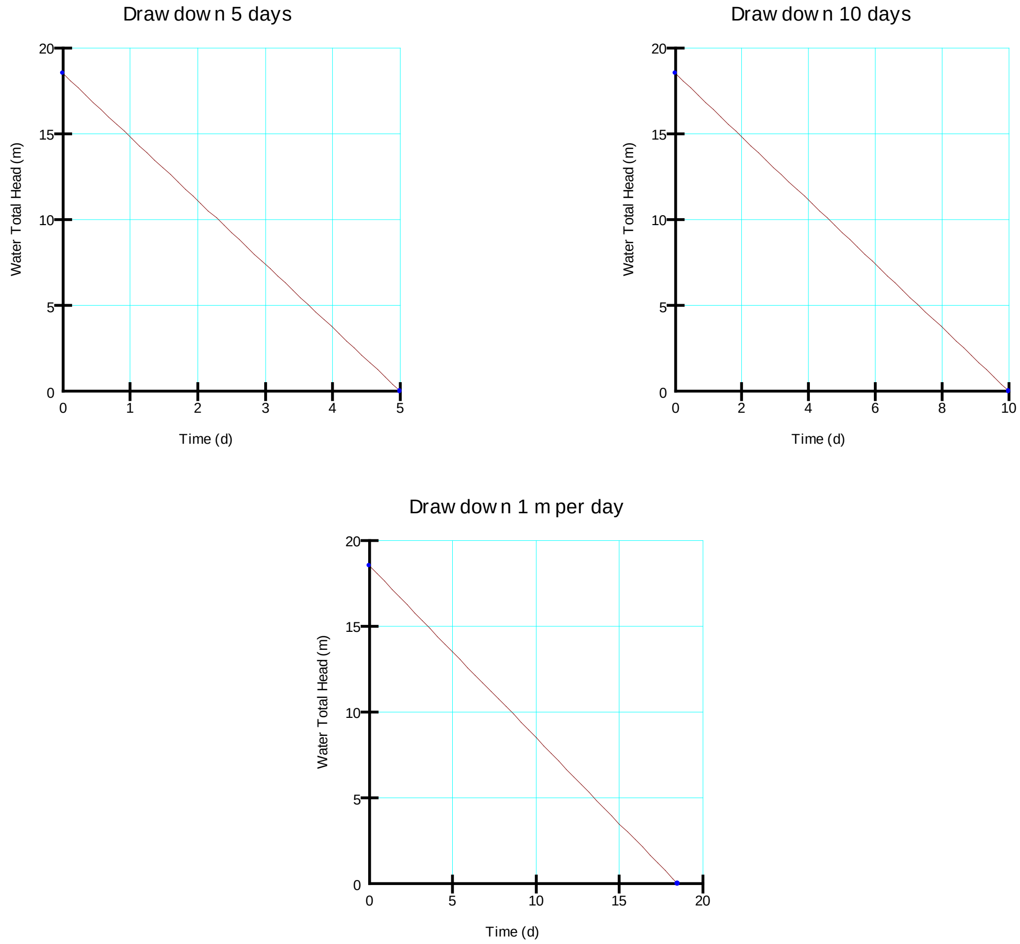


Figure 2. Boundary conditions.

2.4. Slope stability analysis

As previously mentioned, the slope stability models received their pore-water pressures from the seepage analysis models. In general, the slope stability modeling is based on the Morgenstern–Price approach which is a general method of slices established based on the limit equilibrium. Its application requires the fulfillment of equilibrium of forces and moments acting on individual blocks. To generate the blocks, the soil above the slip surface has to be divided by dividing planes [26]. Generally, the method is a limit equilibrium approach used to assess the factor of safety value of the potential failure mass based on satisfaction of both force and moment equilibrium [27].

In this study, the Morgenstern–Price approach was selected due to the fact that it is capable of satisfying the equilibrium conditions and involves the least numerical difficulty [28]. Moreover, it has to be noted that the fundamental supposition governing the Morgenstern–Price method is that the ratio of normal to shear interslice forces through the sliding mass is characterized by an interslice force function resulting as a product of a specified function $f(x)$ and an unknown scaling factor λ.

Several assumptions were incorporated in the formulation of the Morgenstern–Price method to compute the limit equilibrium of forces and moment on individual blocks [28]:

- The planes that divide one block and another are always vertical.

- The action line of the weight of the block passes through the center of the particular segment of slip surface represented by a point.
- The normal force is acting in the center of the particular segment of the slip surface at a point.
- The inclination of forces acting between blocks is different on each block at slip surface endpoints.

2.5. Material characteristics

The embankment was divided into different zones and each zone was assigned a specific type of material based on the heterogeneity of the Aktobe dam. Zone 1 was composed of more non-cohesive materials (coarse materials) mixed with some fine materials with fixed hydraulic conductivity based on the dam material characteristics. Zones 2 (a) and (b) were also characterized by non-cohesive soil (filter materials) with more sand and gravel. On the other hand, Zone 3 was mainly composed of relatively high cohesive soil material including fine-grained materials (clay). Moreover, Zone 4 was mainly composed of coarse material with relatively very little content of fines materials. In general, the liquid from all the zones ranged from 18 % to 52 %. From Table 1 it can be observed that some other parameters such as diameter at passing 10 %, diameter at passing 60 %, internal angle of friction (degree), as well as unit weight were specified in the model. Fig. 3 presents the summary of the volumetric water content and hydraulic conductivity functions assigned to the model from Zone 1 and 2.

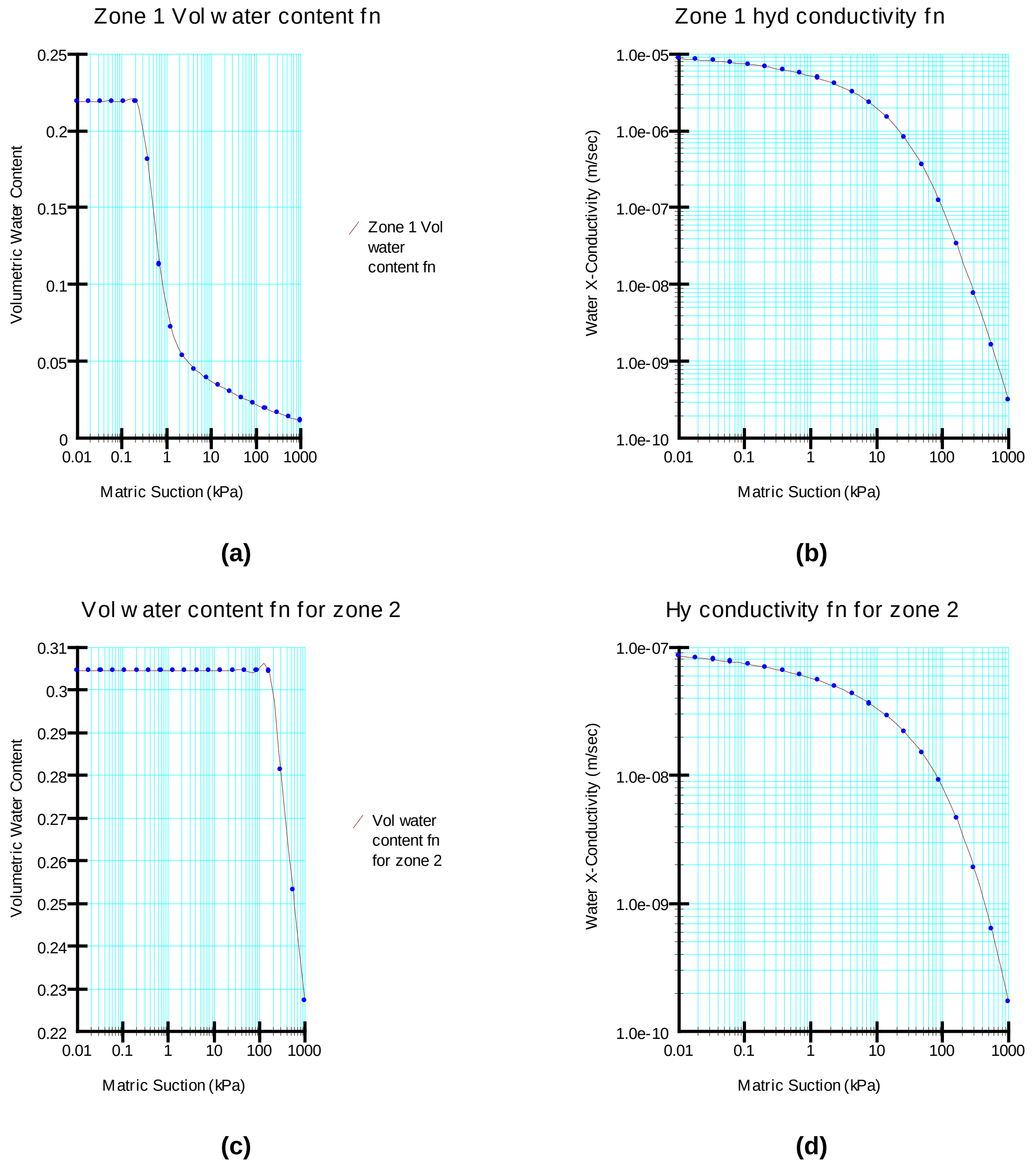


Figure 3. Volumetric water content and hydraulic conductivity functions for different zones.

Table 1. Material properties.

Parameter	Zone			
	Zone 1	Zone 2	Zone 3a,b	Zone 4
Saturated hydraulic conductivity (ksat), m/s	$1.2 \cdot 10^{-5}$	1.42×10^{-8}	1.1×10^{-4}	5.2×10^{-5}
Diameter at passing 10 % (mm)	0.1	0.002	0.2	0.1
Diameter at passing 60 % (mm)	40	0.05	0.8	40
Liquid limit (%)	25 to 45	50		
Unit weight (kN/m3)	20.5	20	18.5	20.5
Saturated water content (%)	29.6	36.8	40.1	29.6
Internal angle of friction (degree)	40	28	38	40
Cohesion (kPa)	-	15	-	-

3. Results and Discussion

Both seepage and slope stability analyses were successfully executed. As previously mentioned, the investigation process is based on the different drawdown rates to investigate their influence on the stability of a heterogeneous embankment. Each investigated case started with seepage analysis followed by slope stability; whereby, the seepage model acted as a parent to the slope stability model. Also, both steady-state and transient flow conditions were taken into consideration.

3.1. Seepage analysis

Generally, seepage flow within an embankment is the movement of water from the upstream side of the dam (where the reservoir is located) to the downstream side crossing the dam body preferably below the foundation. Due to the potential stability issues that can be associated, it is of significant importance to control seepage in earth-fill dams, especially during the design and construction phases of the dam.

From Fig. 4 it can be observed that, based on the material arrangements from the Aktobe dam, the modeling revealed that under long-term steady-state conditions the seepage within the embankment is safely carried without crossing the downstream face of the embankment. In the literature, it has been observed that seepage flow through earth-fill embankments is the principal cause that leads to failure due to some factors such as eroding, scouring, as well as piping [29].

Moreover, it is also important to investigate the long-term steady-state seepage because when the reservoir is filled, immediately water starts seeping through the body of the embankment. Whereby, after a certain time the seepages reach steady conditions, and a distinct phreatic line is generated; that means the embankment soil under the distinct phreatic line is relatively saturated and is under seepage pressure. Also, according to Perri et al., [30] an increase in embankment pore water pressures a phenomenon that is linked to the development of the long-term steady-state seepage condition can also result in an associated decrease in effective stress in the soil; whereby, the decrease in effective stresses leads to a reduction of the available effective strength of the soil.

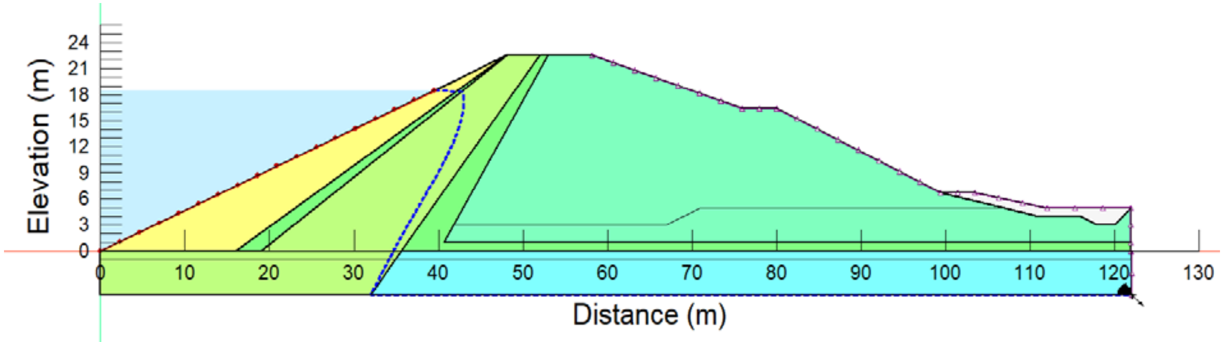


Figure 4. Steady-state seepage.

From Fig. 5 it can be observed that the seepage line heights keep on decreasing with the decrease in water levels in the reservoir. It is also important to be noted that, the first seepage line indicates the initial water level in the reservoir. Then when the reservoir drawdown was simulated by instantaneously removing all the water, the water level was relatively sustained at the level of the toe of the slope making more of the seepage lines to be concentrated at the embankment toe [31].

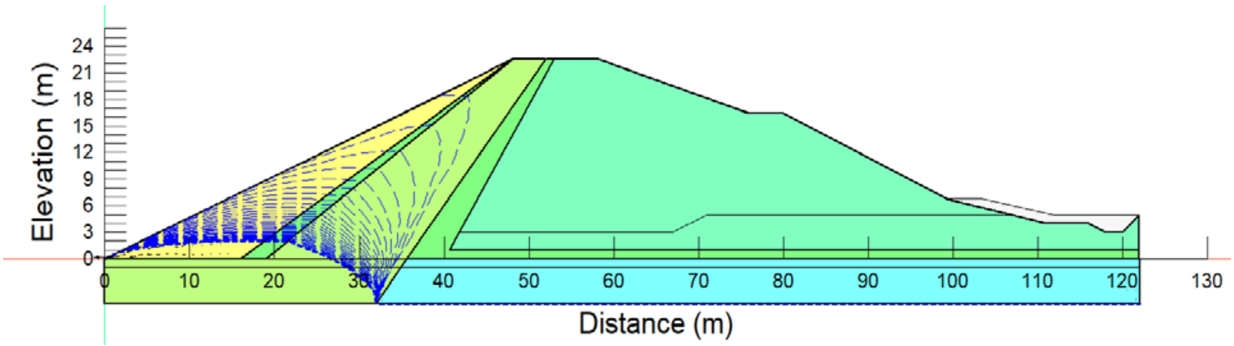


Figure 5. Instantaneous seepage.

3.2. Slope stability analysis

The evaluation of slope stability is mainly based on the factor of safety values. From Fig. 6 it can be seen that the long-term steady-state factor of safety value is 1.784 which is highly acceptable in terms of slope stability.

According to the Washington State Department of Transportation Geotechnical Design Manual [32], it is recommended that for slope stability analysis of permanent cuts, fills, and landslide repairs, 1.25 is adopted as the minimum safety factor value. Furthermore, it is recommended that larger safety factors must be adopted in a case when there is a potential uncertainty in the analysis input parameters. Also, according to Jiri H. et al., [33], some other authorities recommend a minimum factor of safety of 1.5 for slope stability analysis of embankments.

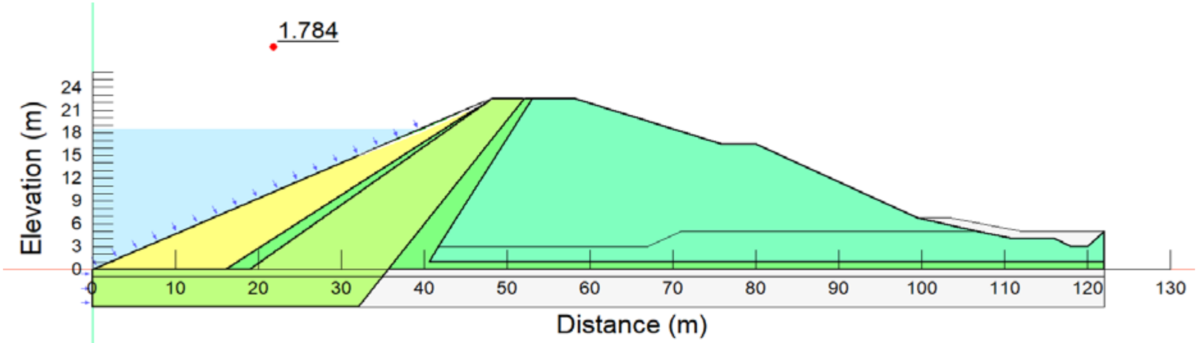
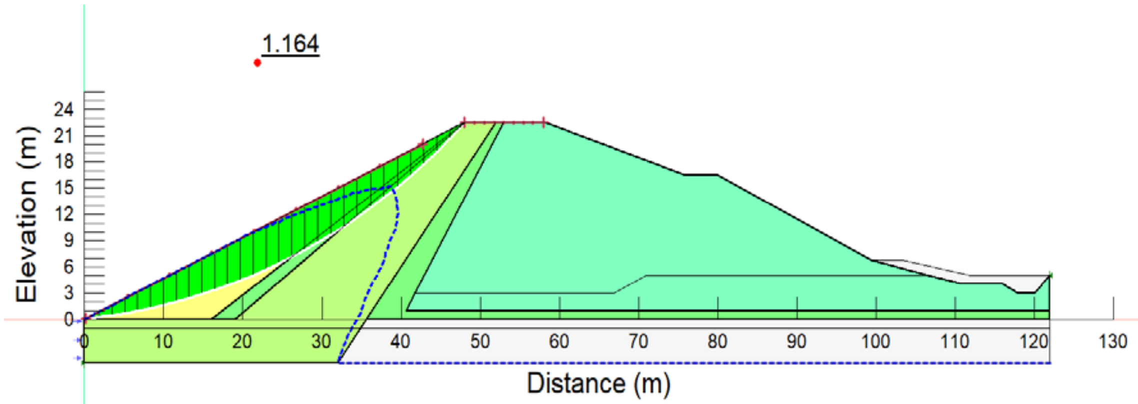
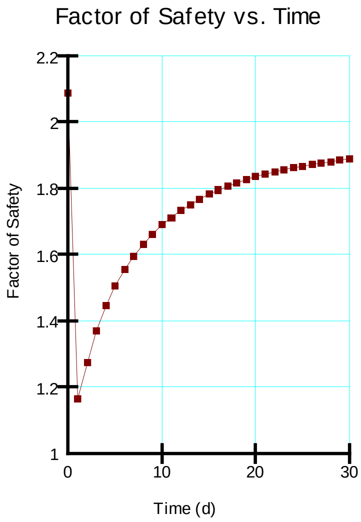


Figure 6. Steady-state slope stability.

When the embankment was subjected to the instantaneous a minimum factor of safety of 1.164 was retrieved; whereby, based on the recommendation of some authorities the obtained factor of safety is an indication of a potential failure. Also, from Fig. 7(b) it can be observed that the lowest factor of safety value was obtained within the first day of the instantaneous drawdown; that means, the potential failure is of immediate effect when the embankment is subjected to an instantaneous drawdown.



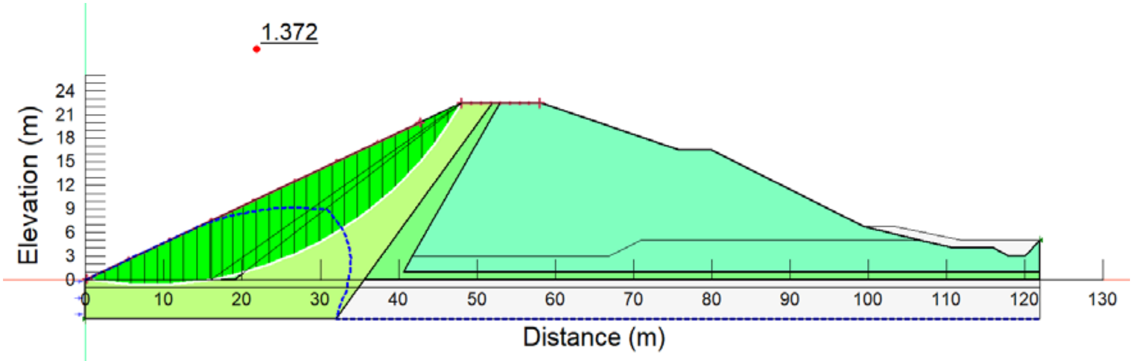
(a)



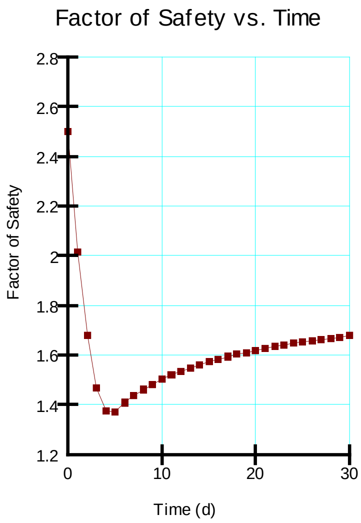
(b)

Figure 7. Instantaneous slope stability.

Also, when the embankment was subjected to 5 days drawdown rate a factor of safety of 1.372 was achieved which is a bit higher than the instantaneous drawdown (equivalent to a 17.9 % increase). However, with the fact that some other authorities recommend a minimum factor of safety of 1.5 to consider an embankment safe during loading, the 1.372 factor of safety value may also signify a potential failure. From Fig. 8 it can be observed that the minimum factor of safety value is obtained within the fourth and fifth day of the drawdown.



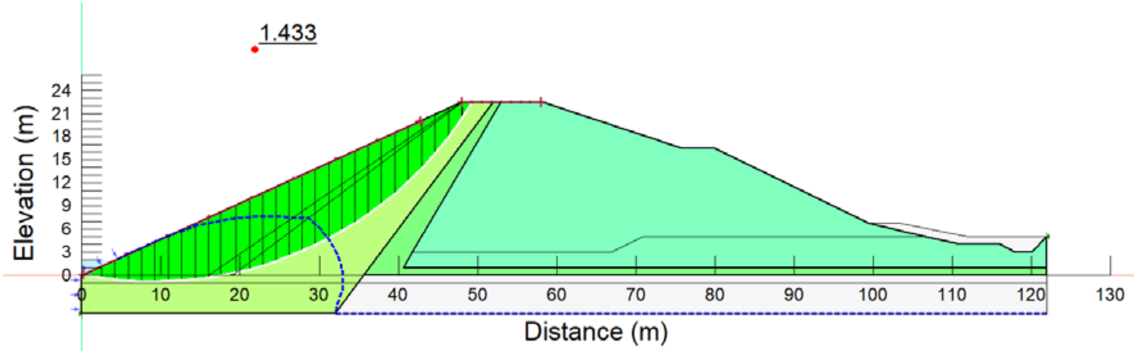
(a)



(b)

Figure 8. Drawdown 5 days.

Moreover, when the embankment body was subjected to 10 days drawdown rate, a minimum factor of safety of 1.433 was achieved; equivalent to a 4.4 % increase from the 5 days drawdown rate and 23.1 % from the instantaneous drawdown rate. From Fig. 9 it can be observed that the minimum factor of safety value is obtained within the 9th day of the reservoir draining.



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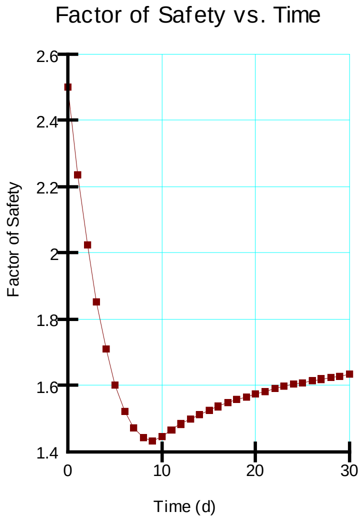
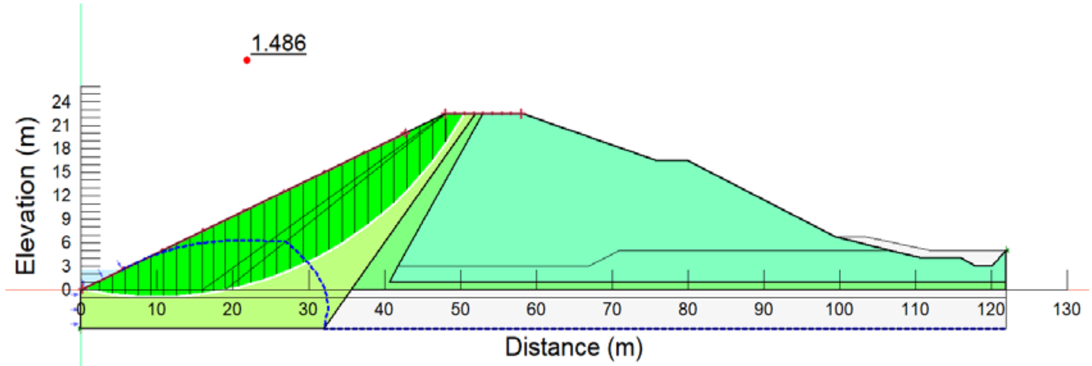


(b)

Figure 9. Drawdown 10 days.

Another case that was taken into account in this study is the 1 m per day drawdown rate (Fig. 10); whereby, when the embankment was subjected to the 1 m per day drawdown rate a minimum factor of safety value of 1.486 was retrieved from computations. The factor of safety value is equivalent to a 3.7 % increase from the 10 days drawdown rate and 8.3 % from the 5 days drawdown rate and 48.6 % from the instantaneous drawdown.

Furthermore, in the literature rapid reservoir draining has been noted to be among the critical factors in the stability of embankment slopes that were initially submerged from the upstream face. Therefore, the reduction process of water level leads to two main consequences; firstly, a decrease in terms of the external stabilizing hydrostatic pressure due to the unloading effect of removing water, and secondly, alteration of the internal pore water pressure [34].



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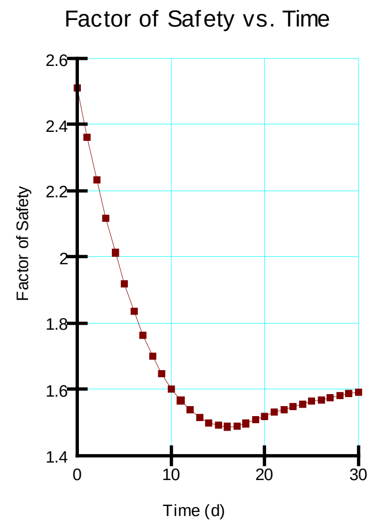

(b)

Figure 10. Drawdown 1m per day.

From Table 2 it can be observed that the minimum (min) factor of safety values were increasing with the decrease in drawdown rates. A similar phenomenon can be observed from the median, arithmetic mean (mean), and standard deviation. (STD). However, the maximum (max) factor of safety values remained constant as they are determined by the long-term steady state.

As previously mentioned, the minimum factor of safety when the embankment was subjected to the instantaneous drawdown case was 1.164, while the same embankment was subjected to the 1 m per day drawdown rate the minimum factor of safety was 1.49; which is equivalent to 48.6 % increase.

In most cases the minimum factor of safety is of interest because in geotechnical engineering, for instance, a factor of safety provides an overall picture of how much stronger a structure is than it needs to be for a specific type of loading; also expressed as the ratio of the capacity of the structure to the appropriate demand [35, 36]. Another key aspect to note is that these values are normally computed using detailed analysis due to the fact that comprehensive testing can be associated with feasibility issues on many engineering projects. However, the structure's ability to sustain potential loading conditions should be well checked in principle to resolute to a sensible accurateness. Moreover, well-designed with a sufficient value of factor of safety has the potential to increase the safety of people that in turn reducing the risk of failure of the particular structure [37–39].

Table 2. Summary of the factor of safety values from the investigated drawdown rates.

Drawdown type	Min	Max	median	Mean	STD
Instantaneous	1.164	2.512	1.556	1.552	0.201
Drawdown-5 days	1.372	2.512	1.562	1.583	0.202
Drawdown-10 days	1.433	2.512	1.567	1.624	0.231
Drawdown-1 m per day	1.486	2.512	1.569	1.692	0.271

On the other hand, Fig. 11 presents the summary of the factor of safety values distribution. It can be seen that, the data distribution from the instantaneous, 5 days, and 10 days drawdown rates is almost symmetrical; which means there was an equal data distribution with the list of factors of safety values. However, from the 11 m per day drawdown rate, the median is observed to be closer to the lower quartile of the boxplot meaning that the data distribution was positively skewed with higher values than the lower values.

In summary, the observed effects of the rapid drawdown loading conditions can be again linked to the fact that when the water in the reservoir is removed relatively fast the supporting water load from the upstream face of the embankment in combination with the changes in pore water pressure results in an undrained unloading condition in which total stresses decrease that in turn increases shear stresses within the embankment [40].

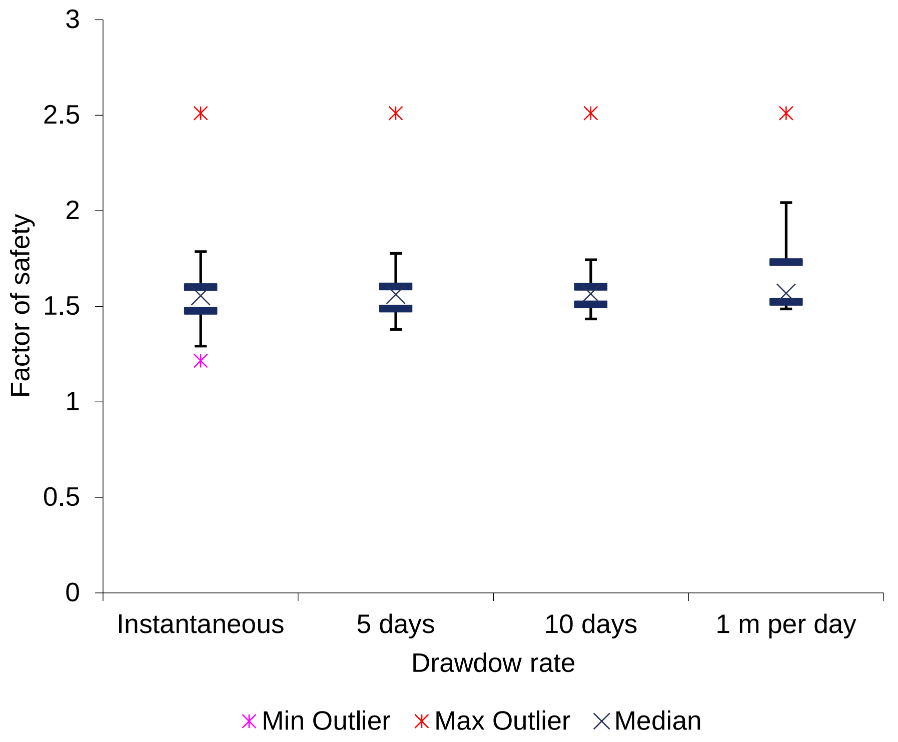

Figure 11. Distribution of factor of safety values for the investigated drawdown rates.

4. Conclusions

1. The influence of rapid drawdown loading conditions on the stability of the embankment dam was investigated with the help of numerical modeling for the case of the Aktobe dam in Kazakhstan.

2. From the investigation results, it was observed that when the embankment was subjected to the 1 m per day drawdown rate, a minimum factor of safety value of 1.486 was retrieved from computations.

3. The factor of safety value is equivalent to a 3.7 % increase from the 10-days drawdown rate, 8.3 % from the 5-days drawdown rate, and 48.6 % from the instantaneous drawdown.

4. However, some authorities recommend a minimum factor of safety of 1.5 for an embankment to be regarded as safe enough in terms of slope stability.

5. Moreover, the results in this study further revealed that even a heterogeneous dam supplied with a core in the embankment can be highly susceptible to failure when subjected to rapid drawdown loading conditions.

6. Therefore, it is of significant importance to investigate the response of an embankment dam subjected to a rapid drawdown condition during the design phase of the embankment to avoid potential failure when the dam is already in operation.

7. The process ensures the stability of the structure as well as provides protection against health impacts and property damage.

5. Conflict of Interests

The authors declare that there is no conflict of interest regarding the publication of this paper.

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