STABILITY ANALYSIS OF AN OLD EARTH SAMARKAND DAM IN KAZAKHSTAN UNDER RAPID DRAWDOWN CONDITIONS

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Abstract: *Despite being potential historical sites, old embankment dams are subjected to many stability challenges due to many factors, including a lack of sufficient stability assessment tools by the time the dam was built and changes in embankment material properties induced by natural and human activities. Therefore, with the current advancement in technology is of great importance to investigate the state of old embankment dams under different potential loading conditions. The stability challenges become of more significant concern when the embankment is subjected to a rapid drawdown loading scenario. In this study, the Samarkand dam located in Karaganda province in Kazakhstan which was put into operation in 1941 is investigated in terms of seepage and slope stability with the help of numerical modelling. Both steady and transient (rapid drawdown) flow conditions are taken into consideration. e finite element method-based modelling is achieved using SEEP/W and SLOPE/W of the GeoStudio software. From the analysis results, it was observed that the old dam can be subjected to a potential failure under rapid drawdown conditions as the minimum factor of safety values were decreasing with the increase in the drawdown rates. For instance, the minimum factor of safety from the instantaneous drawdown rate was equivalent to 32.85% less than the factor of safety retrieved from the long-term steady-state conditions. Also, from Analysis of Variance (ANOVA), a p-value of 9.97×10^{-29} was obtained after subjecting the factor of safety values from instantaneous, 5 days, 10 days, and 1 m per day drawdown rates to ANOVA, indicating that the factor of safety differences among the analyzed drawdown rates were statistically significant.*
Keywords: *embankment dam; factor of safety; numerical modelling; rapid drawdown; slope stability.*

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1. INTRODUCTION

Dams are marked as among the significant historic structures. The Jawa Dam in northern Jordan being among the oldest operational dam in the world (Fahlbusch, 2009); whereby, is well-known as the oldest proto-urban development in Jordan, dating from the late 4th millennium BC. Dams can carry a lot of historical information that can be passed from generation to generation (Sharma and Kumar, 2013). Moreover, dams play an important role in the provision of water for domestic, industrial, and irrigation purposes (Altinbilek, 2002; Ho et al., 2017). They are also often used to produce hydroelectric power as well as for river navigation. To be more specific, the domestic uses of water from dams include water for drinking, cooking, bathing, washing, and lawn and garden watering. Nevertheless, dams and their reservoirs provide recreation areas for fishing and boating; while mitigating or reducing floods. These structures can also act as a good material for students to learn more about why dams are built with the associated activities (Hong et al., 2020).

Normally, the operational mechanism of dams is based on the fact that, during times of excess water flow, dams store water in the reservoir; then, they release water at a controlled rate during times of low flow when natural flows are inadequate to meet water demand. Therefore, when designing embankment dams, all these factors have to be taken into account. In the old days, dams were primarily made of earth, wood, or stone (alone or in combination) (Adamo et al., 2020). Nowadays, dams have evolved from just simple and small to advanced, huge, and complex structures parallel to advances in technical achievements and knowledge on the utilization and handling of watercourses (Castillo-Rodríguez et al., 2017). In that matter, the choice of design and materials is also highly influenced by increasing requirements of modern security and supervision.

However, the process of promoting the preservation and gaining public acceptance of a dam as a historical and cultural heritage raises many social issues. It is well known that the older an object is the easier it is accepted as a historical and cultural asset. However, it has also been observed that the smaller the scale and the more traditional (preferably handicraft) an object is, the easier it is accepted as a cultural asset; therefore, at some point, this factor can significantly affect the cultural perspective of old embankment dams. It is also a matter of perception that, cultural environments and objects representing modernization and technological development are often large-scale, complex, and unattractive to the eye, hence challenging our sense of time, history, size, technology, and aesthetics in general (Boyé and Vivo, 2016).

In the literature, dams are marked as historic sites or structures when are 50+ of age (Adamo et al., 2020). The Samarkand reservoir in Kazakhstan is marked as one of the oldest embankment dams in Central Asia that was put into operation in 1941(80 years of operation by 2021) (Toxanbayeva et al., 2021). The reservoir itself has a length of 25 km, and width is 7 km. The height above sea level is 489 m; while the area is 82 km² and the volume is 0.260 km³. Moreover, the Nura River feeds the Samarkand reservoir. The development of hydraulic engineering construction in the Soviet Union, associated with the rapid growth of the country's industrialization, the collectivization of agriculture, and the reconstruction of the national economy, raised the question of the use of such types of dams, which would ensure the possibility of giving the dams a large height and stability and solved the problem of cost reduction construction by making maximum use of local materials.

Despite the potential of old dams as a cultural heritage, their stability is of significant concern because they are highly prone to failure (Dounias, Potts and Vaughan, 1996). The phenomenon can be highly linked to the fact that with time the embankment materials may be weathered (altering the natural conditions of the materials) and the flow characteristics in the catchment can change. It is also a matter of fact that old dams were designed when the technology was less advanced.

Therefore, it is of great importance to investigate different stability factors associated with old embankment dams with time. Numerical modeling is among the useful approaches that can be used to investigate the state of embankment dams (Mkilima, 2021). With the help of technological advancement, the application of numerical modeling for the investigation of slope stability in embankment dams has become more convenient and reliable. In the recent past, there has been significant growth in numeral modeling software, especially for seepage and slope stability including GeoStudio (GeoSlope) and Plaxis (2D and 3D) (Utepov et al., 2021).

In this study, the potential effect of rapid drawdown scenarios on the stability of old dams for the case of Samarkand in Kazakhstan is investigated. The dam has a maximum depth of 12 m and a length of 25 km located in Karaganda province in Kazakhstan that was put into operation in 1941. Both seepage and slope stability with the help of numerical modeling are investigated based on steady and transient (rapid drawdown) flow conditions. The finite element method-based modeling is achieved using SEEP/W and SLOPE/W of the GeoStudio software.

2. MATERIALS AND METHODS

2.1. Case study description

Samarkand is a dam located in the Karaganda region, Kazakhstan with the region font code of Eastern Europe. Its coordinates are 50°5'54" N and 73°0'55" E in DMS (Degrees Minutes Seconds) or 50.0983 and 73.0153 (in decimal degrees). Its UTM position is CR55 and its Joint Operation Graphics reference is NM43-04. Karaganda is the fourth most populous city in Kazakhstan, behind Almaty, Nur-Sultan, and Shymkent. In 2020 the population in Karaganda was estimated to be 497,777 (projected) as well as 459,778 (2009 Census results); 436,864 (1999 Census results). Karaganda is approximately 230 km southeast of Kazakhstan's capital Nur-Sultan (formerly known as Astana).

Karaganda has a humid continental climate with warm summers and very cold winters. Precipitation is moderately low throughout the year, although slightly heavier from May to July. Snow is frequent, though light, in winter. The lowest temperature on record is −42.9 °C, recorded in 1938, and the highest temperature is 40.2 °C (104.4 °F), recorded in 2002. The geology of Kazakhstan includes extensive basement rocks from the Precambrian and widespread Paleozoic rocks, as well as sediments formed in rift basins during the Mesozoic. Small synclines in the Karaganda Foredeep Basin show Deepwater limestone and shale 450 meters thick from the Carboniferous and Permian, as well as 4.5-kilometer-thick coal-bearing molasse. Within the Tengiz Basin, deposits are never more than two kilometers thick and grow thicker to the south. The Chu Basin is filled with undeformed Middle Devonian through Permian red molasse and carbonate deposits. Calc-alkaline magmatism was extensive in the southeast Kazakh Uplands and the Tien Shan Mountains.

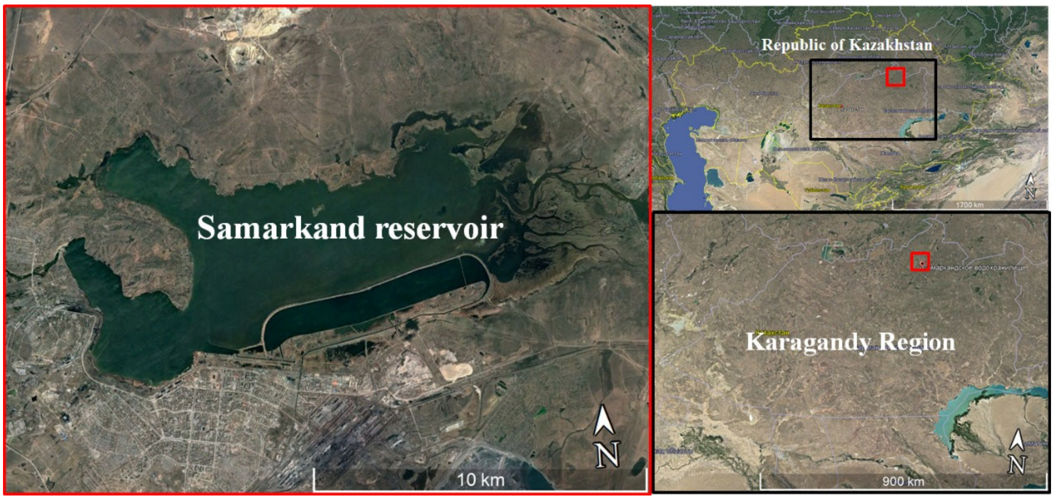


Figure 1. Case study location (Utepov, Mkilima and Abisheva, 2021).

2.2 The historical perspective of the Samarkand dam

The construction of the Samarkand hydroelectric complex was done in 5 years, from 1934. When the construction started, people became the main labor force; it was with their hands that the dam was constructed because the first excavator appeared on the construction site only in 1936. Mainly, during the time, the main labor force was the prisoners of KarLAG, two departments of which were specially transferred closer to construction, to the village of Samarkand. However, it should also be noted that the Samarkand dam is not the only artificial dam on Nura, but it is the largest of these artificial reservoirs. From 1934, the construction process was completed in 1939, which turned out to be arid and therefore the dam was able to be under full operation in 1941, which for this reason is mistakenly considered the year of completion of its construction. The dam erected on Nura was 20 meters high and 300 meters wide. The process of filing an area of 8000 hectares with water lasted a lot - 22 years, until 1961 when the reservoir mirror was formed.

After the construction of the Samarkand dam, it became the most significant artificial reservoir in Central Kazakhstan. According to the Kazakh Academy of Sciences, the total length of the reservoir was 20 kilometers, the width - was 6.5 kilometers, and the maximum depth - was 17 meters.

Then later in 1982, a new hydroelectric complex started to be constructed and was delayed for various reasons. In 1988, the facility was put into operation, but its technical re-equipment and bringing into line with modern standards became possible today when the construction was transferred to the balance of the state. The old dam is currently associated with a number of geotechnical issues, making the operation of the hydroelectric complex of more significance. However, the fact that people used to live on the site of the dam has been producing a lot of mysterious rumors, to the extent that people believe that there is an old cemetery at the bottom of the reservoir. However, local historians cannot confirm this information, since there is no official data on any burials in this area.

2.3 General modelling process

The potential influence of the rapid drawdown scenarios on the stability of the embankment dam was investigated with the help of the finite element method. The other parameters in the analyses were kept constant while changing the drawdown rates. The embankment geometry (as shown in Figure 2) is composed of four different zones with zones 1a and 1b being similar. Generally, the investigation was categorized into five different cases based on the drawdown rate: steady-state, instantaneous drawdown, 5 days drawdown, 10 days drawdown, and 1m drawdown rate stability factors were investigated at the end of the modeling process in all the investigated cases. In this study, the instantaneous drawdown was considered the most extreme condition (worst scenario). Moreover, the analyses were accomplished using the SEEP/W (Arshad, Babar and Javed, 2016)s mainly for seepage analysis, and SLOPE/W is mainly for stability analysis. The modeling processes in the two sub-units of the GeoStudio used slip surfaces, pore-water pressure conditions, soil properties, and loading conditions as inputs.

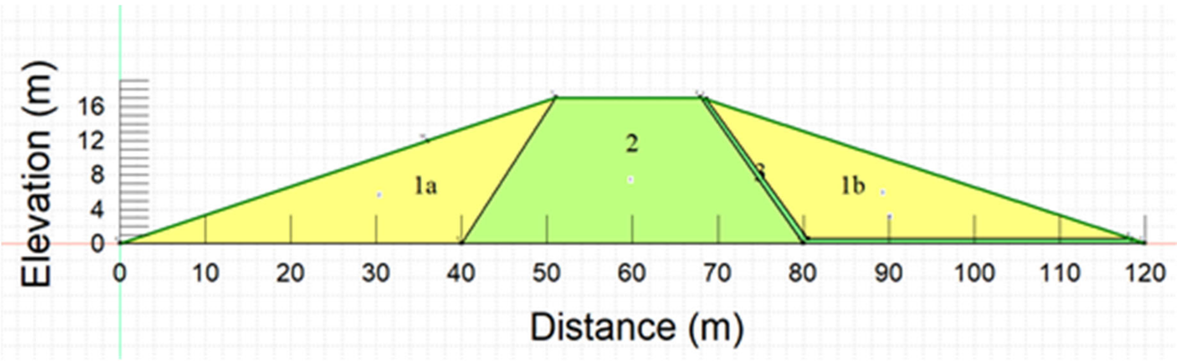


Figure 2. Embankment geometry.

2.4 Seepage analysis through the embankment

Before the simulation of the transient conditions based on the drawdown rates, the model was subjected to a long-term steady-state simulation using the Steady-state analysis method. The transient modeling used the seepage-induced pore-pressures generated from the long-term steady-state. The boundary condition approach was used to specify the extent of the water level variations during the rapid drawdown process (as shown in Figure 3). Moreover, in the study, the transient seepage analyses were used as parents to the slope stability analyses.

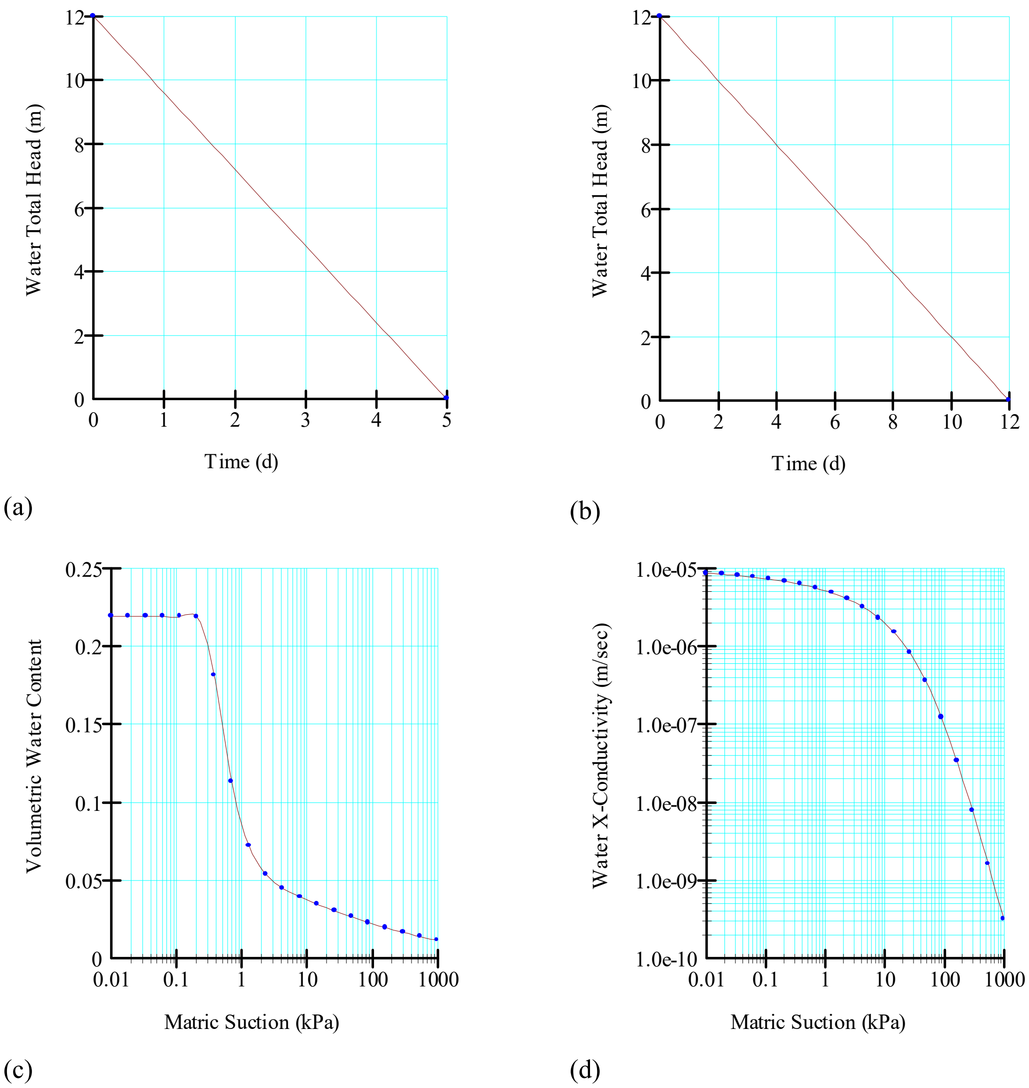


Figure 3. Some of the defined functions: (a) the boundary condition for 5 days drawdown rate (b) the boundary condition for 1 m per day drawdown rate (c) volumetric water content function from zone 1(d) hydraulic conductivity function from zone 1.

2.5 Slope stability analysis

On the other hand, the help of the SLOPE/W of the GeoStudio accomplished the investigation of the embankment slope stability. The Morgenstern–Price (El-Ramly, Morgenstern and Cruden, 2002) analysis method under the general limit equilibrium (GLE) (Lam and Fredlund, 1993) was used in the slope stability modeling. To be more specific, the Morgenstern–Price is a general method of slices that works based on limit equilibrium with the sustaining equilibrium of forces and moments acting on individual blocks. To create the blocks the soil above the slip surface has to be divided by dividing planes (Atashband, 2015). It is also important to be noted that, the interslice shear forces used in the general limit equilibrium methodology are dealt with in an equation developed by Morgenstern and Price (Morgenstern and Price, 1965) (Equation 1).

$$X = E\lambda f(x) \qquad (1)$$

Whereby: *f(x)* represents a function, λ represents the percentage (in decimal form) of the function used, *E* represents the interslice normal force, and X represents the interslice shear force.

2.6 Material characteristics

The dam embankment is divided into different zones based on the material properties; zone 1 (a and b) is more of coarse materials mixed with fine materials (mainly silt and clay) and liquid limit (w_L) ranging from 25% up to 45%. Zone 2 (core) is composed of cohesive material, and fine-grained material (clay). While Zone 3 is more of non-cohesive soil, and filter material (sand and gravel). Table 1 provides a summary of the material characteristics.

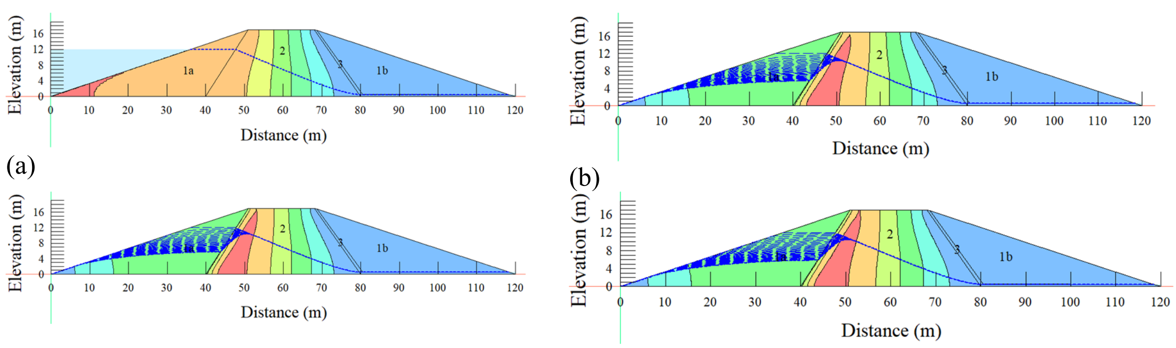
Table 1. Material properties of the embankment

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

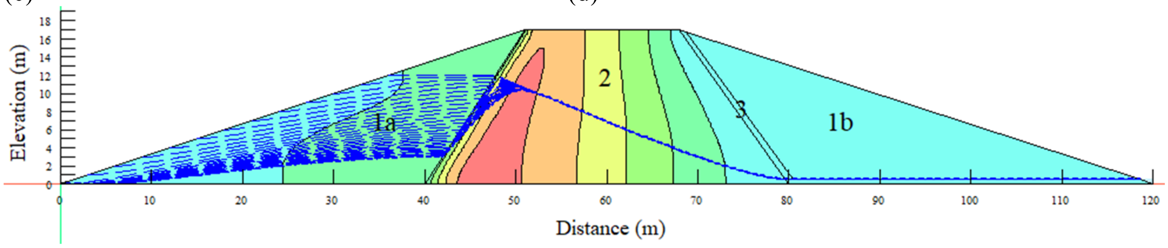
3. RESULTS AND DISCUSSION

3.1 Seepage analysis

The numerical modeling was successfully executed; from Figure 4 it can be observed that the seepage within the embankment was safely carried away through zone 1a and zone 2. The general setup shows that the embankment was properly designed to not allow seepage along the downstream face of the embankment. The phenomenon was similar to all the investigated drawdown cases. Generally, based on the phreatic lines, the seepage within the embankment can be observed to be evenly distributed (more of linear flow), while due to change in soil properties in zone 2 a more parabolic flow can be observed. In the instantaneous drawdown case, it can be observed that most of the phreatic lines are concentrated somewhere close to the foundation of the embankment. The distribution of phreatic lines becomes more evenly when the drawdown rate is reduced from fast to slow.



(c) (d)



(e)

Figure 4. Seepage analysis (a) long-term steady-state (b) instantaneous drawdown (c) 5 days drawdown (d) 10 days drawdown (e) 1m per day drawdown.

Normally, embankment dams are characterized by seepage as the impounded water seeks paths of least resistance through the dam and its foundation. However, seepage must be controlled to prevent erosion of the embankment (Omofunmi et al., 2017). If the seepage forces are relatively large enough within the embankment, there is a high chance that soil will be eroded affecting the stability of the embankment with time. It should also be noted that the seepage control requirement is highly dependent on the quantity, content, and location of the seepage problem. Moreover, reducing the extent of the seepage problem when the embankment is already constructed is difficult and expensive; and it is in most cases not attempted unless the seepage has been threatening the stability of the embankment. During the process of solving the seepage problems in embankment dams, regular monitoring is significantly essential to detect seepage and prevent a potential dam failure. The monitoring activities should include having a clear knowledge of the dam's history; this helps to determine the condition of the seepage (Singh Saluja ZHCET, Mohammad Athar ZHCET and Sarfaraz Ansari ZHCET, 2018).

3.2 Slope stability

Apart from the seepage analysis, the model embankment was also subjected to the slope stability analysis. It is also worth noting that, slope stability analysis is a crucial factor to take into account while managing various mining operations or civil engineering projects. In general, is a measurement of a slope's resistance to failure due to collapse or sliding, whether it be natural or man-made (Utepov et al., 2022). Figure 5 shows that a factor of safety of 2.344 was obtained when the embankment was subjected to the long-term steady-state reservoir conditions. Under long-term steady-state conditions, the retrieved factor of safety value is relatively high and can be regarded as safe for embankment stability. However, subjecting the embankment to the rapid drawdown situation is equally crucial in order to study how the embankment responds in this scenario.

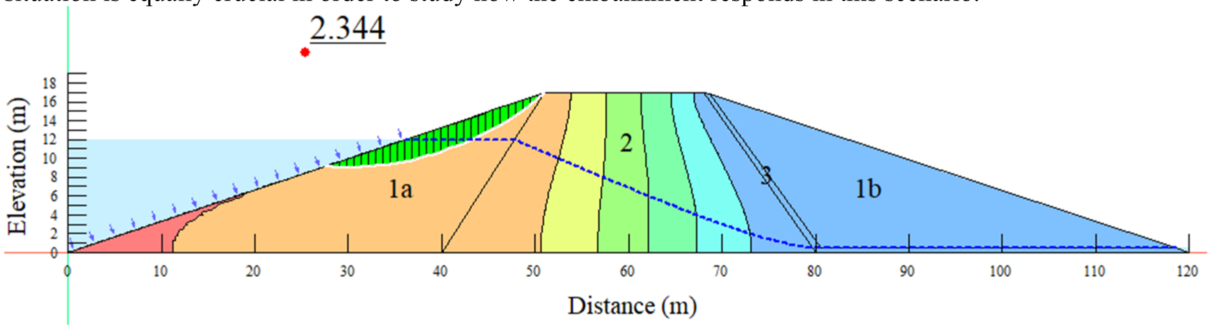
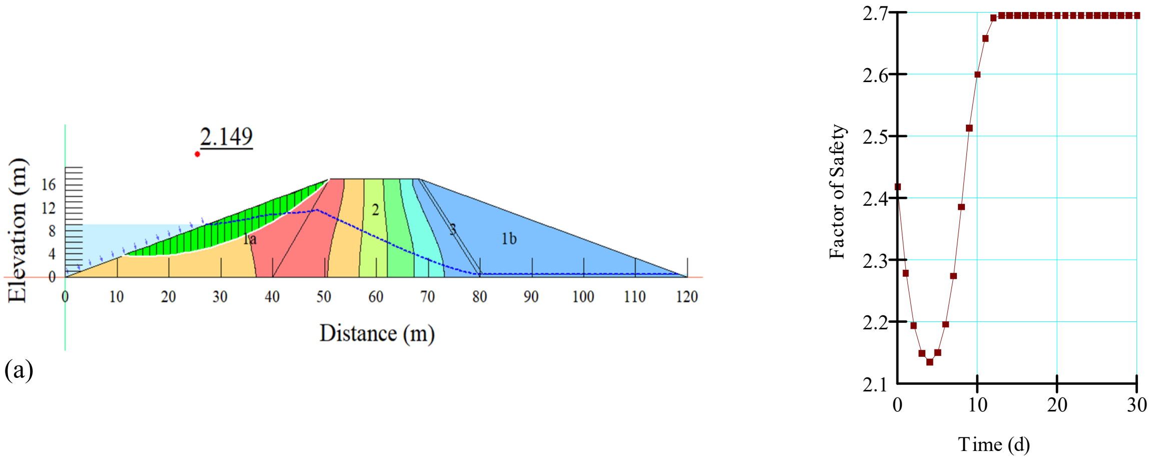


Figure 5. The long-term steady-state factor of safety.

Firstly, the embankment was subjected to the long-term steady-state slope stability analysis; whereby, a factor of safety of 2.344 was achieved. A steady-state flow condition is one in which the pressure at any location in the reservoir remains constant across time. It is also worth noting that, the long-term reservoir steady state plays a significant role in the embankment stability. Figure 6 presents the results when the embankment was subjected to the 1 m per day drawdown rate. The embankment began to lose stability during the first four days and began to restore stability on day five, as shown in the Figure. A minimal factor of safety of 2.149 was also obtained when the embankment was subjected to the 1 m per day drawdown rate; the minimum factor of safety value was attained on the fourth day of the drawdown. The retrieved factor of safety from the 1 m per day drawdown rate is equivalent to 8.32% less than the one retrieved from the long-term steady-state condition.

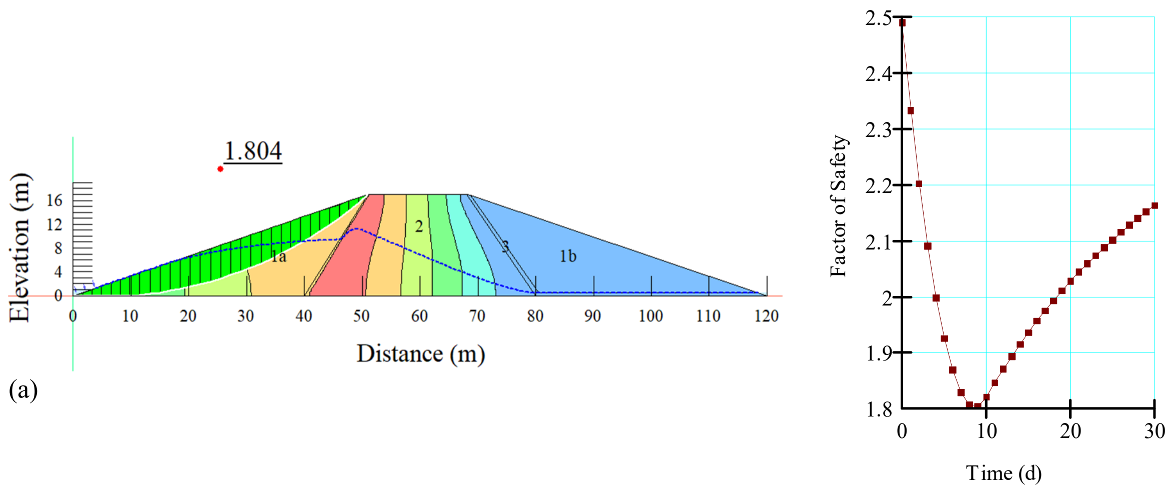


(a)

(b)

Figure 6. Drawdown (1 m per day drawdown rate); (a) embankment (b) graph of the factor of safety values.

Figure 7 presents the results when the embankment was subjected to the 10 days drawdown rate, it can be observed that the embankment was losing stability within the nine first days of the drawdown. Whereby, a minimum factor of safety of 1.804 was achieved from the 9th day of the drawdown. Moreover, it can be observed that the embankment started regaining stability from the 10th day. Additionally, the minimal factor of safety value retrieved when the embankment was subjected to a drawdown rate of 10 days is equal to a decline of 23.04% from the factor of safety value retrieved under long-term steady-state conditions. The factor of safety value shows further that despite the high factor of safety value from the long-term steady condition, the minimum factor of safety value can decrease significantly after subjecting the embankment to rapid drawdown conditions. A similar phenomenon has also been observed in other studies in the literature (A. A. Khattab, 2010; A. Irinyemi, Lombardi and M. Ahmad, 2021).



(a)

(b)

Figure 7. Drawdown (10 days drawdown rate); (a) embankment (b) graph of the factor of safety values.

After the 10 days, the rate was then reduced to 5 days to investigate further the effect of a potential rapid drawdown on the embankment stability. Figure 8 presents the results from the 5 days drawdown rate, and it can be observed that the embankment was losing stability within the five days of the drawdown process; whereby, it started regaining stability from the 5th to 6th day. Also, it can be observed that the minimum factor of safety of 1.706 was obtained within the 5th day of the reservoir draining. Also, when the embankment was subjected to the 5 days drawdown rate, the retrieved minimum factor of safety value is equivalent to a 27.22% decrease if compared to the factor of safety value retrieved from the long-term steady-state condition.

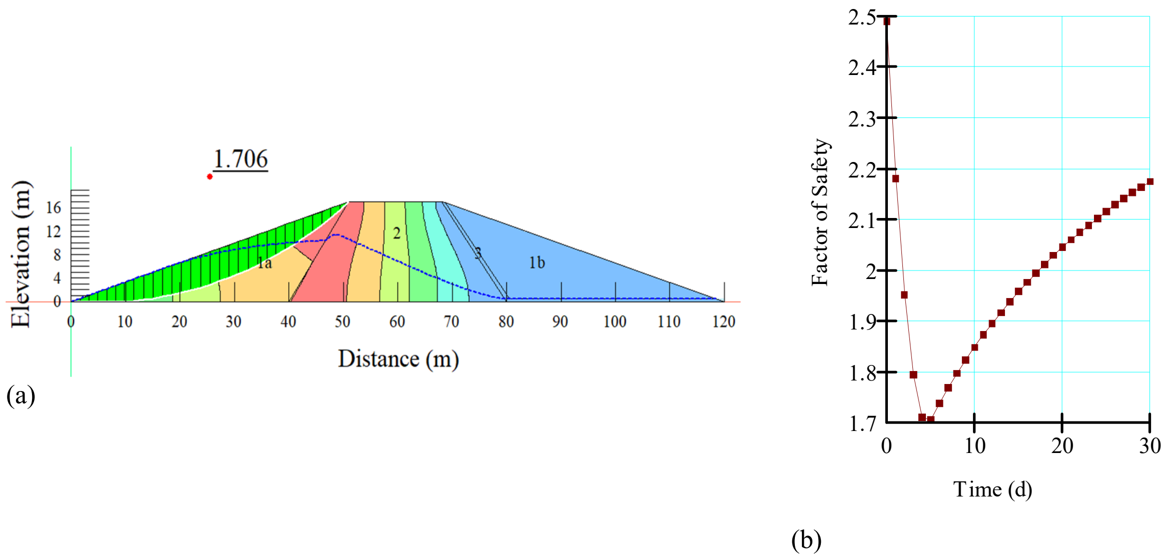


Figure 8. Drawdown (5 days drawdown rate); (a) embankment (b) graph of the factor of safety values.

Figure 8 presents the results when the embankment was subjected to the worst scenario of rapid drawdown (instantaneous), and it can be observed that the embankment lost stability from approximately 2.5 factors of safety to 1.574 within the same day of drawdown. Moreover, it can be observed that the embankment started regaining stability within the same day; however, was not able to reach the 2.5 initial factor of safety which is an indication of a potential failure. The obtained factor of safety from the instantaneous drawdown rate is equivalent to 32.85% less than the factor of safety retrieved from the long-term steady-state conditions.

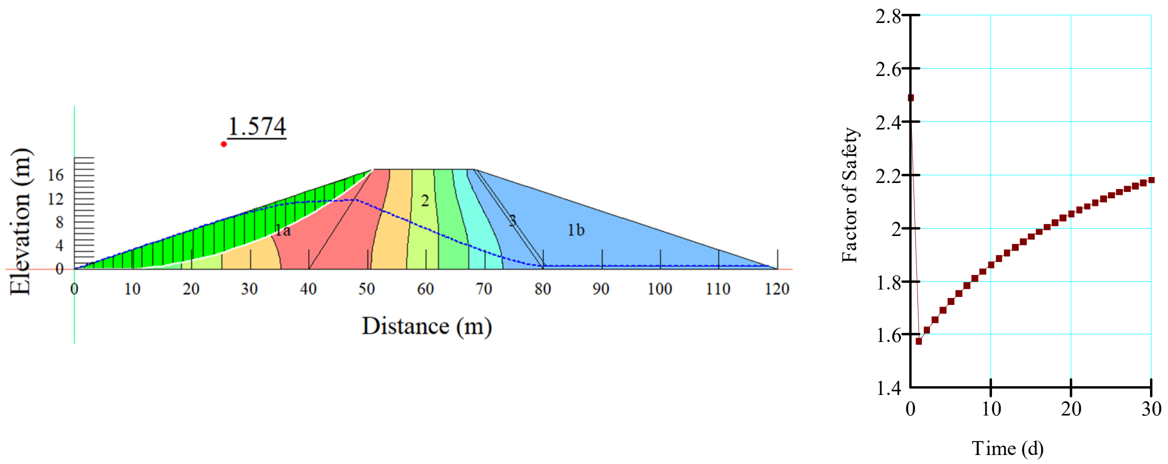


Figure 8. Instantaneous drawdown; (a) embankment (b) graph of the factor of safety values.

In the literature, it has been observed that for a static two-dimensional (2D) a minimum factor of safety of 1.3 is acceptable for temporary or low-risk slopes and 1.5 for permanent slopes (Stark and Ruffing, 2017). However, in most cases, when a factor of safety is below 1 then is considered a total embankment failure.

3.3 Single Factor Analysis of Variance (ANOVA)

Table 2 shows that a p-value of 9.97×10^{-29} was obtained after subjecting the factor of safety values from instantaneous, 5 days, 10 days, and 1 m per day drawdown rates to ANOVA, indicating that the factor of safety differences among the analyzed drawdown rates are statistically significant. It should be noted that a statistically significant p-value is less than 0.05 (usually 0.05). It provides significant evidence against the null hypothesis, as the null hypothesis has a less than 5% chance of being right (and the results are random) (Stoker, Tian and Kim, 2020). The findings also show that a drawdown rate has a substantial impact on an embankment dam's slope stability.

Table 2. Results from ANOVA

SUMMARY						
Groups	Count	Sum	Average	Variance		
Instantaneous	31	60.79289	1.961061	0.040298		
5 days	31	61.64857	1.988664	0.030041		
10 days	31	62.65467	2.021118	0.024648		
1 m per day	31	77.26121	2.492297	0.002294		
ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	5.915494	3	1.971831	81.07681	9.97× 10-29	2.680168
Within Groups	2.918464	120	0.024321			
Total	8.833958	123				

4. CONCLUSIONS

The potential effect of rapid drawdown scenarios on the stability of old dams for the case of Samarkand in Kazakhstan has been investigated. The dam has a maximum depth of 12 m and a length of 25 km located in Karaganda province in Kazakhstan that was put into operation in 1941. Both seepage and slope stability with the help of numerical modelling were investigated based on steady and transient (rapid drawdown) flow conditions. The finite element method-based modelling is achieved using SEEP/W and SLOPE/W of the GeoStudio software. The embankment was first subjected to a long-term steady-state slope stability analysis, which resulted in a factor of safety of 2.344. The pressure at any point in the reservoir remains constant over time in a steady-state flow scenario. It's also worth noting that the reservoir's long-term steady state has a big impact on embankment stability. When the embankment was subjected to a 1 m per drawdown rate, a minimum factor of safety of 2.149 was obtained; the minimum factor of safety value was reached on the fourth day of the drawdown. The factor of safety recovered from the 1 m per day drawdown rate is 8.32 percent lower than the one retrieved from the long-term steady state. Moreover, the factor of safety determined from the instantaneous drawdown rate is 32.85% lower than the factor of safety obtained from long-term steady-state conditions. The results derived in this study revealed further that, it is significantly important to investigate the stability of old embankment dams taking into account different drawdown rates as the factor of safety reduces with the increase in the drawdown rate.

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