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Research paper

The influence of material characteristics on dam stability under rapid drawdown conditions

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Abstract: A fast reduction of a reservoir level may result in instability of an earth dam caused by the high pore water pressures that remain relatively high in the embankment. Moreover, the dissipation of the accumulated pore water pressures is highly dependent on the permeability of the materials used for the embankment and the storage characteristics of the reservoir. Therefore, in the design of embankment dams, the stability analysis under rapid drawdown loading conditions is an important design case. In this study, the influence of different permeability rates on dam stability under different cases of rapid drawdown was investigated using the finite element method in SEEP/W and SLOPE/W of the GeoStudio with a case of the Lugoda dam in Ndembera catchment, Tanzania. The modeling process considers the time-dependent hydraulic conditions and the transient flow conditions using different water levels during rapid drawdown for evaluation of the factor of safety. From the 1m per day drawdown rate; the lowest minimum factor of safety value (0.90) was obtained from the 10^{-7} m/s material permeability of the upstream zone of the dam. It means that, at a drawdown rate of 1m per day, there is a potential for failure of the embankment if the hydraulic conductivity value will be somewhere below 10^{-6} m/s.

Keywords: embankment dam, factor of safety, hydraulic conductivity, pore-water pressure, slope stability

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1. Introduction

A rapid drawdown scenario arises when a slope submerged in water experiences a fast reduction of the external water level leading to the removal of the upstream water pressure [1]. In that matter, when the counterbalancing upstream water pressure has been removed, it roots to a significant effect on the upstream slope. This means the internal pore pressures in the slope cannot reduce fast enough as a result of the fast reduction of water. Moreover, the rapid drawdown case leaves the soils inside the embankment still saturated, which in turn facilitates seepage from the embankment towards the upstream slope [2].

The combination of hydrodynamic pressures and seepage from the embankment towards the upstream slope creates downward forces acting on the upstream slope while destabilizing the embankment, especially on the upstream face [3]. The generated forces are contrary to the stability and create a critical condition to the upstream slope [4]. Among many other factors, extreme flooding events have a significant contribution to rapid drawdown cases because river levels reach peak values and when the extreme event subdues the velocity of decreasing water level tends to reach maximum values also and the water levels will be reduced dramatically also [5, 6]. It is very important to establish the maximum drawdown rate that may safely be carried out is a crucial matter especially for those dams placed in extreme events areas, as the potential influence of rapid drawdown in the cases of upstream slope failures has been highlighted in several studies [7, 8].

Soil properties are among the crucial factors that determine the stability of an earth-fill dam. However, little has been reported on the response of problematic soils when subjected to rapid drawdown scenarios. In general, problematic soils can be defined as a group of soil materials that hinder the appropriate design and construction of a structure [9, 10]. When it comes to geotechnical point of view, specifically, problematic soils, are the soils with high potential to collapse, expand, disperse as well as suffer excessive settlement, or even be subjected to failure under relatively low-stress conditions [11]. The aforementioned soil response phenomena to stress are highly linked to the soil physical properties including soil saturation ratio, grain composition, the degree to which the soil has been compacted, mineralogy, as well as mechanical properties, such as preconsolidation.

Despite many studies conducted in the field of geotechnical engineering related to the embankment dams [12–14], the complexity of the problems puts more demand for studies in the field to ensure safer design and operation of the dams. It has to be noted that, the stability of earth dams for long-term conditions is highly dependent on its geometry, material properties, as well as the forces to which the dam is subjected [15]. This means the response of the upstream slope to a rapid drawdown scenario varies with the aforementioned factors. Generally, the importance of investigating the seepage and slope stability of earth-fill dams during rapid drawdown cases is of high necessity and imperative not only for the existing dams but also for a case of designing and constructing new earth fill dams [16].

Also, with the advancement in technology, the seepage analysis of earth dams has been among the major interesting points in geotechnical engineering. The theory of flow through porous media is among the approaches that can be used to estimate the amount of water seeping through and under an earth dam together with the distribution of the water pressure [17]. Where the governing equations of flow through earth dams to estimate the amount of water seeping through can be solved using the finite element method [18]. There are many computer-based programs developed not only for seepage analysis but also for slope stability [19, 20]. GeoStudio is among the widely applicable software for seepage and slope stability for embankment dams. GeoStudio is an integrated software suite using numerical-based modeling for modeling seepage using its sub-unit SEEP/W, slope stability using SLOPE/W, as well as other functionalities such as ground deformation, and heat and mass transfer in soil and rock [21].

In the recent past, numerical modeling has gained more interest and has become an important tool for defining and tackling geological problems [22–24]. Technological progress has been simplifying the process of understanding soil behavior under different loading perspectives [25].

While previous studies focused on investigating the effects of seepage and forces separately with general embankment case studies under mixed soil types, the present study tries to investigate what would have been the response of an individual soil type applied to an embankment subjected to a rapid drawdown scenario.

In this study, different hydraulic conductivities are tested and investigated in terms of their influence on the slope stability of an embankment dam under different rapid drawdown scenarios. The investigation is achieved using the finite element method with the help of SEEP/W and SLOPE/W of the GeoStudio software for a case of the Lugoda dam in the Ndembera catchment in Tanzania. The modeling process takes into account the time-dependent hydraulic conditions and the transient flow conditions using different water levels during rapid drawdown for evaluation of the factor of safety.

2. Materials and methods

2.1. Case study description

The Ndembera sub-basin of the Great Ruaha catchment is located in the south-central of Tanzania (Fig. 1). In general, the Great Ruaha catchment is located within approximate latitudes 70 41′ and 90 25′, South, and longitudes 330 40′ and 350 40′ East. that also flows through the Usangu wetlands and the Ruaha National Park. The case study is characterized by moderate to steep slopes woodland mainly from Miombo trees. Specifically, the case study is located in the Usangu plains in Mbarali and Mufindi districts at an altitude of 1,050 m above mean sea level. Upon its completion, the Lugoda Dam would be located approximately 50 km upstream of Madibira town.

The climate is characterized by moderate to high temperatures, low wind speeds, and high humidity. Temperatures are usually below 15°C with rainfall ranging between 1,000 to 1,600 mm per annum during a single rain season from November through May. The dry and cold season in this zone lasts from June to September with annual average evapotranspiration of 1,811 mm.

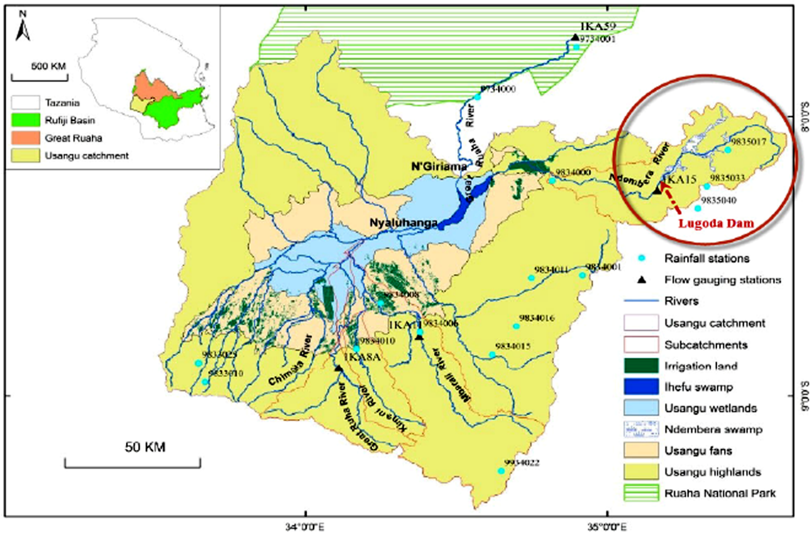

Fig. 1. Case study map [27]

Geologically, the reservoir area in the Ndembera catchment is an incoherent superficial material area (yellow color) that is alluvial and or lacustrine and is composed of gravel sand silt and clay. While, the surrounding area around the dam is comprised of foliated crystalline rock that is gneiss and schist more or less foliated magmatic granites, gneiss, schist, amphibolites granularities, and meta-dolerites [26].

2.2. The embankment geometry and soil characteristics

The embankment geometry (Fig. 2) is composed of five different zones with zones 3a and 3b being similar in terms of material properties. Different material properties were assigned to each zone of the embankment with zone 1 mainly characterized by coarse material mixed with fine materials (silt and clay fraction) under different saturated hydraulic conductivities (k_{sat}) and liquid limit (w_L) ranging from 25% to 45%. Zone 2 is

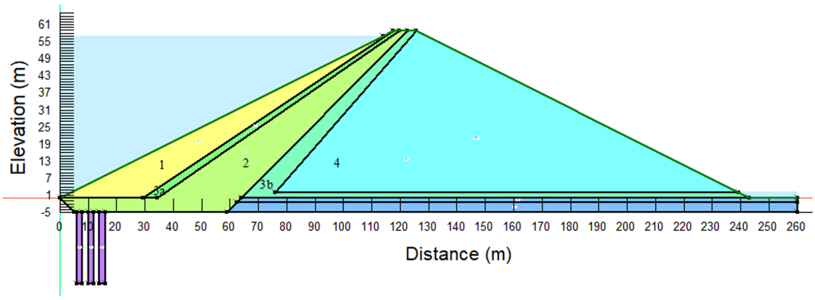

Fig. 2. Embankment geometry

characterized by cohesive material, fine-grained material, clay with different ksat values. While Zone 3a and 3b are characterized by non-cohesive soil, filter material (sand and gravel), and Zone 4 is characterized by coarse material with a very low content of fines.

Table 1 provides a summary of the material characteristics for each zone of the embankment investigated in this study. The geotechnical parameters were derived both from laboratory tests and previous testing.

Table 1. Embankment material properties

Parameter	Zone			
	Zone 1	Zone 2	Zone 3a,b	Zone 4
Saturated hydraulic conductivity (k_{sat}), m/s	$5 \cdot 10^{-5}$	10^{-8}	10^{-4}	$5 \cdot 10^{-5}$
	10^{-5}			
	$5 \cdot 10^{-6}$			
	10^{-6}			
	$5 \cdot 10^{-7}$			
	10^{-7}			
Diameter at passing 10% (mm)	0.1	0.002	0.2	0.1
	0.05			
	0.032			
	0.015			
	0.01			
	0.005			
Diameter at passing 60% (mm)	40	0.05	0.8	40
	36			
	32			
	28			
	24			
	20			
Liquid limit (%)	25 to 45	50		
Unit weight (kN/m^3)	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	–	–

2.3. General modelling process

Finite element method analyses were performed to investigate the potential effect of a dam's rapid drawdown on slope stability of an earth-fill embankment with soil properties as determined by hydraulic conductivity. Five different cases were investigated; steady-state, instantaneous drawdown, 5-days drawdown, 10-days drawdown, and 1m per day drawdown rate to a half of the maximum water level. However, the transient drawdown cases stand to be the main focus of this study. For the second case, it is assumed that water in the dam or reservoir is drawn instantaneously and the stability factors were investigated at the end of the modeling process. For cases three, four, and five, a specific time of 5, 10, and 28.5 days, respectively were assigned to investigate how the stability factors respond with the different drawdown rates. The instantaneous case represents the extreme situation or worst scenario. The seepage analyses were carried out concurrently with stability analysis.

A combination of SEEP/W [28] and SLOPE/W [29] GeoStudio sub-software was used to investigate the problem. Specifically, the seepage analysis was accomplished using SEEP/W in two-dimensional sections, which is based on FEM, while SLOPE/W was used for the slope stability analysis of the embankment based on slip surfaces, pore-water pressure conditions, soil properties, and loading conditions. To capture the effect of the hydraulic conductivity values, other parameters such as the geometry of the embankment were kept constant in all the drawdown cases while changing the hydraulic conductivity values in zone 1. In that matter, each case had a combination of seepage analysis (steady-state and transient) and slope stability analysis.

2.4. Embankment seepage analysis

The simulation of the drawdown behavior of a slope started by establishing a long-term steady-state the using Steady-state type of analysis. The established steady-state was then used as a parent to the transient flow analysis, in which the transient flow analyses used seepage-induced pore pressures from the initially performed steady-state analysis. As noted before, the analyses comprised of different drawdown rates and isotropic hydraulic conductivity values. The variation of water level during the drawdown process was modeled using a linear function that was specified as a boundary condition (Fig. 3) on the upstream

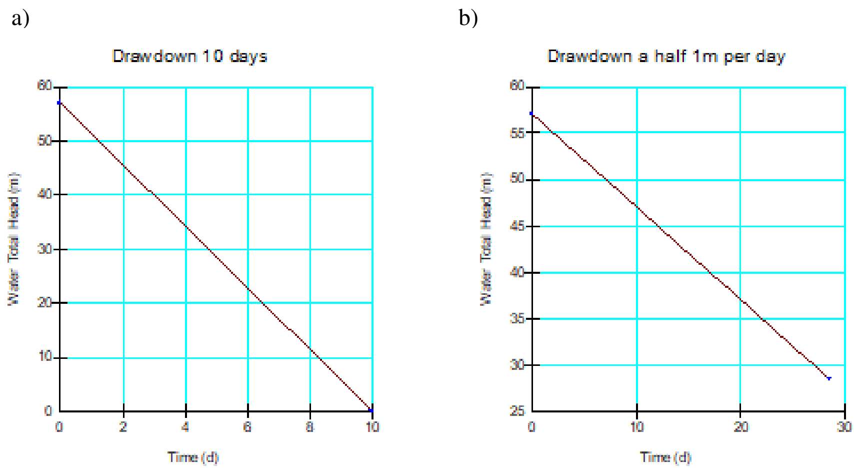

Fig. 3. Drawdown boundary conditions (a) 10 days drawdown rate (b) 1m per day drawdown rate

face of the embankment during the transient seepage analyses. The transient seepage analyses were used as parents to the slope stability analyses. The established flow parameters such as pore water pressures during the transient flow analyses were later used as significant inputs to the stability analysis with SLOPE/W.

2.5. Slope stability analysis

The slope stability analysis was achieved employing the SLOPE/W sub-unit of the GeoStudio software. To accomplish that, a specific analysis was defined for each of the slope stability analyses using the Morgenstern–Price [30] analysis method under the general limit equilibrium (GLE) [31]. Generally, as the general limit equilibrium formulation permits for a range of interslice shear-normal force conditions, the approach has also been founded on two factors of safety equations with the following perspectives:

i. In the first equation, the factor of safety is computed with respect to moment equilibrium (F_m).
ii. The second equation computes the factor of safety with respect to horizontal force equilibrium (F_f).

However, the applicability of the two equations in the computations of a factor of safety was initially published by Spencer [32], (see Equations (2.1) and (2.2)). Spencer's method can be termed as a modified and extended version of Bishop's simplified method. Referring to Bishop's simplified method, a factor of safety (F) is calculated as the ratio of total strength available (S) on the slip surface to the total shear strength mobilized (S_m) [33], as summarized in Equation (2.1).

$$F = \frac{S}{S_m} \tag{2.1}$$

Moreover, in Spencer's analysis, the derived resultant of pair of interslice forces (Q) is computed using Equation (2.2).

$$Q = \gamma H b \left[\frac{\dfrac{c'}{F\gamma H} + \dfrac{h \tan\varphi'}{2HF}(1 - 2r_u + \cos 2\alpha) - \dfrac{h \sin 2\alpha}{2H}}{\cos\alpha \cos(\alpha - \theta) \left[1 + \dfrac{\tan\varphi'}{F} \tan(\alpha - \theta) \right]} \right] \tag{2.2}$$

where: b, h – the width and mean height of slice, respectively, α – the slope of base of the slice, F – a safety factor, θ – the slope of resultant of pair of interslice forces, r_u – the pore-pressure coefficient, γ – the bulk density, H – the height of embankment, φ' – the angle of shearing resistance with respect to effective stress, c' – the cohesion with respect to effective stress.

More specifically, the Morgenstern–Price is a general method of slices based on limit equilibrium with the satisfying equilibrium of forces and moments acting on individual blocks as a requirement. In this method, the aforementioned blocks are created by dividing the soil above the slip surface by dividing planes [34]. Moreover, the interslice shear forces in the general limit equilibrium approach are dealt with an equation firstly proposed by Morgenstern and Price [35], as shown in Equation (2.3).

$$X = E\lambda f(x) \tag{2.3}$$

where: $f(x)$ – a function, λ – percentage (in decimal form) of the function used, E – interslice normal force, X – interslice shear force.

3. Results and discussion

Both the seepage and slope stability analyses were mainly divided into five categories determined by the type of drawdown rate. However, in this study, the main interest was on the 1m per day drawdown rate; where the reservoir was drained to half of the maximum water level. The analyses were accomplished for both steady-state and transient flow conditions, while among many other parameters; the nature of piezometric lines and pore water pressures were investigated.

3.1. Seepage analysis

Figure 4 presents the steady-state seepage analysis results with different hydraulic conductivity values applied in zone 1. The nature of seepage as indicated by the piezometric lines is observed to be sharply moving downward through zone 2 towards the drainage zone.

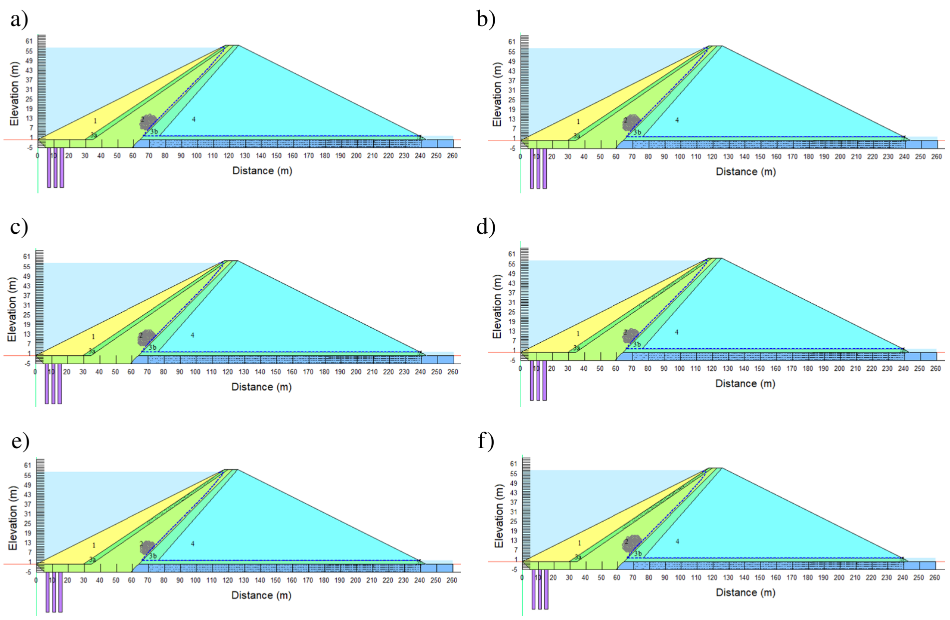

Fig. 4. Steady state seepage: a) $k_{\text{sat}} = 5 \cdot 10^{-5}$ m/s, b) $k_{\text{sat}} = 10^{-5}$ m/s, c) $k_{\text{sat}} = 5 \cdot 10^{-6}$ m/s, d) $k_{\text{sat}} = 10^{-6}$ m/s, e) $k_{\text{sat}} = 5 \cdot 10^{-7}$ m/s, f) $k_{\text{sat}} = 10^{-7}$ m/s

As previously mentioned, the drawdown rate of 1m per day to half of the maximum water level was the main interest of this study. Fig. 5 presents the seepage analysis results with $k_{\text{sat}} = 10^{-5}$ and 10^{-7} m/s in zone 1. It can be observed that, as the hydraulic conductivity reduces in zone 1 making it less permeable, it has a significant effect on the dissipation of pore water pressures after the drawdown. The curves of the piezometric lines in Fig. 5a are flatter than the ones in Fig. 5b. The phenomenon reveals further that, under rapid drawdown scenarios zone 1 has to be more permeable to allow easy dissipation of water pressure and reduce the risk of failure.

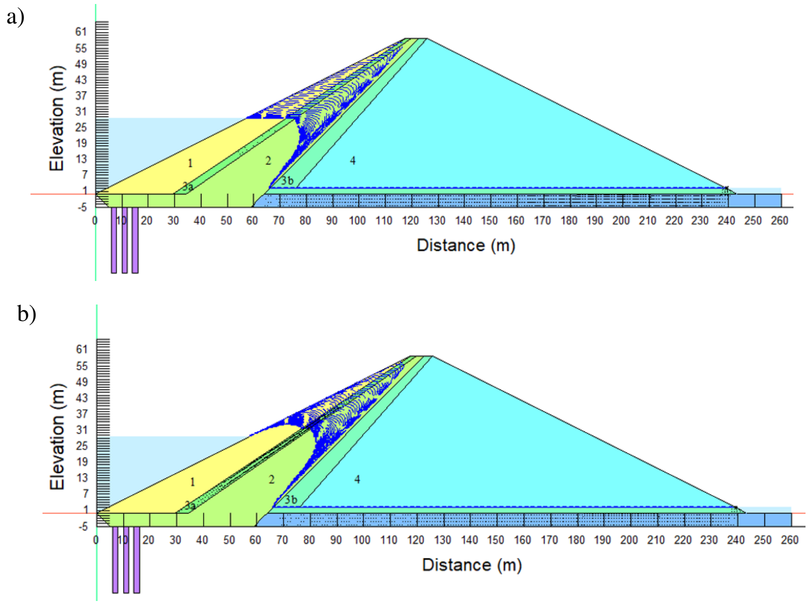

Fig. 5. A half drawdown (1 m per day) seepage: a) $k_{\text{sat}} = 10^{-5}$ m/s, b) $k_{\text{sat}} = 10^{-7}$ m/s

3.2. Slope stability analysis

The slope stability analysis cases were mainly determined by the saturated hydraulic conductivities (permeabilities) in zone 1 and the drawdown rates. However, this study's interest was on the 1m per day drawdown rate as the most realistic case.

Figure 6 presents the slope stability analysis results when zone 1 was subjected to the hydraulic conductivity of 10^{-5} m/s. From Fig. 6, it can be observed that the minimum factor of safety equal to 1.321 was retrieved from the last day of the drawdown (28$^{\text{th}}$ day). Also, the factor of safety started dropping immediately after the reservoir drawdown and kept on dropping to the 28$^{\text{th}}$ day of the drawdown and slowly started regaining stability as the pore-water pressures kept on dissipating in the embankment. However, after a while, the factor of safety value remains almost constant to a value of approximately 1.4 for the entire remaining period of the simulation.

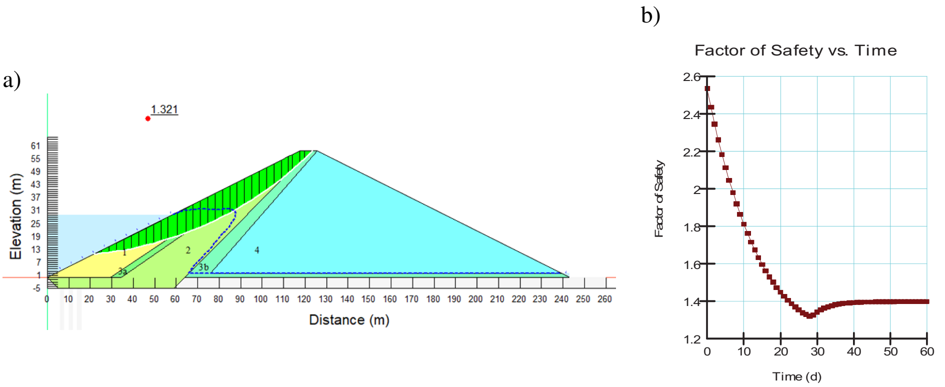

Fig. 6. Slope stability under $k_{sat} = 10^{-5}$ m/s

Figure 7 shows the slope stability analysis results when zone 1 was subjected to the hydraulic conductivity of 10^{-6} m/s. Similarly, as observed from the 10^{-5} m/s, the factor of safety tends to drop immediately after the beginning of the reservoir drawdown process and kept on dropping to the 28th day (last day) of the drawdown and slowly started regaining stability as the pore-water pressures kept on dissipating in the embankment. Contrary to the 10^{-5} m/s, the trend of regaining stability for the hydraulic conductivity of 10^{-6} m/s is a bit sharper than the 10^{-5} m/s, with the factor of safety increasing from approximately 1.2 to 1.4, taking more time than the 10^{-5} m/s.

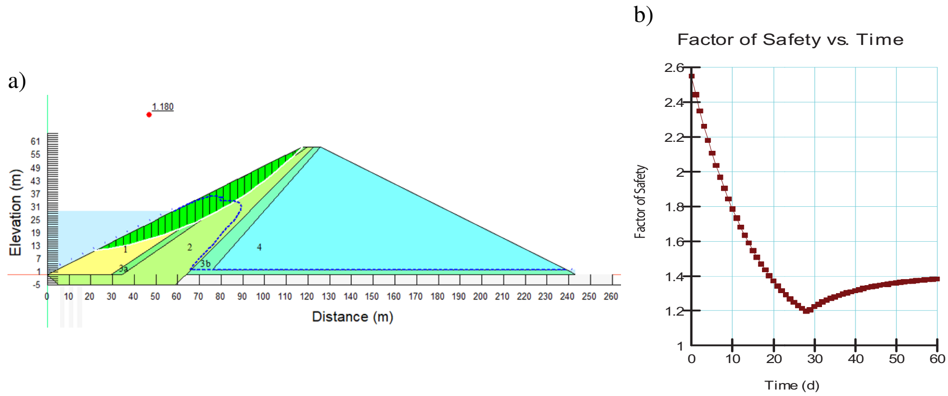

Fig. 7. Slope stability under $k_{sat} = 10^{-6}$ m/s

Figure 8 presents the slope stability analysis results when zone 1 was subjected to the hydraulic conductivity of 10^{-7} m/s. As previously observed, the factor of safety values started reducing following the reservoir drawdown process and kept on reducing to the 28th day (last day) of the drawdown and slowly started regaining stability as the pore-water pressures kept on dissipating in the embankment. However, for the 10^{-7} m/s, the factor of safety values went all the way to below 1 with an alarm of a potential failure. In this phenomenon, it is noticed that, for a combination of the embankment material properties and the drawdown rate of 1 m per day, the zone 1 hydraulic conductivity should be higher than 10^{-7} m/s.

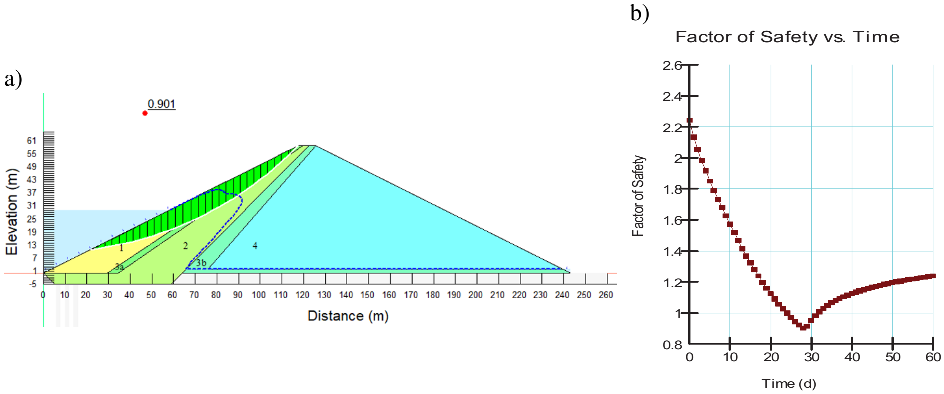

Fig. 8. Slope stability under $k_{sat} = 10^{-7}$ m/s

From the minimum values of factor of safety (Table 2), it is revealed further that, as Zone 1 becomes more impervious following the reduction of saturated hydraulic conductivity, the embankment is subjected to a potential failure. From Table 2, it can be observed that the lowest minimum factor of safety value of 0.901 corresponds to the 10^{-7} m/s saturated hydraulic conductivity. According to [36], if the factor of safety is near or below 1, then severe erosion or shallow slumping is a phenomenon likely to occur. This observation shows the general potential risk of an embankment failure when the factor of safety is below 1. As a slope stability improvement approach, the application of vegetation on the slope can also be useful to reduce such a problem with the fact that the vegetation roots improve soil cohesion [37]. In general, from Table 2, it can be seen that the highest minimum value of factor of safety was achieved from the $5 \cdot 10^{-5}$ m/s and reduces towards 10^{-7} m/s as the lowest hydraulic conductivity value in the list.

Table 2. The minimum values o factor of safety are based on the saturated hydraulic conductivity values in zone 1 under 1m per day drawdown rate

Sat. hydraulic conductivity (m/s)	Minimum values of factor of safety
$5 \cdot 10^{-5}$	1.355
10^{-5}	1.321
$5 \cdot 10^{-6}$	1.296
10^{-6}	1.180
$5 \cdot 10^{-7}$	1.108
10^{-7}	0.901

Moreover, in a real situation is almost difficult to achieve an instantaneous drawdown, but, is always preferable to include potential worst scenarios in a slope stability analysis. Fig. 9 highlights the minimum values of factor of safety from the instantaneous, 5 days and 10 days drawdown rates for the highest ($5 \cdot 10^{-5}$ m/s) and lowest (10^{-7} m/s) saturated hydraulic conductivities. It can be observed that all the factor of safety values are below 1.0, revealing further that for the embankment material properties, the drawdown rate should not be below 1 m per day.

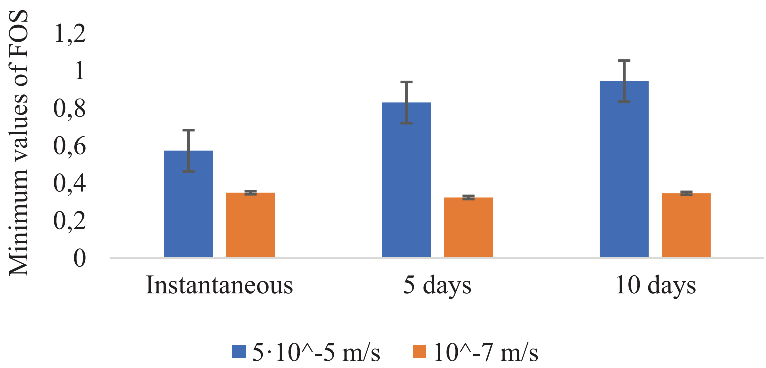

Fig. 9. Minimum values of factor of safety from the instantaneous, 5 days and 10 days drawdown rates under $5 \cdot 10^{-5}$ m/s and 10^{-7} m/s saturated hydraulic conductivities: FOS- factor of safety

4. Conclusion

The potential influence of material characteristics on the slope stability of an embankment dam under rapid drawdown conditions has been investigated. The influence of material characteristics on slope stability was investigated mainly based on the different hydraulic conductivity values assigned to zone 1 of the embankment. The investigation was achieved using the finite element method for a case of the Lugoda dam in the Ndembera catchment in Tanzania. From the analysis results it was observed that, as zone 1 becomes more impermeable, the pore-water pressures in the embankment remain relatively high after the drawdown as the impermeability affects the easy dissipation of pore-water pressures. Also, the lowest minimum factor of safety value is obtained when the hydraulic conductivity value drops to 10^{-7} m/s, with a value of 0.901 which is below 1. The phenomenon indicates that, at a drawdown rate of 1m per day to a half of the maximum water level, there will be a potential failure of the embankment if the hydraulic conductivity value is below 10^{-6} m/s. Alternatively, if the hydraulic conductivity value has to be below 10^{-6} m/s, then a lower drawdown rate has to be applied to eliminate the potential failure. The results in this study revealed further that, there is a significant relationship between slope stability and the combination of a drawdown rate and embankment material properties. Therefore, the phenomenon has to be carefully investigated and considered during the design phase of an embankment dam.

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Wpływ właściwości wbudowanych materiałów na stateczność zapory w warunkach szybkiego obniżenia poziomu wody w zbiorniku

Słowa kluczowe: przewodność hydrauliczna, ciśnienie wody w porach, stateczność skarpy, zapora ziemna, współczynnik stateczności

Streszczenie:

Szybkie obniżenie poziomu zwierciadła wody w zbiorniku może wywołać utratę stateczność zapory ziemnej wynikającą z dużych wartości ciśnienia wody w porach pozostających w strefie odwodnej zapory. Rozpraszanie się ciśnienia wody w porach w zaporze ziemnej zależy od przepuszczalności materiałów użytych w nasypie oraz właściwości retencyjnych zbiornika. W projektowaniu zapór nasypowych analiza stateczności podczas szybkiego opróżniania zbiornika jest ważnym przypadkiem obliczeniowym. W niniejszym artykule przeanalizowano wpływ przepuszczalności materiałów na stateczność zapory przy różnych prędkościach szybkiego opróżniania zbiornika z wykorzystaniem metody elementów skończonych przy pomocy programów SEEP/W i SLOPE/W oprogramowania GeoStudio na przykładzie zapory Lugoda w Ndemberze zlewni w Tanzanii. W procesie modelowania uwzględniono warunki hydrauliczne zależne od czasu oraz przejściowe warunki przepływu przy różnych poziomach wody podczas szybkiego opróżniania zbiornika przy ocenie współczynnika stateczności. Przy szybkim opróżnianiu zbiornika wynoszącym 1 m na dobę zaobserwowano, że najmniejszą wartość współczynnika stateczności (0,90) uzyskano przy wartości przewodności hydraulicznej wynoszącej 10^{-7} m/s. Oznacza to, że przy prędkości obniżania poziomu wody w zbiorniku o 1 m na dobę, istnieje możliwość utraty stateczności nasypu, jeśli wartość przewodności hydraulicznej będzie mniejsza niż 10^{-6} m/s.

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