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Stability Assessment of Homogeneous Embankment Dam Under Variable Drawdown Rates Using Unsaturated Soil Parameters

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ABSTRACT Embankment dams are critical for sustainable water resource management, providing irrigation, hydropower, flood control, and water supply. One of the critical threats to an embankment dam stability is rapid drawdown, when reservoir levels fall faster than pore pressure dissipation in the upstream slope. This condition reduces shear strength and can trigger failure. One of the commonly used methods for rapid drawdown assessment is the three-stage approach developed in the early 1990s, which provides a practical framework by combining drained and undrained soil strength. However, these methods do not explicitly consider the influence of drawdown rate, which can strongly affect stability. This study evaluates the effect of drawdown rate on the stability of an embankment dam using unsaturated soil mechanics framework and compares the results with those from the three-stage method. Numerical analyses were carried out using coupled seepage and slope stability modelling. The soil-water characteristic curve of the clay core was estimated from index properties. Three drawdown rate variations were examined: half a meter per day, one meter per day, and two meters per day. The result showed that the three-stage method produced higher factors of safety than the unsaturated framework. Unsaturated framework also showed lower factor of safety for faster drawdown rates. This study highlights that the three-stage method may overestimate the stability of dam embankment during rapid drawdown. Incorporating unsaturated soil mechanics provides a more realistic assessment and offers insights for improving dam safety, particularly under conditions where faster drawdown may occur.

KEYWORDS Rapid Drawdown; Embankment Dam Stability; Unsaturated Soil Mechanics; Drawdown Rate; Three-Stage Method

1 INTRODUCTION

Embankment dams' safety and long-term performance are paramount, particularly as global water demand continue to rise with population growth. One of the key threats to dam stability is rapid drawdown, a condition in which the external reservoir water pressure drops quickly while pore pressures within the upstream slope dissipate more slowly, leaving the slope in a weakened state.

Duncan et al. (1990) proposed a widely cited three-stage method for rapid drawdown stability. The approach combines drained and undrained strength concepts by first determining effective stresses before drawdown, then applying drained strengths to free-draining zones and undrained strengths to impervious zones after drawdown, and finally correcting cases where drained strengths are lower than undrained values. The method is embedded in dam engineering practice, referenced in USACE (US Army Corps of Engineers) guideline (2003) and implemented in commercial stability software, making it one of the most commonly applied approaches.

More recently, Kim et al. (2023) analysed embankment slope instability under rapid drawdown using unsaturated soil mechanics framework. Their study highlighted the vulnerability of upstream slopes immediately after drawdown and showed how factors such as tension cracks, matric suction, and pore-pressure redistribution influence stability. This approach provides valuable insight into failure mechanisms that are not captured by traditional drained–undrained methods.

The three-stage method from Duncan et al. (1990) offers a practical and reliable framework. However, it does not explicitly account for the rate of drawdown, which directly affects pore-pressure dissipation and stability. Hence, this study aims to address that gap by evaluating the influence of drawdown rate on embankment dam stability using unsaturated soil mechanics analysed in SEEP/W and SLOPE/W integration, and comparing the results with those from the three-stage method. The findings aim to improve current assessment frameworks, particularly under climate change scenarios which may lead to faster drawdown rates than originally considered in the dam design.

2 METHODS

The embankment dam analysed is based on a homogeneous dam located in Riau Island in Indonesia, built using clay and incorporated with toe drain at both upstream and downstream. The upstream slope is protected by rip-rap made of rockfill. The rapid drawdown analysis for both Duncan et al. (1990) method and using unsaturated soil parameters is conducted using Geostudio 2024 software, using the SEEP/W and SLOPE/W/W functions. The cross-section of the dam modelled is displayed in Figure 1.

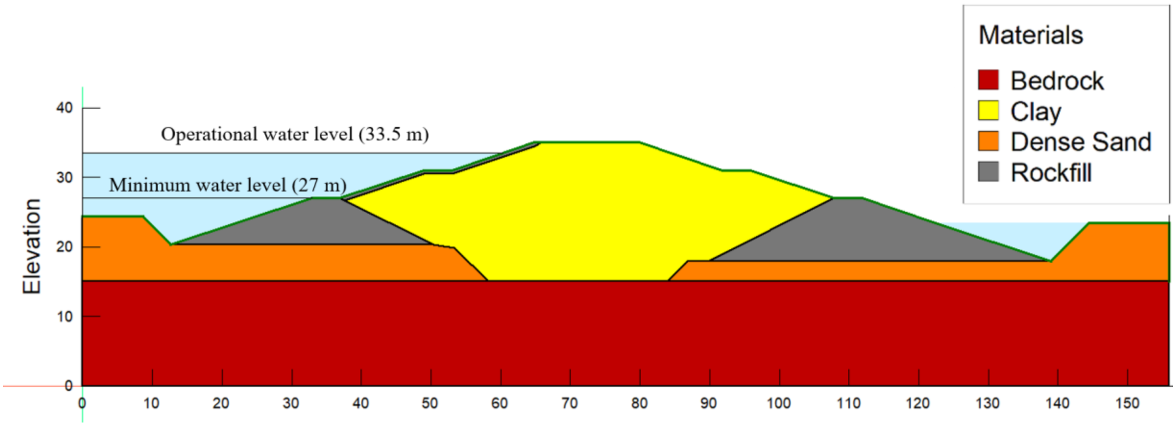

Figure 1. Cross section of embankment dam

The clay material is modelled using unsaturated soil parameters, while the dense sand, which is part of the foundation, is modelled as saturated material only, as the material is always below the water table. The clay parameter is displayed in Table 1.

Table 1. Parameter of clay

Description	Unit	Value
Unit weight (*γ*)	kN/m^3	16.15
Effective cohesion (*c'*)	kPa	15
Friction angle (*ϕ*)	°	24
Undrained strength (s_u)	kPa	54
Plasticity index (*PI*)	-	15
Material passing sieve no 200 (PI_{200})	-	60%
Saturated hydraulic conductivity (*k*)	m/s	3.7 x 10^{-8}
Saturated volumetric water content (θ_s)	-	0.56
Residual water content	-	0.09

The soil water characteristic curve (SWCC) of the clay is determined using Fredlund-Xing's (1994) method as expressed in equation (1).

$$\theta_w = c_\psi \frac{\theta_s}{\left\{ln\left[e + \left(\frac{\psi}{a}\right)^n\right]\right\}^m} \quad (1)$$

Where θ_w is the volumetric water content, c_ψ is the correction function, θ_s is saturated volumetric water content, e is natural number (2.71828), and a, n, m are curve fitting parameters. The curve fitting parameter is obtained by applying equation by Perera et al. (2005) as shown in equations (2) to (4)

$$a = 32.835 \ln (PI * P_{200}) + 32.438 \quad (2)$$

$$n = 1.421 (PI * P_{200}) - 0.3185 \quad (3)$$

$$m = -0.2154 \ln (PI * P_{200}) + 0.7145 \quad (4)$$

The SWCC developed with Fredlund-Xing's (1994) method using the fitting parameters obtained from equations (2) to (4) is displayed in Figure 2.

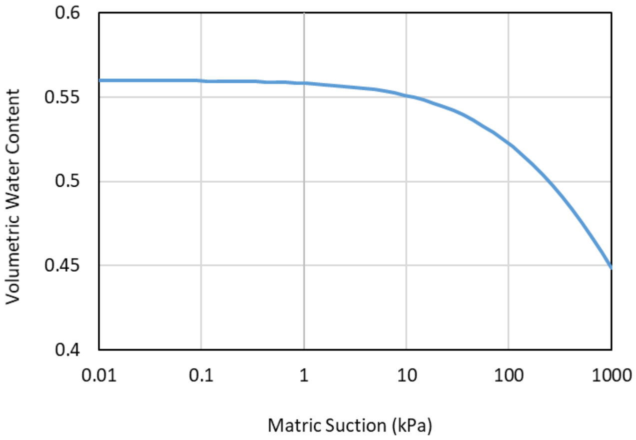

Figure 2. Soil water characteristic curve (SWCC) of the clay material

The hydraulic conductivity curve for partially saturated material can be developed from the SWCC using Van Genuchten's (1980) method by implementing equation (5).

$$k_w = k_s \frac{[(1-(a\psi^{n-1})(1+(a\psi^n)^{-m})]^2}{(1+ a\psi^n)^{m/2}} \quad (5)$$

Where k_w is hydraulic conductivity for a specified water content or matric suction (in m/s), k_s is saturated hydraulic conductivity (in m/s), ψ is matric suction (kPa). The hydraulic conductivity curve developed using equation (5) and SWCC from Figure 2 for clay material is displayed in Figure 3.

The rockfill and dense sand material are defined as saturated only material, as in the upstream slope, both materials are always below the water level. The input parameter is summarized in Table 2.

The rapid drawdown analysis using unsaturated soil parameter are conducted from the operational water level until minimum water level at three different drawdown rates, which are 0.5 m/day, 1 m/day, and 2 m/day. The changes in safety factor are recorded in one-day scale for 20 days duration. All slope stability analysis is conducted using Spencer (1967) method available at SLOPE/W options as recommended by USACE (2003) for embankment dam design final check, as this method satisfies both force and moment equilibrium for all slices, providing a more accurate and stable solution.

The phreatic line obtained from steady state seepage analysis for both operational and minimum water level using SEEP/W is used as reference to conduct total – effective strength parameter with Duncan et al. (1990) method for comparison, as this method requires the phreatic line to be defined before stability analysis conducted, as displayed in Figure 4.

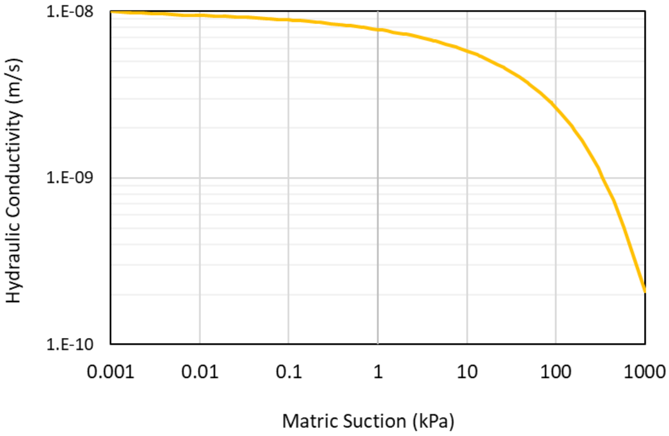

Figure 3. Hydraulic conductivity curve for clay material

Table 2. Parameter of rockfill and dense sand

Description	Unit	Material	
		Rockfill	Dense Sand
Unit weight (γ)	kN/m^3	18	20
Effective cohesion (c')	kPa	-	-
Friction angle (ϕ)	°	36	38
Saturated hydraulic conductivity (k)	m/s	1×10^{-3}	5×10^{-4}
Saturated volumetric water content (θ_s)	-	0.3	0.2

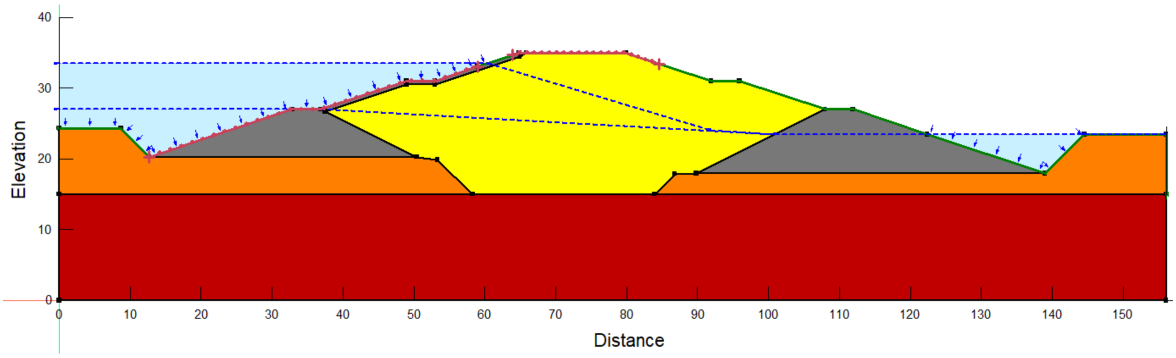

Figure 4. Phreatic line used for Duncan et al. (1990) analysis

3 RESULTS

The evolution of safety factor for the three drawdown rates is shown in Figure 5. On day 0, when the drawdown has yet to occur, the safety factor obtained is 3.637, with the slip surface shown in Figure 6. The drawdown leads to a reduction in safety factor, with higher drawdown rates showing steeper reduction in safety factor. The minimum safety factor reached for 0.5 m/day, 1 m/day and 2 m/day is 2.399 (day 10), 2.328 (day 5) and 2.264 (day 3), respectively. The critical slip surfaces in that instance are shown in Figure 7-9. After the minimum safety factors are reached, the safety factors increase and eventually converge for all three drawdown rates. This can be explained as follows: at the onset of drawdown, the external water pressure supporting the slope decreases rapidly, while the pore pressures within the clay core dissipate more slowly due to its low permeability. As a result, the effective stress along the upstream slope reduces sharply, leading to a temporary drop in stability. After this initial period, the factor of safety gradually increases and stabilizes as pore pressures dissipate and the phreatic surface approaches equilibrium.

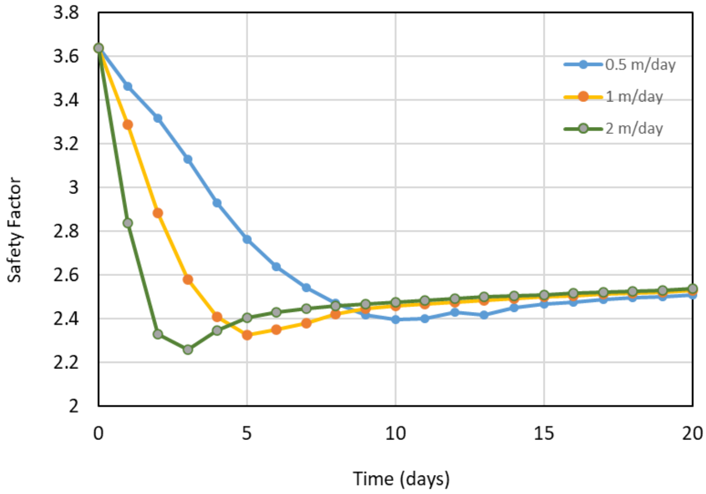

Figure 5. Safety factor progression for each drawdown rate

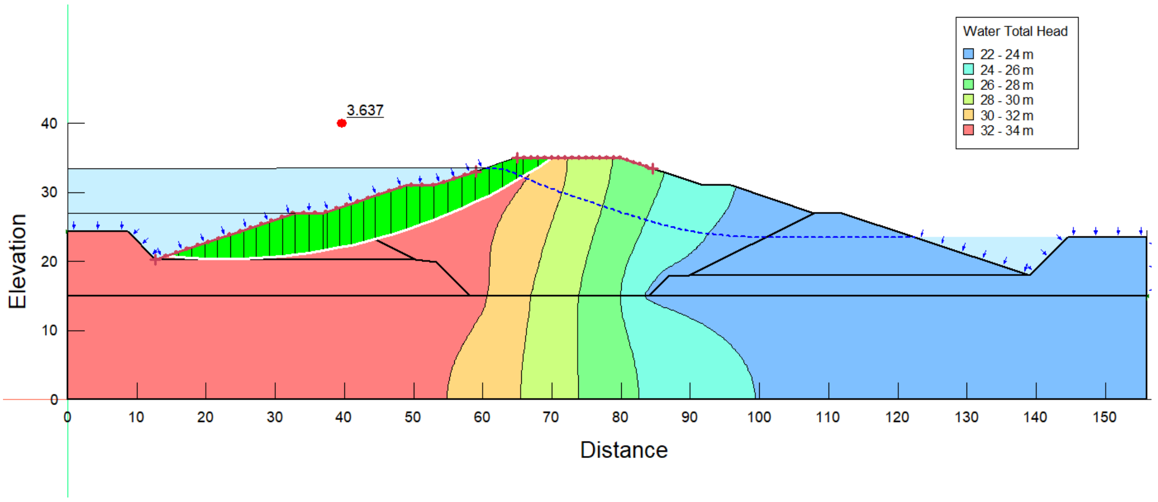

Figure 6. Steady-state slope stability analysis (day 0)

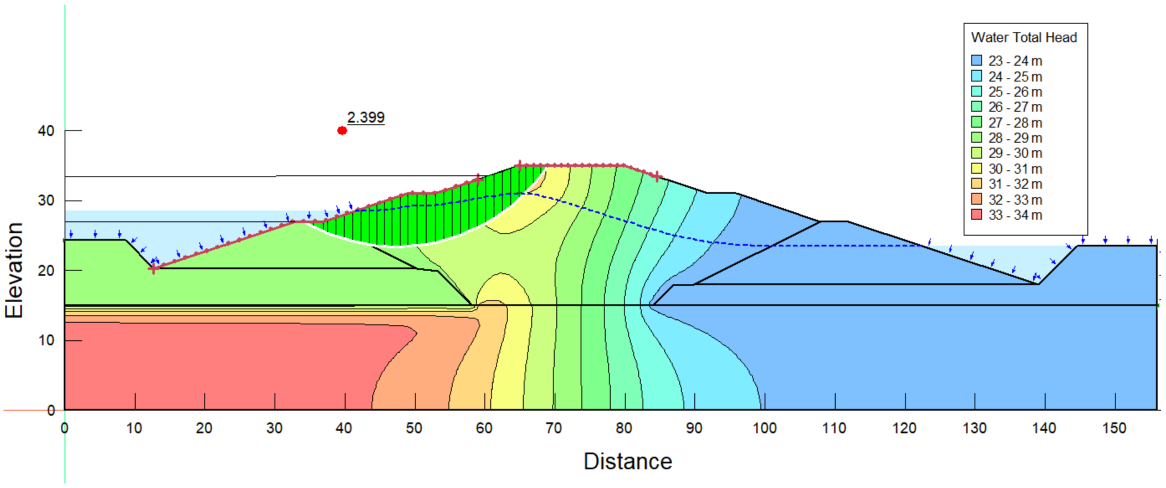

Figure 7. Critical safety factor for drawdown rate 0.5 m/day (day 10)

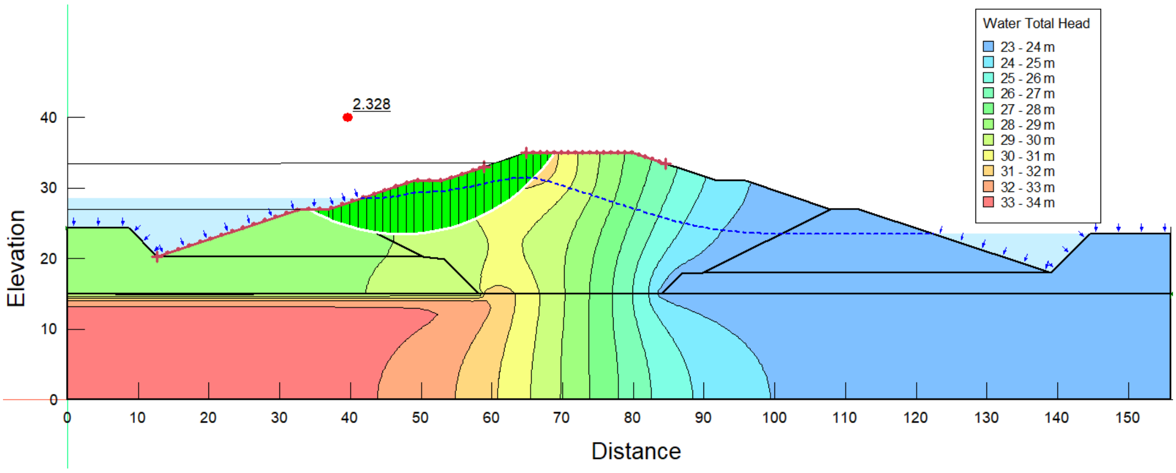

Figure 8. Critical safety factor for drawdown rate 1 m/day (day 5)

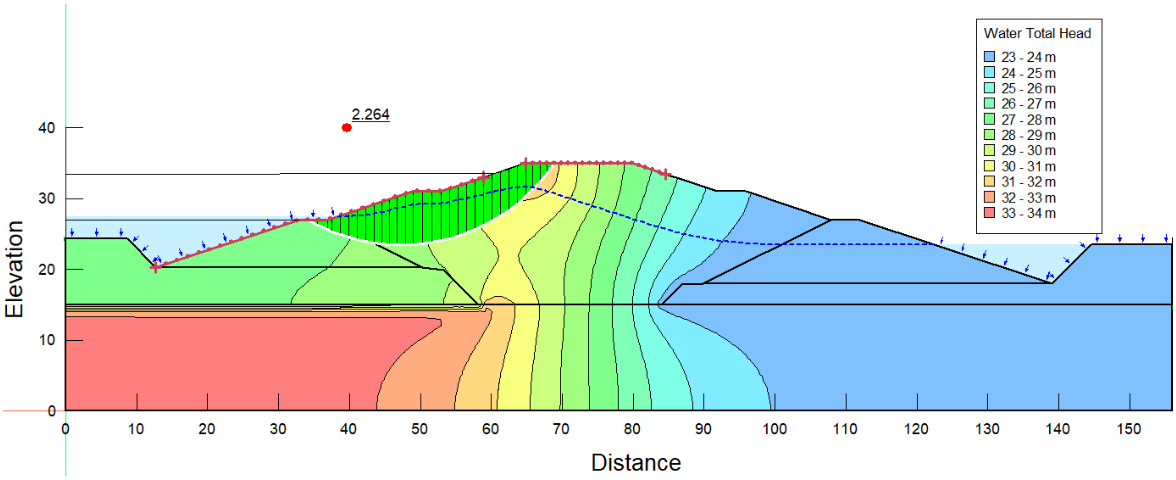

Figure 9. Critical safety factor for drawdown rate 2 m/day (day 3)

The lowest safety factor recorded for every drawdown rate is relatively similar, but an obvious trend can be seen, i.e., higher drawdown rates result in lower safety factor. This trend is consistent with theoretical expectations, as higher drawdown rate allows less time for pore pressure to dissipate from the soil after the confining pressure from the reservoir is reduced. This can also be observed from the evolution of safety factor which shows that the highest drawdown rate reached the lowest safety factor earlier compared to the remaining two drawdown rates. This result shows that drawdown rate has an effect on the safety factor of an embankment dam during rapid drawdown.

The safety factor and critical slip surface using Duncan et al. (1990) method is displayed in Figure 10. The critical slip surface identified using the Duncan et al. (1990) method was broadly consistent with that obtained from analyses incorporating unsaturated soil parameters. However, the factors of safety calculated with the Duncan et al. method was higher than those from any drawdown rate scenario modelled with unsaturated soil parameters, which highlights the importance of verifying stability assessments using unsaturated soil analyses, as reliance on the Duncan et al. (1990) method alone may overestimate the safety factor under rapid drawdown conditions.

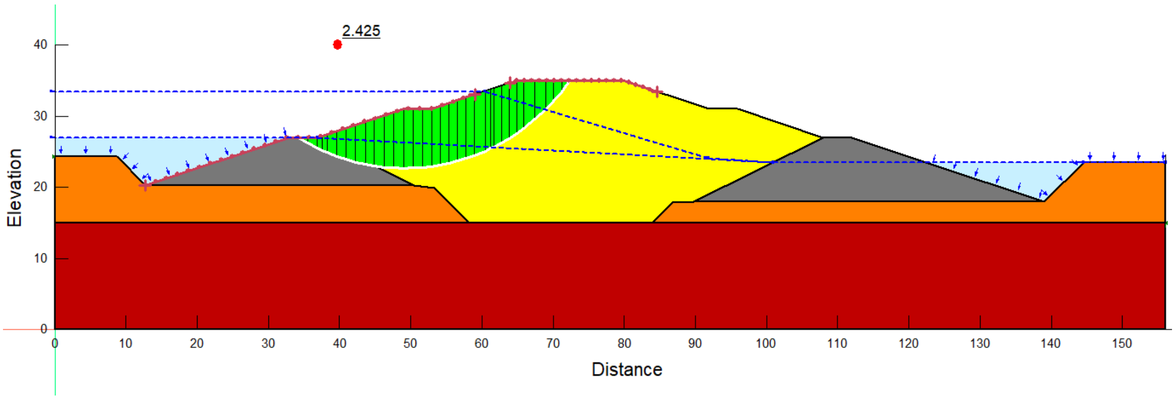

Figure 10. Safety factor obtained using Duncan et al. (1990) method

4 DISCUSSION

This study was conducted to evaluate how the widely applied Duncan et al. (1990) method for rapid drawdown compares with analyses that incorporate unsaturated soil parameters, and to investigate the influence of drawdown rate on embankment dam stability. The motivation was to test whether the simplified drained–undrained framework adequately represents stability conditions during rapid drawdown, or whether important effects are overlooked, particularly in relation to pore-pressure dissipation and suction in partially saturated zones.

The analysis output using Duncan et al. (1990) method shows that the critical slip surface is relatively consistent with those obtained from unsaturated soil analyses. However, the safety factor calculated was higher than those obtained using unsaturated soil approach under all drawdown rate scenarios, suggesting that Duncan's approach may overestimate stability margins by neglecting transient pore-pressure conditions and the role of matric suction dissipation.

A key distinction is the sensitivity to drawdown rate. The Duncan et al. (1990) method does not explicitly incorporate drawdown rate, treating materials as either fully drained or fully undrained. On the contrary, the unsaturated analyses showed a clear reduction in the safety factor as the rate of drawdown increased, consistent with theoretical expectations as drawdown rates limit pore-pressure dissipation. This highlights a critical shortcoming of the Duncan framework: while practical, it cannot capture the time-dependent behaviour of pore pressures during reservoir drawdown.

The analysis result confirms that the Duncan method, though still embedded in practice and guidelines (e.g., USACE, 2003), may give non-conservative results when drawdown occurs rapidly. The result also demonstrated that unsaturated soil mechanics may offer a more realistic framework for capturing rate effects, especially under conditions where climate change could cause more extreme hydrological variability and operational pressures. The implication for practice is that while the Duncan method remains useful as a screening tool, verification with unsaturated analyses should be undertaken in critical cases, particularly for dams with low-permeability zones or where rapid drawdown is anticipated.

This study has some limitations that should be acknowledged. The analyses were conducted with a homogeneous dam, and the soil-water characteristic curve (SWCC) was estimated using available index properties correlation formula instead of being fully determined from laboratory testing. Furthermore, only a limited range of idealised drawdown rates was considered. Future research could extend the analysis to more varied embankment dam type, such as zoned dam, which has more complex geometry, soil types, size and drainage conditions, supported by laboratory testing of unsaturated soil properties. The efforts would provide a stronger foundation for updating design and safety assessment frameworks for embankment dams under changing hydrological conditions.

Another area that could be explored is the effect of cyclic reservoir filling and drawdown on the stability of the dam, which can be investigated using physical modelling, such as a geotechnical centrifuge, coupled with numerical modelling to provide a practical method for embankment dam design for long-term operation under climate change uncertainty.

5 CONCLUSION

This study set out to evaluate how the widely used Duncan et al. (1990) method compares with analyses incorporating unsaturated soil mechanics in assessing embankment dam stability under rapid drawdown, with particular attention to the effect of drawdown rate. The results showed that the Duncan method produced higher factors of safety. This method is also unable to reflect the reduction in stability associated with faster drawdown rates, which were captured in the unsaturated soil analyses, highlighting the importance of transient pore-pressure effects on drawdown stability behaviour.

The study is limited by the use of an idealised embankment and estimated unsaturated soil parameters, but it points to the need for further research using laboratory-derived unsaturated properties, more complex geometries, and coupled finite element approaches. Overall, the analysis output highlights the importance of complementing traditional methods with unsaturated analyses in order to strengthen dam safety assessment frameworks, especially under climate change scenarios that may accelerate drawdown beyond original design assumptions.

DISCLAIMER

The authors declare no conflict of interest.

AVAILABILITY OF DATA AND MATERIALS

All data are available from the author.

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