Kharazmi University

Journal of Engineering Geology

Journal home page https://jeg.khu.ac.ir

OPEN ACCESS

Online ISSN
2981-1600

Effect of the Soil-Water Characteristic Curve (SWCC) parameters on the slope stability of an earth dam in steady state and rapid drawdown

Seyed Ali Asghari Pari[1✉]

1. Assistant Professor, Department of Civil Engineering, Faculty of Engineering, Behbahan Khatam Al Anbia University of Technology, Behbahan, Iran. E-mail: asgharipari@bkatu.ac.ir

Article Info

Article type:
Research Article

Article history:
Received 24 February 2025
Accepted 10 June 2025

Keywords:
Earth dam, Unsaturated soil, Stability analysis, Rapid draw down, GeoStudio.

ABSTRACT

This study investigates the effect of Soil-Water Characteristic Curve (SWCC) parameters on the slope stability of an earth dam under steady-state and rapid drawdown conditions. Given the importance of unsaturated soil behavior in earth dams, this research employs principles of unsaturated soil mechanics to analyze the influence of SWCC parameters on water flow rate and slope stability.The results indicate that parameters a and n positively enhance the flow rate, while an increase in parameter m reduces it. In slope stability analysis, parameters of SWCC showed negligible effects on the downstream slope stability, whereas an increase in m caused a slight reduction in the safety factor. Under rapid drawdown conditions, all parameters initially led to a decrease in the safety factor, but stability was restored after 10 days. Additionally, accounting for the unsaturated unit weight of the soil improved the safety factor in both steady-state and rapid drawdown scenarios. These findings highlight the critical role of unsaturated soil conditions in the design and stability analysis of earth dams.

Introduction

Earth dams are among the most critical and complex engineering structures. They often require substantial investment for their study and construction. Ensuring the safety of these structures during both construction and operation is of paramount importance. According to the International Commission on Large Dams (ICOLD), more than 81% of dams globally are earth dams. These structures provide several benefits, such as lower construction costs, simpler technologies, and high adaptability to various construction conditions. However, operating earth dams requires careful attention to specific conditions, particularly regarding seepage from the dam body and overall stability.

A crucial design consideration for earth dams is the amount of seepage that occurs through their bodies. Over the years, numerous analytical methods have been developed to assess seepage flow. Using Darcy's law, Dupuit (1863) established a relationship to estimate flow through any vertical surface. Dehisce et al. (Djehiche et al., 2012) provided a formula for estimating seepage from a homogeneous earth dam on a permeable foundation. Casagrande (Casagrande, 1925) introduced a methodology to determine the flow rate through an earth structure, considering parameters such as core width, water height behind the dam, and core embankment angle. Stello (1987) developed a chart method to predict the phreatic line and seepage flow in earth dams on impermeable foundations. When compared to modern software analyses, the chart method was found to underestimate results by 18%. More recent studies by Kasimov and colleagues (Kacimov et al., 2021, 2020; Kacimov and Brown, 2015) have explored the use of barrier strips and plant growth patterns to examine flow lines within the dam body. Seepage in earth dams is a critical design consideration; exceeding acceptable limits can lead to dam failure. Despite the

Cite this article: Asghari Pari, A. (2025). Effect of the Soil-Water Characteristic Curve (SWCC) parameters on the slope stability of an earth dam in steady state and rapid drawdown. Journal of Engineering Geology, 19 (5), 627-647. https//doi.org/10.22034/JEG.2025.19.5.1018842

Publisher: Kharazmi University.

DOI: https//doi.org/10.22034/JEG.2025.19.5.1018842

[DOR: 20.1001.1.22286837.1404.19.5.1.2]

[DOI: 10.22034/JEG.2025.19.5.1018842]

availability of various investigation and analysis techniques, inconsistencies in the hydraulic behavior of water and seepage from the dam's body and foundation may still exist (Rezaeeian et al., 2019; Stark and Jafari, 2018). Determining the position of the seepage line, is essential for analyzing the hydraulic performance of both homogeneous and non-homogeneous earth dams, as it allows for the derivation of current flow networks and seepage quantities (Rahimi, 2018).The seepage line (or phreatic line) is the upper boundary of groundwater flow within the body of an earth dam, where the water pressure equals atmospheric pressure (zero gauge pressure). This line represents the surface below which the soil is fully saturated and seepage occurs, while the zone above it remains unsaturated. The degree of saturation in the downstream shell of an earth dam significantly impacts the stability of the structure; excessive saturation can threaten dam integrity. Properly addressing these factors can yield valuable insights for dam designers and operators. Understanding the soil behavior in earth dams necessitates applying unsaturated soil mechanics principles. Compared to classical soil mechanics, unsaturated soil mechanics presents many challenges, primarily due to the complexities of unsaturated soil behavior. An earth dam is considered stable when the stresses applied at any given point are less than the mobilized resistance of that segment. The stability of an earth dam is relative and can vary based on the interplay between destructive forces and resisting forces (Guo et al., 2019). Over recent decades, research has focused on how various elements—such as dam material, cohesion, friction, upstream slope, and discharge rates—affect dam stability and deformation (Athani et al., 2015; Hasani et al., 2013; Mouyeaux et al., 2018; Shan et al., 2020; Wang, 2014).

The soil-water characteristic curve (SWCC) plays a vital role in comprehending unsaturated soil properties (Croney and Coleman, 1954; Fredlund and Rahardjo, 1993). The understanding of unsaturated soil behavior has developed from laboratory research to theoretical models. Initially, the focus was on creating a single-valued effective stress equation for unsaturated soils. However, by the late 1960s, it became evident that two independent stress state variables would better align with the principles of continuum mechanics (Fredlund, 1978). The 1970s saw the proposal and evaluation of various constitutive relations within classical soil mechanics for their uniqueness (Fredlund and Rahardjo, 1993). Early studies primarily addressed topics such as seepage, shear strength, and volume change, leading to the recognition that unsaturated soil behavior naturally evolves from saturated soil behavior (Fredlund, 1978). Many investigations sought to link volume change and shear strength through elastoplastic models, incorporating findings from saturated soil research (Alonso et al., 1990; Blatz and Graham, 2003). Moreover, research into properties connected to contaminant transport, thermal behavior, and air flow in unsaturated soils has advanced understanding through nonlinear soil property functions (Newman, 1995; Lim et al., 1998). Asghari pari and Asghari pari (Asghari pari and Asghari pari , 2025) studied the Seydon Dam in Iran to investigate the impact of unsaturated soil on the deterministic and probabilistic analysis of the stability of earth dams under steady-state conditions.

This study investigates the effects of Soil-Water Characteristic Curve (SWCC) parameters on the stability of earth dam slopes under both steady-state seepage and rapid drawdown conditions. The analysis begins with a theoretical framework on unsaturated soil mechanics, emphasizing its role in governing soil permeability and shear strength. Subsequently, the findings from detailed seepage and slope stability simulations are presented. The paper then evaluates the dam's performance during rapid drawdown, highlighting critical failure mechanisms. Finally, a sensitivity analysis is performed to quantify the influence of saturated and unsaturated unit weight variations on slope stability outcomes.

Methods and Materials

Effect of unsaturated soils on permeability and strength of soils

Unsaturated soils significantly influence both permeability and strength, playing a crucial role in geotechnical engineering. Water movement through soil is essential for understanding seepage rates from structures like dams. Pore pressure related to groundwater flow is a vital factor in this discipline, with both positive and negative pore water pressures impacting the soil's stress state, shear strength, and volume change behavior. Recent studies have highlighted the necessity of comprehending water flow in unsaturated soils for the effective design of geotechnical structures. Historically, groundwater flow analyses have focused on saturated soils, classifying flow scenarios as either confined or unconfined. Flow beneath a structure is generally treated as a confined flow problem, while flow through a homogeneous embankment is considered unconfined. Unconfined flow problems present greater analytical challenges, as they require pinpointing the location of the phreatic surface, which separates positive and negative pore water pressures. However, in these analyses, flow occurring in the capillary region above the phreatic line is often neglected.

The saturated soil model is useful for quickly identifying areas of soil that consistently remain below the phreatic level. However, it is inadequate for soils that may become partially saturated during analysis. In such cases, the unsaturated zone can conduct water at rates similar to saturated soils, potentially leading to overestimations of flow rates and unrealistic free water levels. The soil's ability to transmit water under both saturated and unsaturated conditions is characterized by the hydraulic conductivity function. In saturated soils, all pore spaces are filled with water. When soils become slightly unsaturated, air enters larger pores, making them impermeable for flow and increasing the tortuosity of the flow path, as depicted in Figure 1. This results in a decrease in hydraulic conductivity. As pore water pressure becomes more negative, more pores fill with air, further reducing hydraulic conductivity. This illustrates that the flow capacity through the soil profile depends on the volumetric water content. Although determining the hydraulic conductivity function can be time-intensive and expensive, it can be estimated using various predictive methods based on grain size distribution curves or measured volumetric water content and saturated hydraulic conductivity.

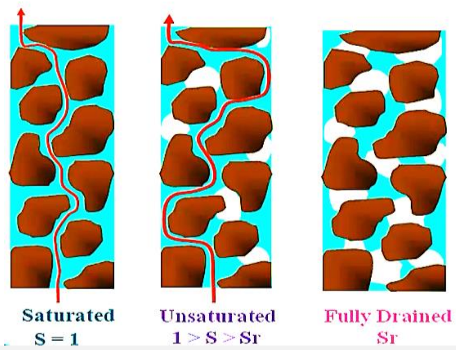


Fig. 1. The flow path in saturated and unsaturated soils(Dong et. al, 2020)

Understanding the connection between pore water pressure and water content is crucial for seepage analysis. Soil comprises solid particles and voids that can be occupied by water, air, or both. In saturated soils, all voids are filled with water, and the volumetric water content (θ_w) equals the soil's porosity, as expressed in the following equation:

$$\theta_w = \text{nS} \tag{1}$$

[DOR: 20.1001.1.22286837.1404.19.5.1.2]

[DOI: 10.22034/JEG.2025.19.5.1018842]

where n represents porosity and S denotes the degree of saturation. In unsaturated soils, the volume of water in the pores varies with matric suction, defined as the difference between air pressure (u_a) and water pressure (u_w), or $u_a - u_w$.

Water content is not constant over time or space, necessitating a function to describe how it changes with varying pressures in the soil. The volumetric water content function characterizes the soil's capacity to retain water under changes in matric pressure. A typical volumetric water content function is depicted in Figure 2, illustrating the volume of voids filled with water as the soil drains. The three primary properties defining this function are porosity (n), air entry value (AEV), and residual volumetric water content (θ_{res}). The AEV indicates the level of negative pore water pressure at which the largest voids begin to drain freely, influenced by the maximum pore size and pore size distribution within the soil. The residual volumetric water content represents the percentage of water content beyond which further increases in negative pore water pressure do not significantly alter the water amount in the soil.

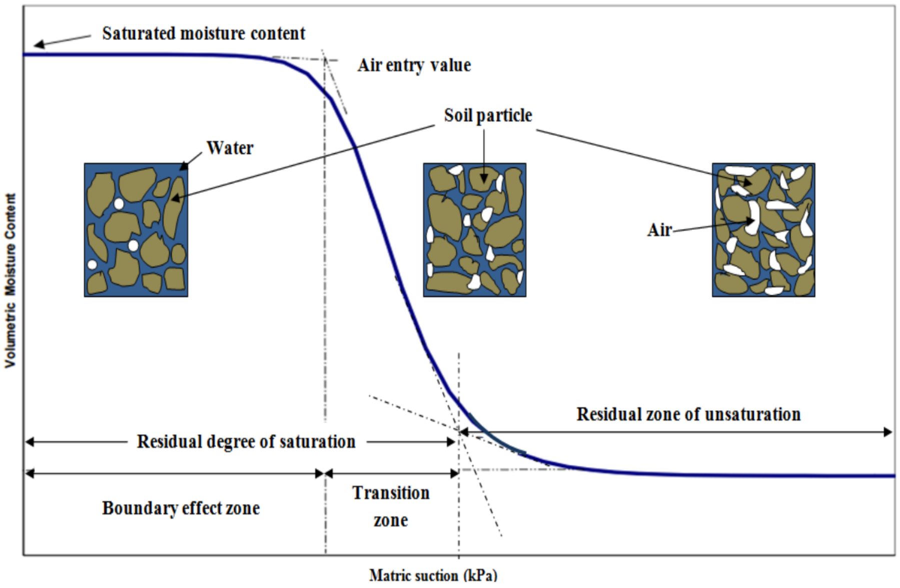


Fig. 2. Function of volumetric water content (Azmi et. al, 2016)

There are several methods to estimate the volumetric water content function or SWCC. Fredlund and Xing (Fredlund and Xing, 1994) used the closed-form equation that requires curve fitting parameters to generate the SWCC as follows.

$$\theta_w = C(\Psi)\frac{\theta_{sat}}{\ln\left[e+\left(\frac{\Psi}{a}\right)^n\right]^m} \qquad (2)$$

where $\boldsymbol{a}$, $\boldsymbol{n}$ and $\boldsymbol{m}$ are curve-fitting parameters that control the shape of the volumetric water content function, C(Ψ) is a correlation function, Ψ is equal to the matric suction value, θ_{sat} is the volumetric water content in the saturated state. Volumetric water content functions exist for a variety of soil particle size distributions, from clay to sand. These functions are generated using the characteristic curve fitting parameters in Equation 2. To estimate the value of hydraulic conductivity, we use the equation proposed by Fredlund et al. (1994). The parameters in the equation are generated by using curve-fitting parameters from the volumetric water content function and an input value for saturated hydraulic conductivity (K_{sat}). The closed-form equation for hydraulic conductivity in general is as follows:

$$K_w(\theta_w) = K_{sat}\frac{\int_{\theta_{res}}^{\theta_w}\frac{\theta_w - x}{\Psi^2(x)}dx}{\int_{\theta_{res}}^{\theta_{sat}}\frac{\theta_{sat} - x}{\Psi^2(x)}dx} \qquad (3)$$

In the investigation of soil slope stability in geotechnical engineering, the shear strength parameters of each soil type are typically determined in the laboratory based on water content and degree of compaction. Using these parameters, the safety factor of stability can be calculated for a given sliding surface. However, it is important to recognize that earth slopes—particularly in earth dams—exist under unique conditions where the soil is neither fully saturated nor completely dry, but rather in an unsaturated state.

Consequently, when analyzing the stability of earth dams using unsaturated soil mechanics theory, the input parameters may differ significantly from those used in saturated or dry conditions. One of the most critical factors in unsaturated soils is the influence of pore water pressure and pore air pressure variations. Additionally, shear strength is affected by matric suction, which is highly variable and dependent on factors such as degree of saturation, permeability, and time.

The study of the unsaturated condition of soils has been started since the 1960s and so far, several researches have been conducted on it in the form of laboratory, calculation and theory. From a practical point of view, these theories and the results of related experiments have been analyzed and evaluated in terms of the specific conditions of executive projects. The mechanical behavior of soil can be described by the terms of the state of stress in that soil, and the state of stress also includes certain combinations of variables, known as stress state variables. These variables are independent of the physical properties of the soil and their number mainly depends on the number of phases that make up the soil. To describe the mechanical behavior of unsaturated soil according to the number of its constituent phases, at least two stress state variables are necessary. After much research, scientists concluded that any combination of three stress-state variables $(\sigma - u_a), (\sigma - u_w)$ and $(u_a - u_w)$ can be used for this purpose. In the current study, two variables $(\sigma - u_a)$ and $(u_a - u_w)$ are used, which are called effective normal stress and matric suction, respectively. The Coulomb equation for shear strength is commonly used to determine the shear strength of soils. The equation is typically expressed as:

$$\tau = c' + (\sigma - u)\tan\phi' \qquad (4)$$

Where: τ is the shear strength, c' is the effective cohesion, σ is the normal stress, u is the pore water pressure, and ϕ' is the effective angle of internal friction. This equation is indeed valid for saturated soils. In unsaturated soils, the shear strength is influenced by factors such as matric suction, which affects the pore water pressure, and the soil-water characteristic curve, which describes the relationship between water content and suction. Therefore, when dealing with unsaturated soils, it is important to consider these additional factors in determining the shear strength. However, for unsaturated soils, the pore water pressure (u) and the effective cohesion (c') need to be adjusted to account for the soil's unsaturated state. The unsaturated shear strength angle (ϕ_b) can be determined through laboratory testing using techniques such as the direct shear test or triaxial shear test, with consideration for the soil's degree of saturation.

The linear form of the shear strength equation proposed by Fredlund et al. (1978) took the form of an extension of the Mohr-Coulomb failure criterion

$$\tau = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\phi_b \qquad (5)$$

According to the above, due to the complexity of the analysis and evaluation of the stability of unsaturated soil slopes, usually in the designs and normal executive works, there is not a lot of interest in entering this topic. This proposition and prejudgment are often satisfied that if the soil is Unsaturated, the analysis is based on saturated soil, and the results are reliable. However, nowadays, the discussion of optimal design, cost, and reliability of projects has

[DOR: 20.1001.1.22286837.1404.19.5.1.2]

[DOI: 10.22034/JEG.2025.19.5.1018842]

caused more precise methods to be used in the design of earth dams.

Software specification

In this paper, we used Geostudio 2018 software to analyze seepage and slope stability. GeoStudio 2018 is a comprehensive software suite utilized for geotechnical analysis and design, focusing on tasks such as slope stability, seepage, and soil-structure interaction. Widely used by civil engineers and geotechnical professionals, GeoStudio includes several modules like SLOPE/W for evaluating slope stability, SEEP/W for modeling groundwater flow and pore pressure, and SIGMA/W for stress-deformation analysis. It can simulate various environmental and engineering scenarios, incorporating factors such as soil properties and boundary conditions to ensure accurate and reliable results. The software supports both steady-state and transient analyses, making it an essential tool for assessing the safety and stability of geotechnical structures under different conditions.

Specifications of the Earth Dam

Consider a homogeneous earth dam with a height of 12 meters and a water level inside the reservoir at 10 meters (Figure 3). The dam's primary material is clay soil, with specifications listed in Table 1. To examine the impact of various SWCC parameters, other parameters are held constant at values in Table 1. Parameter **a** is varied with values of 10, 30, 50, 70, 90, and 110, and its effect on the SWCC is shown in Figure 4. For parameter **m** values of 5, 10, 15, 20, and 30 are analyzed, with corresponding impacts shown in Figure 5. Parameter **n** is studied with values of 1.5, 2, 3, 4, and 5, as depicted in Figure 6. Lastly, saturated water content ($\boldsymbol{\theta_{sat}}$) values of 0.3, 0.35, 0.4, 0.45, and 0.5 are used to assess its effect on the curve, shown in Figure 7.

Table 1. Characteristics of earth dam parameters

Name	Slope stability parameters				SWCC parameters				
	Material Model	Unit Weight (kN/m³)	Cohesion (kPa)	Friction Angle (°)	a	n	m	θ_{sat}	$\theta_{res}(\% \ of \ \theta_{sat})$
Dam material	Mohr-Coulomb	20	30	30	50	2	15	0.45	50

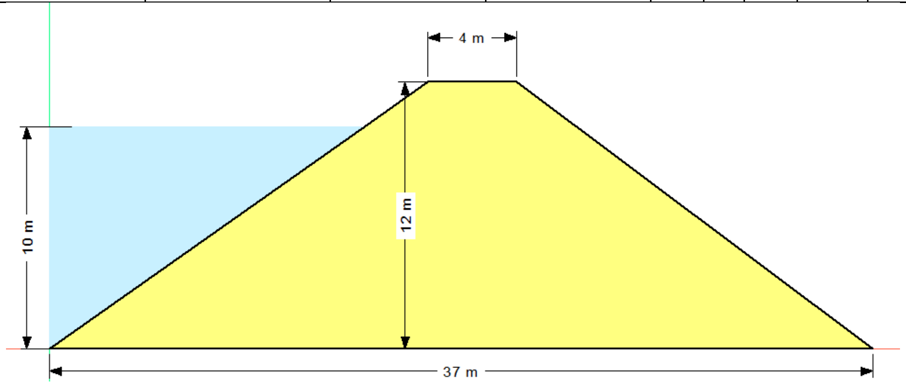


Fig. 3. Specifications of the Earth Dam

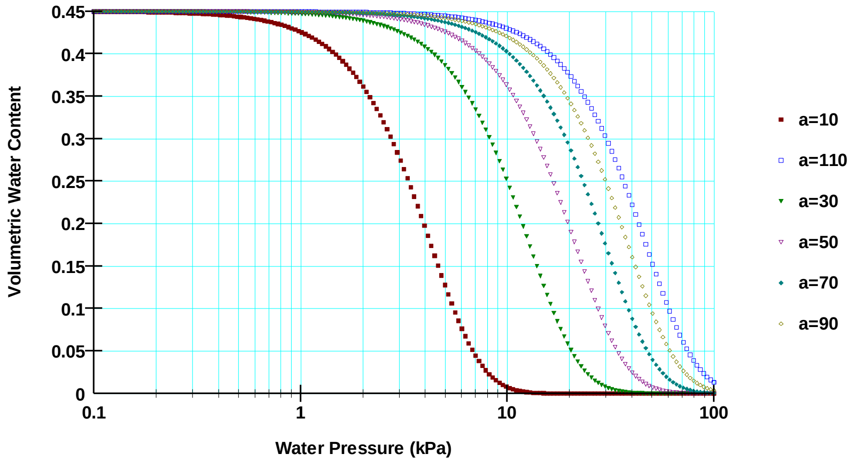


Fig. 4. Effect of **a** parameter on SWCC

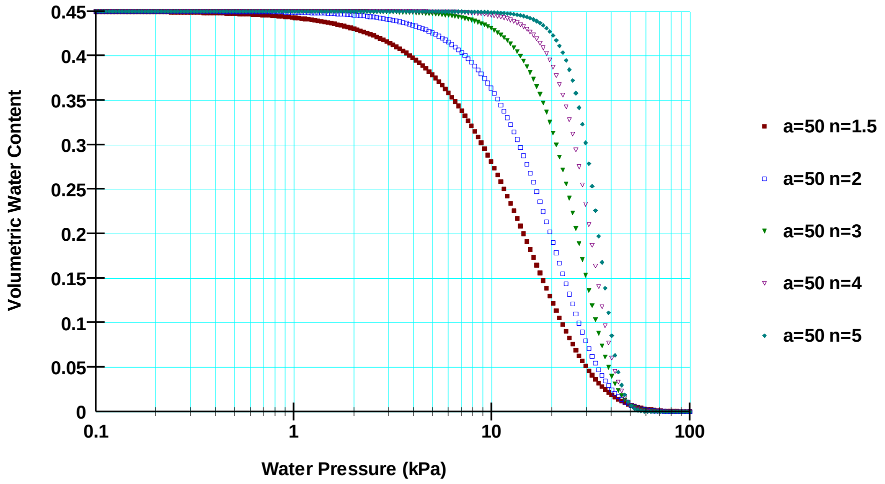


Fig. 5. Effect of **n** parameter on SWCC

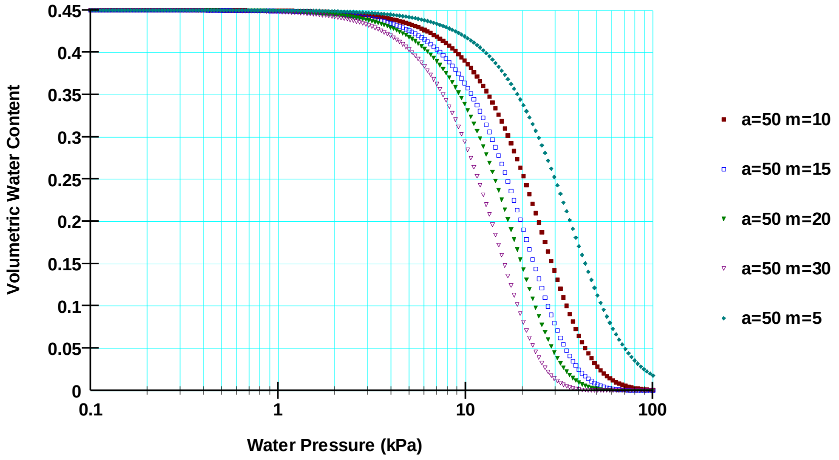


Fig. 6. Effect of **m** parameter on SWCC

[DOR: 20.1001.1.22286837.1404.19.5.1.2]

[DOI: 10.22034/JEG.2025.19.5.1018842]

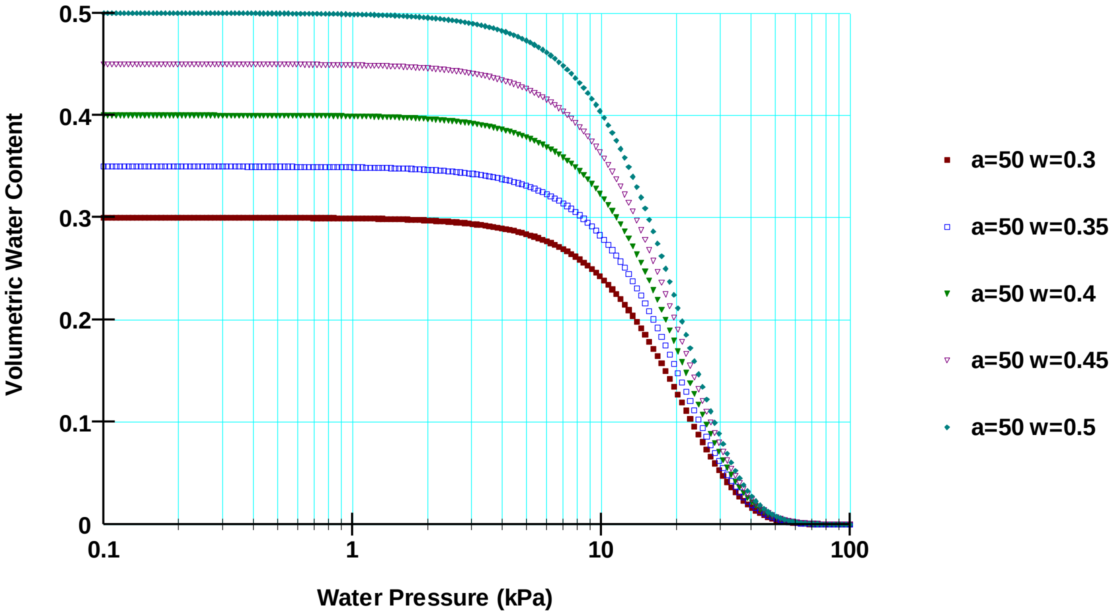


Fig. 7. Effect of $\boldsymbol{\theta_{sat}}$ parameter on SWCC

Results and discussion

Steady-state analysis results

To investigate the effect of different parameters of SWCC, first, the analysis of the steady state of the earth dam was carried out. The saturated hydraulic conductivity value of the material is determined to be 0.85 m/day. Based on the SWCC of the soil material, the hydraulic conductivity curve in terms of matric suction is prepared for different conditions and included in the analysis. As an example, the effect of parameter **a** on the permeability curve is given in Figure 8**.**

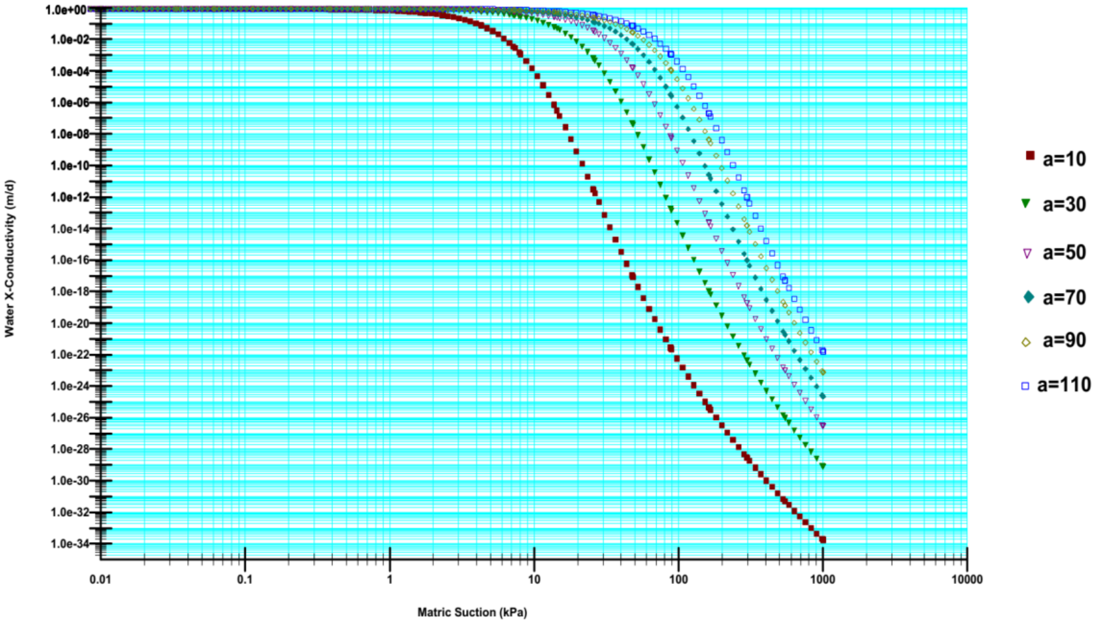


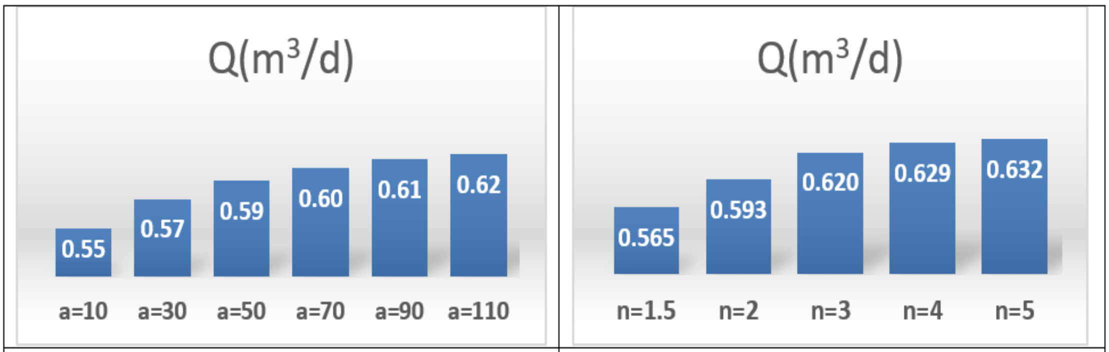
Fig. 8. Effect of **a** parameter on hydraulic conductivity function

The steady-state analysis results are presented in Figure 9. The findings demonstrate that the flow rate through the dam exhibits a positive correlation with parameter **a**, indicating that an

[DOR: 20.1001.1.22286837.1404.19.5.1.2]

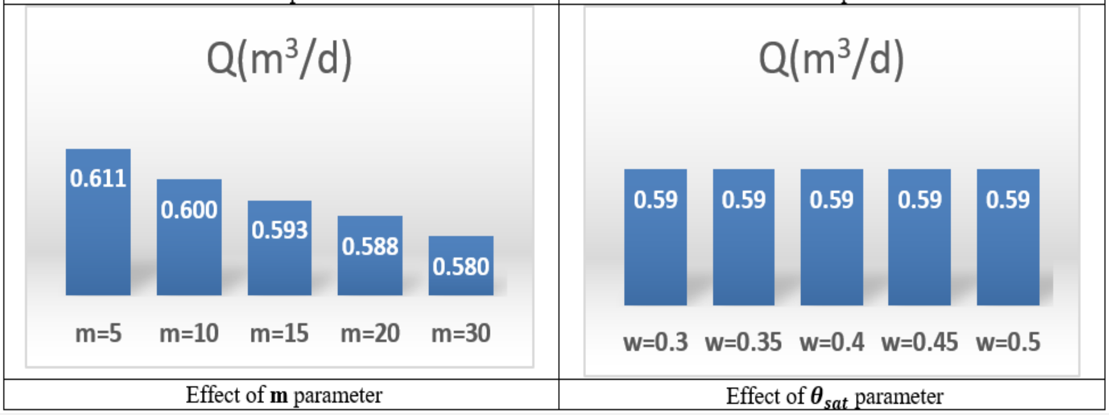
[DOI: 10.22034/JEG.2025.19.5.1018842]

increase in **a** enhances the dam's flow capacity. This suggests that **a** improves hydraulic efficiency, facilitating greater water discharge.Conversely, the flow rate decreases with higher values of parameter **m**, implying that **m** introduces flow resistance or restrictive hydraulic conditions, thereby reducing permeability.Parameter **n** exhibits a more complex relationship with flow rate: as **n** increases, the flow rate initially rises but stabilizes when **n** exceeds 4. This behavior indicates a saturation effect, where further increases in **n** yield diminishing returns in flow enhancement.In contrast, the results reveal that $\boldsymbol{\theta}_{sat}$ has no discernible impact on flow rate, suggesting that it plays an insignificant role in the dam's hydraulic performance under the studied conditions.



Effect of **a** parameter

Effect of **n** parameter

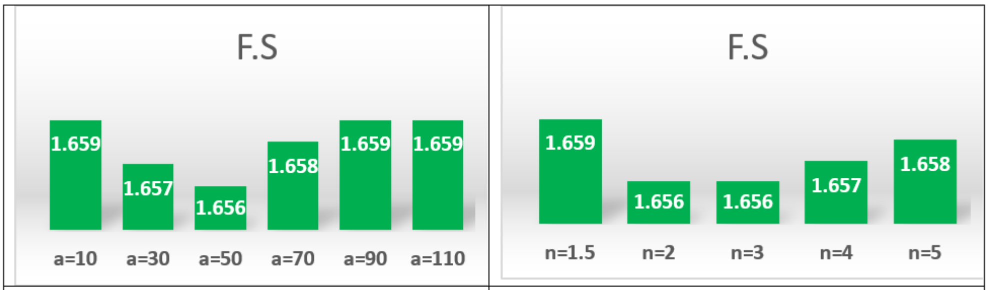


Effect of **m** parameter

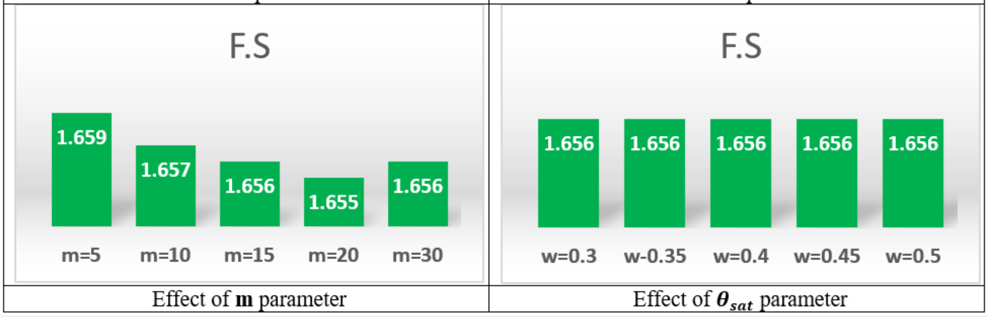
Effect of $\boldsymbol{\theta}_{sat}$ parameter

Fig. 9. The results of the seepage analysis in steady-state condition

The stability analysis results for the downstream slope under steady-state conditions are presented in Figure 10. The findings reveal the following key observations: Parameter (**a**): The factor of safety (FoS) remains relatively stable across the tested range of **a**, with only minor fluctuations. This indicates that variations in **a** have no significant influence on slope stability, suggesting a robust design within the examined parameter space. Parameter (**n**): Similar to **a**, the FoS exhibits minimal variation with changes in **n**, as the values remain closely clustered. This implies that slope stability is largely insensitive to adjustments in **n** under the given conditions. Parameter (**m**): A slight decrease in FoS is observed as **m** increases, reaching a minimum at m = 20, after which it stabilizes. While higher values of **m** introduce a marginal reduction in stability, the overall impact is negligible, and the slope maintains sufficient stability across the tested range. Parameter (**θ**□$_{\mathbf{a}}$□): The FoS remains constant for all values of **θ**□$_{\mathbf{a}}$□, confirming that this parameter does not affect the stability of the downstream slope under steady-state conditions.indicating that this parameter does not influence the stability of the downstream slope. This suggests that variations in saturation do not significantly affect the slope's stability under the conditions tested.



Effect of **a** parameter | Effect of **n** parameter



Effect of **m** parameter | Effect of $\boldsymbol{\theta_{sat}}$ parameter

Fig. 10. The results of the stability analysis of the downstream slope under steady-state conditions

Results of rapid drawdown analysis

Figure 11 presents the results of the rapid drawdown analysis, which was conducted using a transient analysis with logarithmically increasing time intervals. The reservoir was assumed to drain at a rate of 1 meter per day. Given an initial water height of 10 meters, complete emptying occurs within 10 days. To thoroughly investigate the rapid drawdown process and assess the stability of the upstream slope, a total duration of 90 days was considered, with time steps selected to capture critical phases of the drawdown. The analysis illustrates the variations in the dam's water level throughout the drawdown process, providing insights into slope behavior under transient conditions.

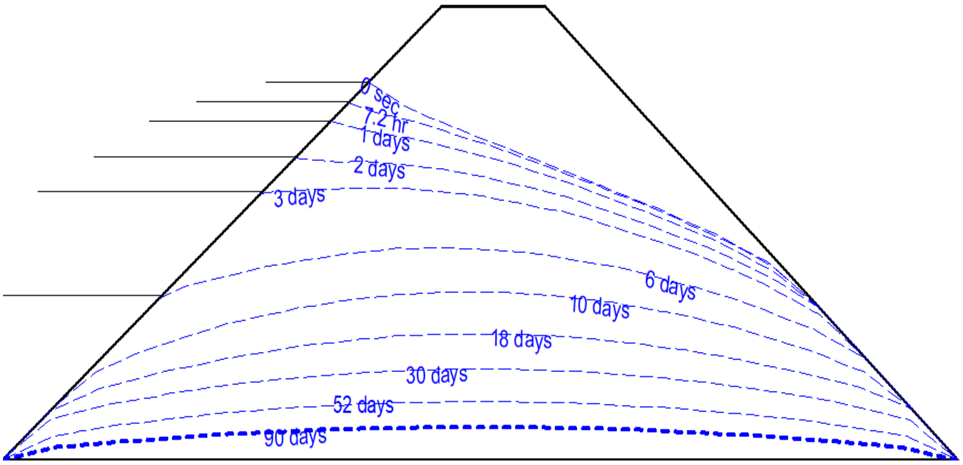


Fig. 11. the result of the analysis of the rapid drawdown

The results of the stability analysis of the upstream slope during the rapid drawdown process and the effect of the SWCC parameters on it are presented in Figures 12 to 15. The results of Figure 12 showed that at the beginning of the drawdown process (around day 0 to day 10), there was a noticeable drop in the factor of safety for all values of ***a***. This indicates that the rapid drawdown significantly affects the stability of the upstream slope during the initial phase,

[DOR: 20.1001.1.22286837.1404.19.5.1.2]

[DOI: 10.22034/JEG.2025.19.5.1018842]

likely due to the sudden reduction in hydrostatic pressure. After the initial drop, the factor of safety stabilizes around 2.2 for all values of ***a*** from approximately day 10 onward. This suggests that, despite the initial instability, the slope reaches a new equilibrium state where it remains stable throughout the remainder of the 90-day period. The F.S. values for different ***a*** values (10, 30, 50, 70, 90, and 110) show very little variation after the initial drop. This indicates that the stability of the slope is relatively consistent across these parameter settings, suggesting that the slope design is robust against variations in ***a***. All F.S values remain above 1.5, which is typically considered a safe threshold in engineering contexts. This indicates that the slope remains stable and safe throughout the drawdown process.

Based on Figure 13 we can see that at the beginning of the drawdown (0 to 10 days), there is a noticeable decline in the factor of safety for all values of ***n***. This indicates that the rapid drawdown significantly impacts the stability of the slope during this initial period, likely due to the sudden decrease in hydrostatic pressure. After the initial drop, the factor of safety stabilizes around 2.1 to 2.3 for all values of ***n***. This suggests that, despite the initial instability, the slope reaches a new equilibrium state where it remains stable throughout the remainder of the 90-day period. The F.S values for different ***n*** values show minimal variation after the initial drop. All curves converge around the same range (approximately 2.1 to 2.3), indicating that the stability of the slope is relatively consistent across these parameter settings. This suggests that the design is robust against variations in the *n* parameter.

The results in Figure 14 showed that all curves have a significant initial drop in the factor of safety during the first 10 days. This indicates that the rapid drawdown process has a pronounced effect on slope stability, likely due to the sudden reduction in hydrostatic pressure. After the initial drop, the factor of safety stabilizes for all values of ***m***. The F.S. values settle around 2.0 to 2.3, indicating that the slope reaches a new equilibrium state. This suggests that, despite the initial instability, the slope remains stable throughout the remainder of the 90-day period. The curves for different *m* values show that the factor of safety remains relatively consistent across all values after the initial drop. The highest F.S is observed for ***m*=5**, while the lowest is for ***m*=30**. However, all values remain above the safety threshold of 1.5, indicating a stable condition.

Figure 15 illustrates the impact of the saturation parameter θsat on the factor of safety (F.S) of the upstream slope during a rapid drawdown process over a 90-day period. The results showed that all curves exhibited a significant drop in the factor of safety during the first 10 days same as the ***a***, ***n*,** and ***m*** parameters. After the initial drop, the factor of safety stabilizes around 2.1 to 2.3 for all values of $\boldsymbol{\theta_{sat}}$. This suggests that, despite the initial instability, the slope reaches a new equilibrium state where it remains stable throughout the remainder of the 90-day period. The curves for different $\boldsymbol{\theta_{sat}}$ values show that the factor of safety remains relatively consistent after the initial drop. The highest F.S is observed for $\boldsymbol{\theta_{sat}}$ =0.3, while the lowest is for $\boldsymbol{\theta_{sat}}$ =0.5. However, all values remain above the safety threshold of 1.5, indicating a stable condition. This indicates that the design is resilient to variations in the saturation parameter $\boldsymbol{\theta_{sat}}$.

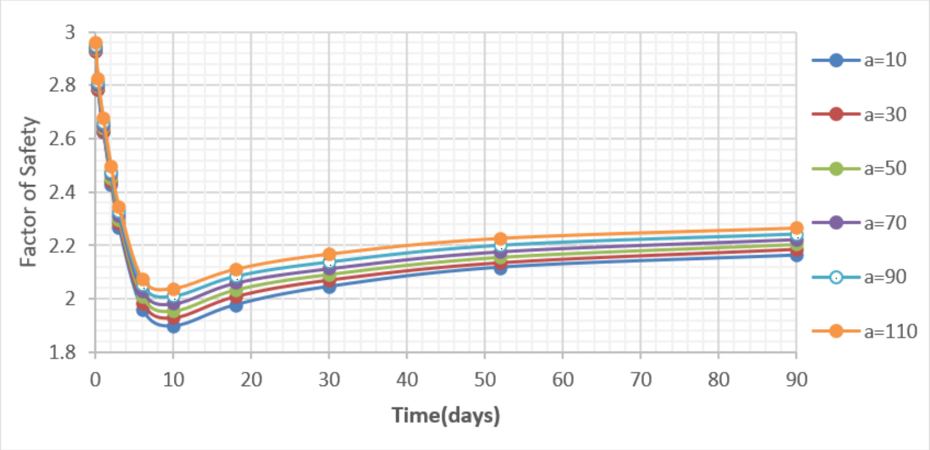


Fig. 12. Effect of **a** parameter on the safety factor of upstream slope in rapid drawdown

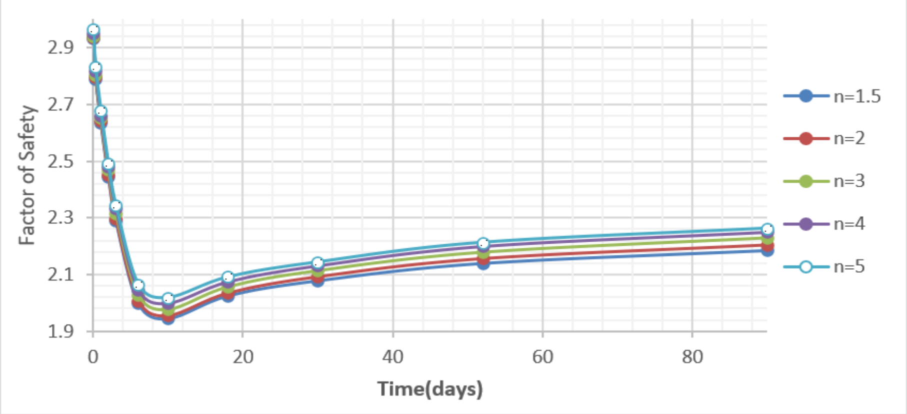


Fig. 13. Effect of **n** parameter on the safety factor of upstream slope in rapid drawdown

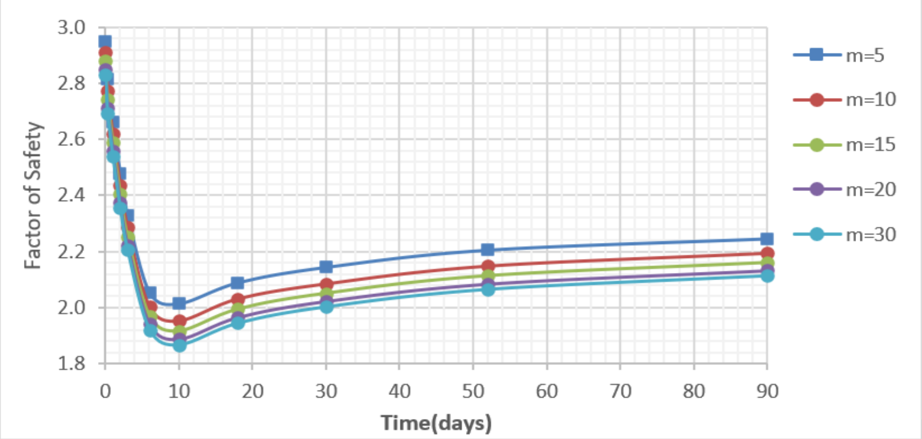


Fig. 14. Effect of **m** parameter on the safety factor of upstream slope in rapid drawdown

[DOR: 20.1001.1.22286837.1404.19.5.1.2]

[DOI: 10.22034/JEG.2025.19.5.1018842]

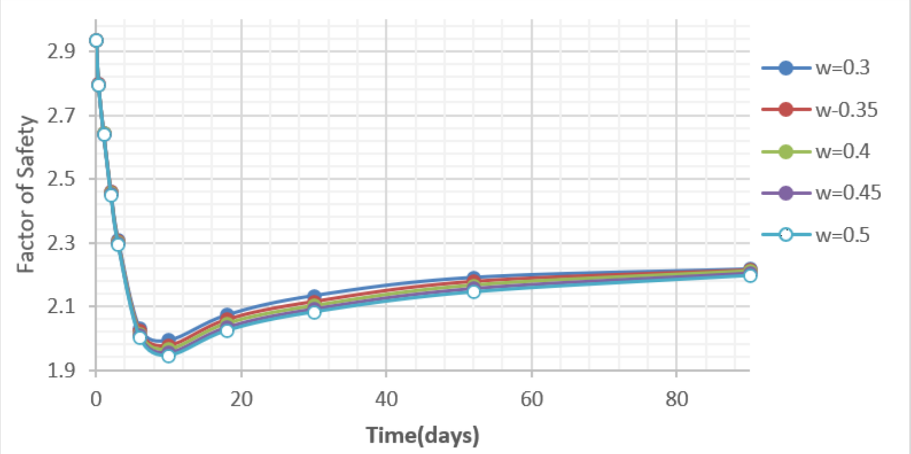


Fig. 15. Effect of $\boldsymbol{\theta_{sat}}$ parameter on the safety factor of upstream slope in rapid drawdown

Effect of unsaturated unit weight

In slope stability analysis, the total unit weight is typically used to define soil weight. It is commonly understood that the unit weight is significantly lower above the water table since the soil is unsaturated. However, in practice, there isn't a distinct change in unit weight at the water table, as the soil remains saturated in the capillary zone above it, with the saturation decreasing as you move further up. Consequently, the unit weight above the water table can vary, as it is influenced by the water content.

In SLOPE/W, the total unit weight is typically considered to be the saturated unit weight, denoted as $\boldsymbol{\gamma_{sat}}$, which corresponds to the saturated volumetric water content (VWC) represented by $\boldsymbol{\theta_{sat}}$. However, SLOPE/W also can calculate the unit weight of unsaturated soil based on its VWC denoted by $\boldsymbol{\theta}$. To do this, a VWC function for the soil must be established, indicating how water content varies across a range of pore water pressures which is known as SWCC (see Figure 2). Therefore, if the negative pore-water pressure above the water table is known, the water content can be derived from the VWC function, and the soil's unit weight can be computed using the following equation:

$$\gamma = \gamma_{sat} - [\gamma_w * (\theta_s - \theta)] \qquad (6)$$

where γ_w represents the unit weight of water.

As illustrated in Figure 16, the transition from saturated to unsaturated unit weight conditions demonstrates negligible impact on flow rates through the dam body. This hydraulic insensitivity suggests that pore water pressure redistribution under unsaturated conditions does not significantly alter the seepage regime, maintaining stable flow characteristics regardless of saturation state.

The analysis reveals two critical stability improvements when accounting for unsaturated conditions:

In Steady-State Conditions, A measurable increase in the downstream slope's factor of safety (FoS) is observed under unsaturated unit weight assumptions. This enhancement suggests that matric suction effects provide additional shear strength, thereby improving the slope's inherent stability margin during prolonged steady-state operation.

[DOR: 20.1001.1.22286837.1404.19.5.1.2]

[DOI: 10.22034/JEG.2025.19.5.1018842]

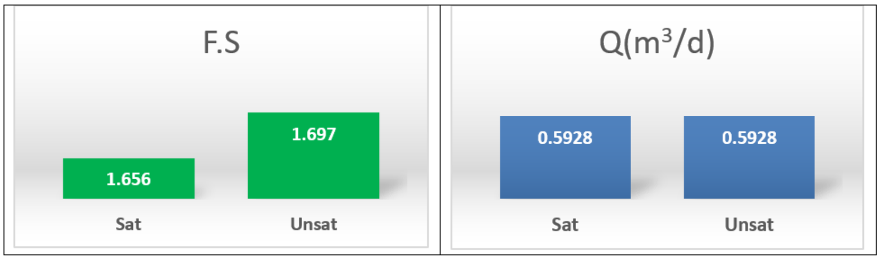


Fig. 16. The effect of unit weight in steady state condition

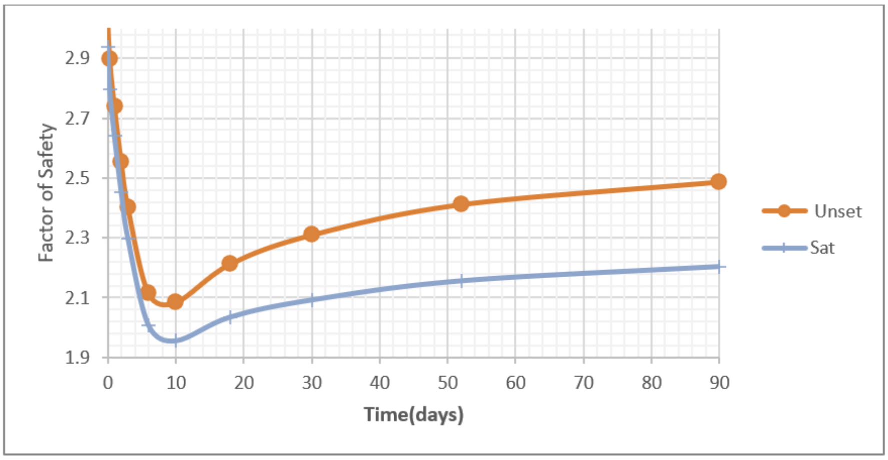


Fig. 17. The effect of unit weight in rapid drawdown condition

The 90-day drawdown simulation reveals consistently enhanced slope stability under unsaturated conditions, with the safety factor (FoS) demonstrating a 6.7% improvement (2.08 vs 1.95) by the 10th day compared to saturated conditions. This stability advantage persists throughout the entire drawdown period, confirming that unsaturated soil mechanics - particularly the development of matric suction - provide sustained reinforcement against potential slope failure during rapid water level fluctuations. The time-dependent analysis underscores how unsaturated zone contributions become progressively more influential during reservoir depletion, offering critical protection during this hydrologically vulnerable phase.This behavior underscores the importance of unsaturated soil mechanics in maintaining slope integrity during transient hydraulic events.

Pseudo-Static Analysis of Earth Dam

This study evaluates the stability of an earth dam under seismic loads using the pseudo-static analysis method in GeoStudio. In this approach, the seismic effect is represented as an equivalent horizontal force proportional to the soil mass weight. A pseudo-static coefficient of 0.15 was applied as the horizontal seismic acceleration, selected based on common geotechnical engineering standards, regional seismicity, and the structure's importance.The stability analysis was performed using SLOPE/W (part of the GeoStudio suite), where the factor of safety (FoS) of the dam slope was calculated under combined static and pseudo-static loading conditions. Figure 18 demonstrates the effects of Soil-Water Characteristic Curve (SWCC) parameters on the dam's behavior during rapid drawdown conditions in Pseudo-Static Analysis.

[DOR: 20.1001.1.22286837.1404.19.5.1.2]
[DOI: 10.22034/JEG.2025.19.5.1018842]

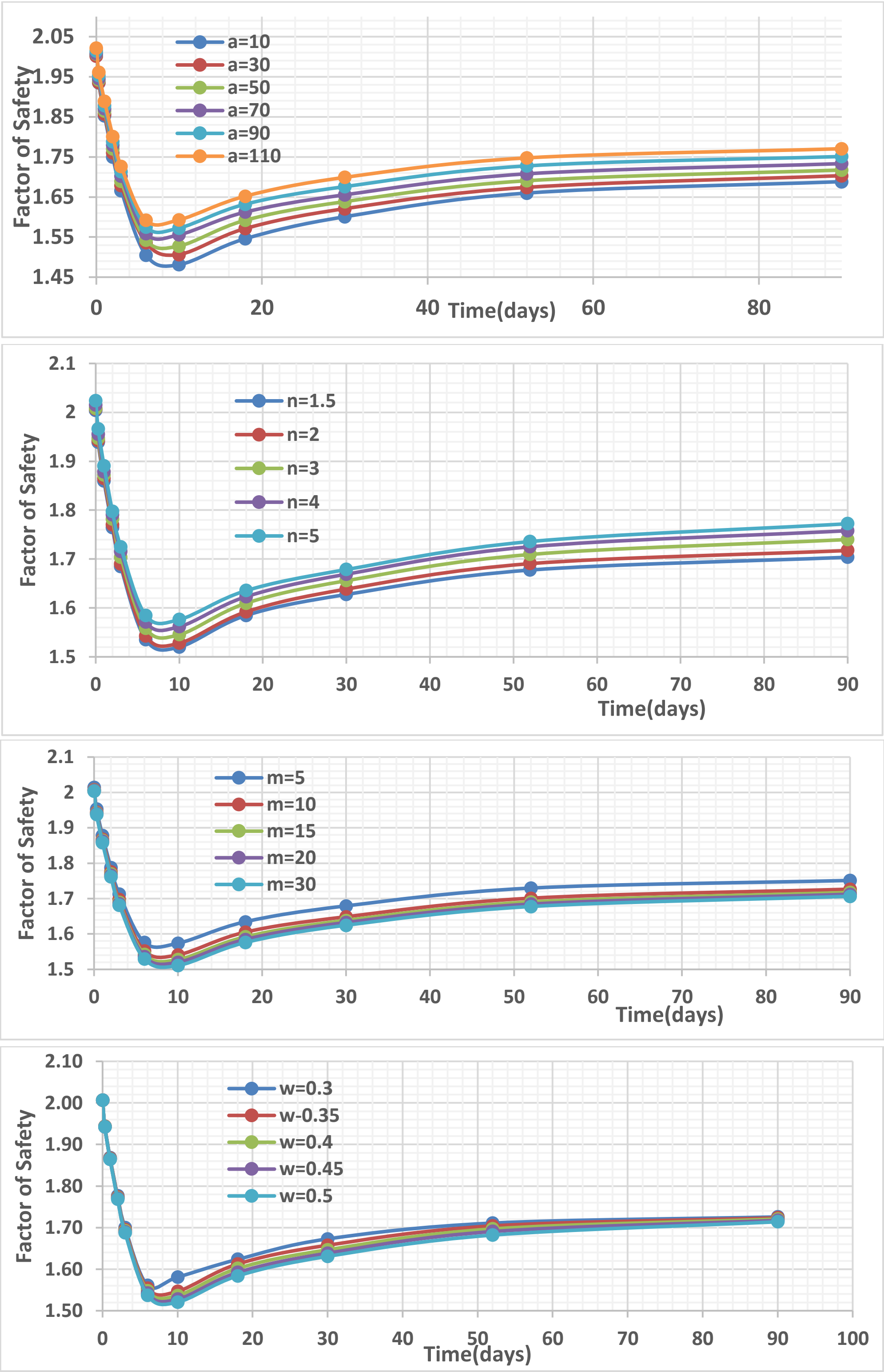


Fig. 18. Effect of SWCC parameters on the FoS of upstream slope in rapid drawdown (Pseudo-Static Analysis)

The results indicate an approximately 20% reduction in the safety factor due to all parameters of SWCC compared to the static analysis.The results indicate that with a seismic coefficient of 0.15, the dam remains in a stable condition, with the obtained FoS exceeding the allowable limit.

[DOR: 20.1001.1.22286837.1404.19.5.1.2]

[DOI: 10.22034/JEG.2025.19.5.1018842]

Effect of Reservoir Drawdown Rate on Stability Analysis Results

The influence of reservoir drawdown rate on the stability analysis was investigated by varying the rate from the initially assumed value of 1 m/day to 0.5, 2, and 4 m/day. The results, as illustrated in Figure 19, depict the relationship between the Factor of Safety (FoS) and time for different drawdown rates.the results showed that a slower drawdown rate (e.g., 0.5 m/day) generally leads to a more gradual reduction in the FoS, allowing for longer-term stability as the pore pressure dissipates more slowly. Conversely, faster drawdown rates (e.g., 2 and 4 m/day) result in a sharper decline in the FoS, indicating a higher risk of instability in the short term due to rapid pore pressure changes. The curves for t=2.5, 5, 10, and 20 days demonstrate that the FoS stabilizes over time, but the rate of stabilization is heavily dependent on the drawdown rate. These findings highlight the critical role of drawdown rate in slope stability assessments, emphasizing the need for careful consideration of reservoir operation strategies to mitigate potential failure risks.The numerical labels (4, 2, 1, 0.5 m/day) in the figure show the reservoir drawdown rate.

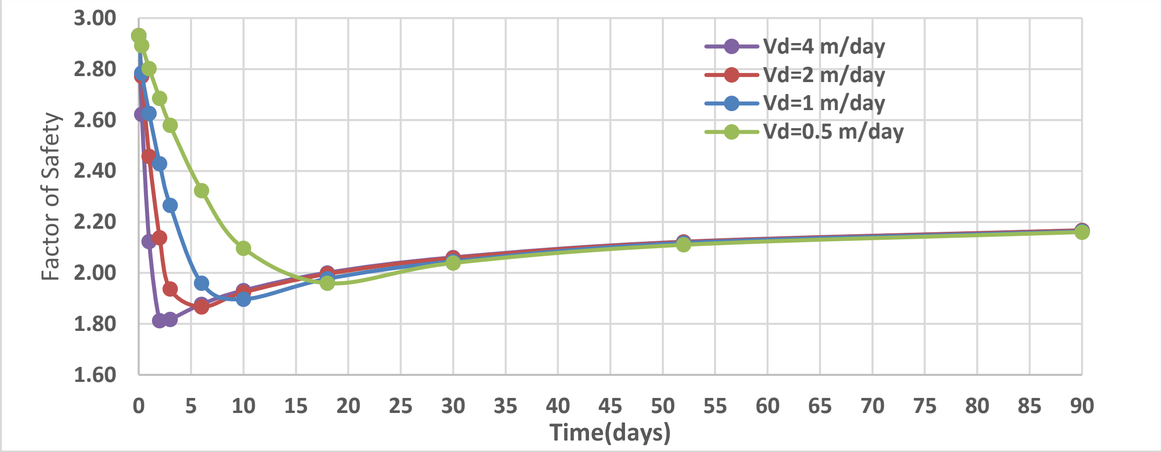


Fig. 19. Effect of Reservoir Drawdown Rate on Stability Analysis Result

Conclusion

This study investigates the influence of Soil-Water Characteristic Curve (SWCC) parameters on the hydraulic and stability behavior of earth dam materials under steady-state and rapid drawdown conditions. Given that earth dams often exhibit partially unsaturated conditions, understanding the hydro-mechanical response of soils in such states is critical. The key findings are summarized as follows:

Flow Dynamics Optimization:

1- Parameters **a** and **n** significantly influence seepage flow through the dam, with optimization of these parameters enhancing flow efficiency.

2- Parameter **m** requires careful management to avoid reductions in flow performance.

3- Higher values of **n** lead to flow stabilization, underscoring the need to identify optimal parameter ranges for improved hydraulic performance.

4- Saturated water content (**θ**□$_{\mathbf{a}}$□) exhibits negligible impact on flow dynamics, suggesting its exclusion in flow management strategies.

Downstream Slope Stability:

5- Variations in parameters **a**, **n**, and **θ**□$_{\mathbf{a}}$□ have minimal influence on downstream slope stability, with only marginal fluctuations in the factor of safety (FoS).

6- While higher values of **m** slightly reduce stability, the slope remains secure across all tested ranges, indicating robust design resilience.

Upstream Slope Stability During Rapid Drawdown:

7-The upstream slope experiences transient instability during rapid drawdown but stabilizes rapidly (FoS≈2.2) across all tested **a** values, confirming design robustness under transient hydraulic conditions.

8- Similar stability trends (FoS ≈ 2.1–2.3) are observed for varying **n** and **m** values, reinforcing the slope's resilience to parameter fluctuations.

9- Saturation levels (**θ□$_{a}$□**) do not significantly alter post-drawdown stability (FoS ≈ 2.1–2.3), further validating the slope's adaptive capacity.

Role of Unsaturated Conditions in Stability:

10-Steady-state analyses reveal that unsaturated unit weight conditions enhance the safety factor without affecting flow.

11- During rapid drawdown, the transition to unsaturated conditions markedly improves the FoS, highlighting the slope's increased resilience.

Effect of Reservoir Drawdown Rate:

12. The drawdown rate significantly impacts slope stability, with slower rates (e.g., 0.5 m/day) resulting in a more gradual reduction in FoS, while faster rates (e.g., 4 m/day) cause sharper declines. However, the slope stabilizes over time, emphasizing the importance of controlled drawdown strategies to mitigate short-term instability risks.

Pseudo-Static Analysis Under Seismic Conditions:

13. Under seismic loading (pseudo-static coefficient of 0.15), the dam remains stable, though the FoS is reduced by approximately 20% compared to static conditions. This highlights the need to account for seismic forces in design, even though the structure maintains stability within acceptable limits.

The study demonstrates that while SWCC parameters influence flow and transient stability, the dam's design exhibits strong adaptability to hydraulic and mechanical variations. The consistent stability under rapid drawdown and the negligible impact of θ□$_{a}$□ underscore the importance of parameter optimization in earth dam engineering. Incorporating unsaturated soil behavior into stability analyses is essential for enhancing the safety and durability of dam structures.

References

Alonso, C. J. (1990). The Spanish American regional novel: Modernity and autochthony (No. 2). Cambridge University Press.

Asghari Pari, S. A., & Asghari Pari, S. A. (2025). Effect of unsaturated soil on deterministic and probabilistic analysis of the stability of an earth dam in steady state (case study: Seydon dam–Iran). Irrigation Science and Engineering, 47(4), 51–67. https://doi.org/10.22055/jise.2024.47355.2127.

Athani, S. S., Solanki, C. H., & Dodagoudar, G. R. (2015). Seepage and stability analyses of earth dam using finite element method. Aquatic Procedia, 4, 876–883. https://doi.org/10.1016/j.aqpro.2015.02.110

Azmi, M., Yusoff, S. A. M., Ramli, M. H., & Hezmi, M. A. (2016). Soil water characteristic curves (SWCCs) of mining sand. Electronic Journal of Geotechnical Engineering, 21(22), 6987–6997.

Blatz, J. A., & Graham, J. (2003). Elastic-plastic modeling of unsaturated soil using results from a new triaxial test with controlled suction. Géotechnique, 53(1), 113–122. https://doi.org/10.1680/geot.2003.53.1.113

Casagrande, A. (1925). Seepage through earth dams. Contribution to soil mechanics 1940.

Croney, D., & Coleman, J. D. (1954). Soil structure in relation to soil suction (pF).

Djehiche, A., Amieur, R., & Gafsi, M. (2012). Seepage through earth dams with chimney drain on previous foundation. In Advanced Materials Research (pp. 538–542). Trans Tech Publications.

Dong, Y., Miller, S. A., & Kelley, L. (2020). Improving irrigation water use efficiency: Using soil moisture sensors. Agricultural Water Management, 230, 105901. https://doi.org/10.1016/j.agwat.2019.105901

Dupuit, J. (1863). Études théoriques et pratiques sur le mouvement des eaux dans les canaux découverts et à travers les terrains perméables: avec des considérations relatives au régime des grandes eaux, au débouché à leur donner, et à la marche des alluvions dans les rivières à fond mobile. Dunod.

[DOR: 20.1001.1.22286837.1404.19.5.1.2]

[DOI: 10.22034/JEG.2025.19.5.1018842]

Fredlund, D. G. (1978). Usage, requirements and features of slope stability computer software (Canada, 1977). Canadian Geotechnical Journal, 15(1), 83–95. https://doi.org/10.1139/t78-008

Fredlund, D. G., & Rahardjo, H. (1993). An overview of unsaturated soil behavior. Geotechnical Special Publication, 1(1).

Fredlund, D. G., & Xing, A. (1994). Equations for the soil-water characteristic curve. Canadian Geotechnical Journal, 31(3), 521–532. https://doi.org/10.1139/t94-061

Guo, X., Dias, D., & Pan, Q. (2019). Probabilistic stability analysis of an embankment dam considering soil spatial variability. Computers and Geotechnics, 113, 103093. https://doi.org/10.1016/j.compgeo.2019.103093

Hasani, H., Mamizadeh, J., & Karimi, H. (2013). Stability of slope and seepage analysis in earth fills dams using numerical models (case study: Ilam Dam-Iran). World Applied Sciences Journal, 21, 1398–1402.

Kacimov, A. R., Al-Maktoumi, A., & Obnosov, Y. V. (2021). Seepage through earth dam with clay core and toe drain: The Casagrande–Numerov analytical legacy revisited. ISH Journal of Hydraulic Engineering, 27(2), 264–272. https://doi.org/10.1080/09715010.2019.1574614

Kacimov, A. R., & Brown, G. (2015). A transient phreatic surface mound, evidenced by a strip of vegetation on an earth dam. Hydrological Sciences Journal, 60(2), 361–378. https://doi.org/10.1080/02626667.2014.897407

Kacimov, A. R., Yakimov, N. D., & Šimůnek, J. (2020). Phreatic seepage flow through an earth dam with an impeding strip. Computational Geosciences, 24(1), 17–35. https://doi.org/10.1007/s10596-019-09895-8

Lim, J., Carilli, C. L., White, S. M., Beasley, A. J., & Marson, R. G. (1998). Large convection cells as the source of Betelgeuse's extended atmosphere. Nature, 392(6676), 575–577. https://doi.org/10.1038/33375

Mouyeaux, A., Carvajal, C., Bressolette, P., Peyras, L., Breul, P., & Bacconnet, C. (2018). Probabilistic stability analysis of an earth dam by Stochastic Finite Element Method based on field data. Computers and Geotechnics, 101, 34–47. https://doi.org/10.1016/j.compgeo.2018.04.011

Newman, J. (1995). Optimization of porosity and thickness of a battery electrode by means of a reaction-zone model. Journal of the Electrochemical Society, 142(1), 97. https://doi.org/10.1149/1.2043758

Rahimi, H. (2018). Earth dam. Tehran University Press.

Rezaeeian, A., Davoodi, M., & Jafari, M. K. (2019). Determination of optimum cross-section of earth dams using ant colony optimization algorithm. Scientia Iranica, 26(3), 1104–1121. https://doi.org/10.24200/sci.2018.20350

Shan, Y., Chen, S., & Zhong, Q. (2020). Rapid prediction of landslide dam stability using the logistic regression method. Landslides, 17(12), 2931–2956. https://doi.org/10.1007/s10346-020-01475-7

Stark, T. D., & Jafari, N. H. (2018). San Luis dam case history: Seepage and slope stability analyses and lessons learned. In IFCEE 2018 (pp. 317–329).

Stello, M. W. (1987). Seepage charts for homogeneous and zoned embankments. Journal of Geotechnical Engineering, 113(8), 996–1012. https://doi.org/10.1061/(ASCE)0733-9410(1987)113:8(996)

Van Genuchten, M. T. (1980). A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Science Society of America Journal, 44(5), 892–898. https://doi.org/10.2136/sssaj1980.03615995004400050002x

Vanapalli, S. K., & Fredlund, D. G. (2000). Comparison of different procedures to predict unsaturated soil shear strength. In Advances in Unsaturated Geotechnics (pp. 195–209).

Vanapalli, S. K., Fredlund, D. G., Pufahl, D. E., & Clifton, A. W. (1996). Model for the prediction of shear strength with respect to soil suction. Canadian Geotechnical Journal, 33(3), 379–392. https://doi.org/10.1139/t96-060

Wang, Y. (2014). Probabilistic assessments of the seismic stability of slopes: Improvements to site-specific and regional analyses (Doctoral dissertation).

دسترسی آزاد
شاپا الکترونیکی
۲۹۸۱-۱۴۰۰
نشریه زمین شناسی مهندسی
Journal home page https://jeg.khu.ac.ir
دانشگاه خوارزمی

تاثیر پارامترهای SWCC بر پایداری شیب سد خاکی در حالت جریان پایدار و تخلیه سریع مخزن

سید علی اصغری پری [1] ✉

۱. استادیار، گروه مهندسی عمران، دانشکده فنی و مهندسی، دانشگاه صنعتی خاتم الانبیاء(ص) بهبهان، بهبهان، ایران. رایانامه: asgharipari@bkatu.ac.ir

اطلاعات مقاله

نوع مقاله: مقاله پژوهشی

تاریخ دریافت: ۱۴۰۳/۱۲/۰۶
تاریخ پذیرش: ۱۴۰۴/۰۳/۲۰

کلیدواژه‌ها:
سد خاکی، خاک غیرا شباع، منحنی مشخصه رطوبتی خاک (SWCC)، تحلیل پایداری شیب، GeoStudio

چکیده

این مطالعه به بررسی تأثیر پارامترهای منحنی مشخصه رطوبتی خاک (SWCC) بر پایداری شیب یک سد خاکی تحت شرایط حالت پایدار و افت سریع سطح آب می‌پردازد. با توجه به اهمیت رفتار خاک غیرا شباع در سدهای خاکی، این پژوهش از اصول مکانیک خاک غیرا شباع برای تحلیل تأثیر پارامترهای SWCC بر نرخ جریان آب و پایداری شیب استفاده می‌کند. نتایج نشان می‌دهد که افزایش پارامترهای a و n نرخ جریان را افزایش می‌دهد، در حالی که افزایش پارامتر m آن را کاهش می‌دهد. در تحلیل پایداری شیب، پارامترهای SWCC تأثیر قابل‌چشم‌گیری بر پایداری شیب پایین‌دست نداشتند، اما افزایش پارامتر m موجب کاهش جزئی ضریب ایمنی شد. تحت شرایط افت سریع سطح آب، همه پارامترها در ابتدا منجر به کاهش ضریب ایمنی شدند، اما پایداری پس از ۱۰ روز بازیابی شد. علاوه بر این، در نظر گرفتن وزن مخصوص غیرا شباع خاک، ضریب ایمنی را در هر دو سناریوی حالت پایدار و افت سریع سطح آب بهبود بخشید. این یافته‌ها نقش حیاتی شرایط خاک غیراشباع در طراحی و تحلیل پایداری سدهای خاکی را برجسته می‌کند.

مقدمه

سدهای خاکی به عنوان پرکاربردترین نوع سد در جهان، نقش حیاتی در مدیریت منابع آب و توسعه پایدار ایفا می‌کنند. رفتار هیدرو-مکانیکی این سازه‌های عظیم به دلیل حضور همزمان فازهای جامد، مایع و گاز در محیط متخلخل خاک، از پیچیدگی‌های قابل توجهی برخوردار است. درک رفتار خاک در شرایط غیراشباع، به ویژه از طریق منحنی مشخصه رطوبتی خاک (SWCC)، یکی از جنبه‌های اساسی در طراحی و تحلیل پایداری این سازه‌ها محسوب می‌شود. این پژوهش با هدف بررسی سیستماتیک تأثیر پارامترهای کلیدی SWCC شامل پارامترهای شکل‌دهنده منحنی (a, n, m) و محتوای آب اشباع (θ_a) بر عملکرد هیدرولیکی و پایداری سازه‌ای یک سد خاکی در شرایط مختلف بارگذاری شامل حالت ماندگار، افت سریع سطح آب، و بارگذاری لرزه‌ای انجام شده است.

مواد و روش‌ها

تئوری خاک‌های غیراشباع و تأثیر آن بر نفوذپذیری و مقاومت خاک: نفوذ آب از طریق خاک یکی از فرآیندهای اساسی در مهندسی ژئوتکنیک است. مدل‌های سنتی تحلیل جریان آب زیرزمینی به خاک‌های اشباع محدود می‌شوند، در حالی که تحلیل خاک‌های غیراشباع نیازمند درک پیچیده‌تری از رفتار خاک است.

منحنی مشخصه خاک-آب:این منحنی نقش مهمی در درک خواص خاک‌های غیراشباع دارد و پارامترهایی مانند

استناد: اصغری پری، ع. (۱۴۰۴). تاثیر پارامترهای SWCC بر پایداری شیب سد خاکی در حالت جریان پایدار و تخلیه سریع مخزن. مجله زمین شناسی مهندسی، ۱۹ (۵)، ۶۲۷-۶۴۷. https://doi.org/10.22034/JEG.2025.19.5.1018842

ناشر: دانشگاه خوارزمی.

ارزش ورودی هوا (AEV)، میزان آب حجمی در حالت اشباع (θ_{sat}) و آب حجمی باقیمانده (θ_{res}) را شامل می‌شود.

این مطالعه به صورت عددی و با استفاده از نرم‌افزار پیشرفته GeoStudio 2018 انجام شده است. مدل مورد بررسی یک سد خاکی همگن به ارتفاع ۱۲ متر با سطح آب مخزن ۱۰ متر بوده که مصالح تشکیل‌دهنده آن خاک رسی با مشخصات مفصل ارائه شده در جدول ۱ مقاله می‌باشد.

برای تحلیل جامع، از ماژول SEEP/W برای شبیه‌سازی نفوذ و از ماژول SLOPE/W برای تحلیل پایداری استفاده شد. روش تحقیق مبتنی بر آنالیز حساسیت بوده به طوری که هر یک از پارامترهای a (در بازه ۱۰ تا ۱۱۰)، n (۱/۵ تا ۵)، m (۵ تا ۳۰) و θ□a□ (۰/۳تا ۰/۵) به صورت مجزا تغییر داده شده و تأثیر هر کدام بر پاسخ‌های هیدرولیکی و مکانیکی سد بررسی گردید.

شرایط افت سریع با نرخ ۱ متر بر روز و به مدت ۹۰ روز به صورت تحلیل گذرا مدلسازی شد. همچنین اثرات دینامیکی با استفاده از روش شبه‌استاتیکی و با اعمال ضریب شتاب افقی ۰/۱۵ مورد ارزیابی قرار گرفت. تأثیر نرخ‌های مختلف افت آب (۰/۵، ۲ و ۴ متر بر روز) و نیز اثر در نظر گیری وزن مخصوص غیراشباع خاک به صورت جداگانه تحلیل شد.

نتایج و بحث

رفتار هیدرولیکی: نتایج حاصل از تحلیل نفوذ نشان داد که پارامترهای a و n رابطه مستقیمی با نرخ جریان عبوری از بدنه سد دارند، به طوری که افزایش این پارامترها منجر به افزایش قابل ملاحظه نفوذپذیری خاک می‌گردد. در مقابل، پارامتر m اثر معکوس بر نرخ جریان دارد. پارامتر θ□a□تأثیر محسوسی بر میزان نفوذ نشان نداد که نشان‌دهنده استقلال نفوذپذیری از این پارامتر تحت شرایط بررسی شده می‌باشد.

پایداری استاتیکی: در شرایط پایدار، پارامترهای a ، n و θ□a□ تأثیر ناچیزی بر پایداری شیب پایین‌دست داشتند. افزایش پارامتر m موجب کاهش جزئی در ضریب ایمنی شد، اما مقادیر ضریب ایمنی در تمام موارد در محدوده قابل قبول قرار داشتند.

پایداری در شرایط افت سریع: در خلال ۱۰ روز اول افت سریع سطح آب، تمامی پارامترهای مورد مطالعه منجر به کاهش قابل توجه ضریب ایمنی شیب بالادست شدند. با این وجود، پس از این دوره گذرا، سیستم به تعادل جدیدی دست یافت و ضریب ایمنی حول مقادیر ۲ تا ۲/۳ برای تمامی پارامترها تثبیت شد.

اثر وزن مخصوص غیراشباع: در نظر گیری اثرات خاک غیراشباع و استفاده از وزن مخصوص واقعی منجر به بهبود قابل توجه ضریب ایمنی در تمامی شرایط بارگذاری شد. این بهبود در روز دهم تحلیل افت سریع در حدود ۶/۷٪ محاسبه شد که ناشی از اثرات مثبت مکش ماتریک در افزایش مقاومت برشی خاک می‌باشد.

تحلیل لرزه‌ای: اعمال بار لرزه‌ای با ضریب ۰/۱۵ منجر به کاهش حدود ۲۰٪ در ضریب ایمنی نسبت به شرایط استاتیکی گردید. با این حال، سد در این شرایط نیز پایداری خود را حفظ نمود.

تأثیر نرخ افت: بررسی نرخ‌های مختلف افت نشان داد که نرخ‌های کندتر افت (۰/۵ متر بر روز) منجر به کاهش تدریجی‌تر و کم‌خطرتر ضریب ایمنی می‌شوند، در حالی که نرخ‌های سریع‌تر (۴ متر بر روز) موجب کاهش ناگهانی و شدید ضریب ایمنی در کوتاه‌مدت می‌گردند.

نتیجه‌گیری

این پژوهش به صورت جامع به بررسی تأثیر پارامترهای SWCCبر عملکرد سدهای خاکی پرداخته است. یافته‌ها نشان می‌دهند که این پارامترها تأثیر تعیین‌کننده‌ای بر رفتار

[DOR: 20.1001.1.22286837.1404.19.5.1.2]
[DOI: 10.22034/JEG.2025.19.5.1018842]

[DOR: 20.1001.1.22286837.1404.19.5.1.2]

[DOI: 10.22034/JEG.2025.19.5.1018842]

هیدرولیکی و پایداری گذرای سد دارند. بهینه‌سازی پارامترهای a و n می‌تواند به مدیریت هدفمند نرخ نفوذ کمک نماید، در حالی که پارامتر m نیازمند کنترل و مدیریت دقیق‌تری می‌باشد. اگرچه پایداری شیب پایین‌دست نسبت به تغییرات این پارامترها حساسیت کمتری نشان می‌دهد، اما پایداری شیب بالادست در شرایط افت سریع به صورت موقت تحت تأثیر قرار می‌گیرد. با این وجود، سد از قابلیت بازگشت به حالت پایدار برخوردار است. مهم‌ترین دستاورد این پژوهش تأکید بر ضرورت در نظر گیری رفتار خاک غیراشباع و اثرات مکش ماتریک در تحلیل‌های پایداری سدهای خاکی می‌باشد. استفاده از وزن مخصوص غیراشباع به جای فرض اشباع کامل منجر به محاسبه ضریب ایمنی واقع‌بینانه‌تر و اقتصادی‌تر می‌شود. همچنین، مدیریت نرخ افت سطح آب مخزن به عنوان یک ابزار کارآمد در کنترل پایداری سد در شرایط اضطراری پیشنهاد می‌گردد. نتایج این مطالعه می‌تواند مبنای علمی مناسبی برای تدوین دستورالعمل‌های دقیق‌تر طراحی و بهره‌برداری از سدهای خاکی فراهم نماید.