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Original Paper

Effect of unsaturated soil on deterministic and probabilistic analysis of the stability of an earth dam in steady state (case study: Seydon dam – Iran)

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Abstract

The stability and flow rate of earth dams are influenced by several factors, including geometric characteristics, material permeability, and the height of water upstream. To effectively understand the behavior of unsaturated soils in earth dams, it is essential to apply the principles of unsaturated soil mechanics, given the complexities involved. Neglecting uncertainties in geotechnical assessments can lead to incorrect estimates of safety factors for dam slope stability. This research investigates the impact of unsaturated soil conditions on seepage discharge and the safety factor for the downstream of the earth dam under varying scenarios, with a focus on the Seydon Dam in Khuzestan province, Iran. The findings indicate that modeling the dam's soil as a saturated-unsaturated system decreases the computed flow rate through the dam and enhances the downstream slope's safety factor in both probabilistic and deterministic analyses. Additionally, a sensitivity analysis reveals that the earth dam shell's parameters significantly influence downstream slope stability. Spatial variation analysis further indicates that accounting for spatial changes in soil parameters can decrease the safety factor of the downstream slope compared to a standard assessment.

Introduction

Earth dams are one of the most important and complex engineering structures that spend a lot of money on studying and implementing these types of projects. As a result, their safety issues during construction and operation are of particular importance. According to the statistics of the International Commission on Large Dams (ICOLD), more than 81% of the dams built in the world are earth dams. The most important advantage of earth dams, along with features such as lower implementation costs and simpler technology, is the relatively high adaptability to a wide range of diverse conditions of different constructions. However, the operation of this type of dam also requires taking into account special conditions, which may be the most important factor in the design, the discussion of the amount of seepage from the body, and the stability of earth dams.

One of the important factors that is considered in the design of earth dams is the amount of seepage from the dam body. Various analytical methods were proposed to check the seepage flow from the body of earth dams during different years. Using Darcy's law, Dupuit (1863) proposed a relationship to calculate the flow through any vertical surface. Djehiche et al. (2012) presented a relation to calculate seepage from a homogeneous earth dam body on a permeable foundation. Casagrande (1961) presented a relationship to calculate the amount of flow passing through the body of an earth structure, in which the effect of the core width parameters, the water height behind the dam, and the core embankment angle were considered.

Stello (1987) presented a chart to predict the phreatic line in the body of earth dams and the amount of flow passing through their body, which is placed on an impermeable foundation. Then he compared the obtained results with the analysis of the software and it was found that there is about 18% difference between the results. Finally, he proposed a relationship to calculate the discharge from the dam. Among the most recent research conducted in the field of investigation of seepage level, we can refer to the research of Kasimov and his colleagues (Kacimov et al., 2021, 2020; Kacimov and Brown, 2015) who used barrier strips and plant growth lines to investigate the flow line in the body of the dam.

The issue of seepage in earth dams is one of the important issues in design, and if it exceeds the specified value, there will be a possibility of failure in the earth dam. Despite the various methods to investigate and analyze seepage, sometimes there is a difference in the hydraulic behavior of water and seepage from the body and foundation of the earth dam (Rezaeeian et al., 2019; Stark and Jafari, 2018).

In the body of earth dams, the degree of saturation of the shell downstream can have a significant effect on the stability of the body. So excessive saturation of the downstream can be a threat to the stability of the dam. If this issue is properly investigated and evaluated, it can provide appropriate information to dam designers and operators. An accurate understanding of soil behavior in earth dams requires the use of unsaturated soil mechanics laws. At this time, unsaturated soil mechanics is facing many unknowns compared to classical soil mechanics, and the main reason for this is the complexity of soil behavior in unsaturated conditions. In this research, the effect of unsaturated soil on the amount of seepage from the body of the Seydon dam in Iran is investigated.

On the other hand, an earth dam is stable when the result of the applied stresses in each part of the dam is smaller than the mobilized resistance in that part. The stability of an earth dam is a relative issue, and depending on the relative change in the number of destructive and resistant forces, there can be different degrees of stability (Guo et al., 2019). During the last decades, many researchers have investigated the effect of various factors such as the material of the dam body, cohesion, friction, upstream slope, and water discharge rate from the dam, on the stability and settlement of the dam (Athani et al., 2015; Hasani et al., 2013; Mouyeaux et al., 2018; Shan et al., 2020; Wang, 2014; Siacara et. al 2021, 2024; Salmasi et. al 2020; Eslamian et al. 2021).

This paper provides a comprehensive exploration of the impact of unsaturated soil modeling on the stability of the downstream slope of an earth dam, specifically within a steady-state context. The initial section delves into unsaturated soil theory, highlighting its critical role in influencing both soil permeability and shear strength. This theoretical background sets the foundation for understanding how these factors can affect dam stability. Using the Seydon earth dam as a case study, the paper discusses specific construction characteristics that are pertinent to the analysis. This lays the groundwork for the subsequent seepage analysis, which assesses water movement through the dam structure and its potential effects on stability. The stability analysis of the downstream slope is then presented, drawing on the results of the seepage analysis to evaluate safety margins against failure. To rigorously assess the risk associated with the dam, a probabilistic analysis is implemented using two distinct methodologies: the global minimum method and the overall slope method. The discussion of these results offers insights into the reliability and stability of the dam under various conditions. A sensitivity analysis follows, designed to determine how variations in key parameters influence the stability outcomes. Furthermore, a spatial variation analysis is conducted to understand the implications of changes in soil properties across different areas of the dam, providing deeper insight into how localized conditions can affect overall stability. The findings throughout the paper emphasize the importance of considering unsaturated soil mechanics in dam safety assessments, contributing valuable knowledge to the field of geotechnical engineering.

Materials and Methods

Unsaturated soils and their effect on permeability and strength

Water flow in soil is a fundamental process in geotechnical engineering, particularly in quantifying seepage from dam reservoirs. Pore water pressure, whether positive or negative, significantly influences the stress state, shear strength, and volume change behavior of soil. Recent research emphasizes the importance of understanding water flow in unsaturated soils for optimal geotechnical design.

Historically, groundwater flow analysis has concentrated on saturated soils, categorizing flow problems as confined (under structures) or unconfined (through embankments). Unconfined flow is more complex due to the variable location of the phreatic level, and any flow in the capillary region above this level is often overlooked. While saturated soil models are useful for defining regions below the phreatic level, they are inadequate for soils that may become partially saturated during analysis, potentially leading to overestimated flow rates and unrealistic water levels.

The hydraulic conductivity function reflects a soil's ability to conduct water in both saturated and unsaturated states. In saturated soils, all pore spaces are filled with water, but as soils become unsaturated, air enters larger pores, decreasing hydraulic conductivity due to increased tortuosity of flow paths (Figure (1)). As pore water pressure becomes more negative, more pores fill with air, further reducing conductivity. Thus, the capacity for water flow through soil depends on the volumetric water content. Although measuring hydraulic conductivity can be time-consuming and costly, it can be estimated using various prediction methods based on grain size distribution curves or measured volumetric water content and saturated hydraulic conductivity. Understanding the relationship between pore water pressure and water content is very important in seepage analysis. Soil consists of a set of solid particles and interstitial voids. The pore spaces or voids can be filled with water or air or a combination of both. In a saturated soil, all empty spaces are filled with water and the volumetric water content (θ_w) is equal to soil porosity according to the following relationship:

$$\theta_w = nS \qquad (1)$$

where n is the value of porosity and S is the degree of soil saturation.

In an unsaturated soil, the volume of water stored in the pores will vary depending on the matric suction, where the matric suction is defined as the difference between air pressure (u_a) and water pressure (u_w) as $u_a - u_w$.

There is no constant water content in time and space, and therefore a function is needed to describe how water content changes with different pressures in the soil. The volumetric water content function describes the ability of the soil to store water under changes in matric pressures.

A typical function for volumetric water content is shown in Figure (2). The volumetric water content function describes what volume of voids remains filled with water when the soil is drained. The three main properties that define the volumetric water content function are porosity (n), air entry value (AEV), and residual volumetric water content (θ_{res}). The air entry value (AEV) corresponds to the amount of negative pore water pressure when the largest voids or pores begin to drain freely. This value is a function of the maximum pore size in the soil and is also influenced by the pore size distribution in the soil. The percentage of residual volumetric water content indicates the percentage of volumetric water content in which a further increase in negative pore water pressure does not cause significant changes in the amount of water in the soil.

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

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

Van Genuchten (1980) proposed the following relationship to calculate the volumetric water content.

$$\theta_w = \theta_{res} + \frac{\theta_{sat}-\theta_{res}}{[1+(a'\Psi)^n]^m} \quad (3)$$

where a, a', n and 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 and θ_{res} is residual volumetric water content. Note that the parameter a in Equation (2) has units of pressure and is related to the parameter a' (a' = 1/a) used by Van Genchten (1980) in Equation (3). 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 (3). To estimate the value of hydraulic conductivity, we use the equation proposed by Van Genuchten (1980). 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:

$$K_w(\Psi) = K_{sat}\frac{\left\{1-(a'\Psi)^{n-1}\left[1+(a'\Psi)^n\right]^{-m}\right\}^2}{[1+(a'\Psi)^n]^{\frac{m}{2}}} \quad (4)$$

In geotechnical engineering, the stability of soil slopes is typically assessed using resistance parameters determined in laboratory conditions based on water content and compaction. However, earth slopes, particularly in earth dams, often exist in an unsaturated state rather than being fully saturated or dry. This unsaturated condition necessitates a different approach to stability analysis, as the parameters used in calculations can differ significantly from those in saturated or dry soils. Key factors influencing unsaturated soils include changes in pore water and air pressure, as well as the resistance provided by matric suction, which varies based on saturation percentage, permeability, and time.

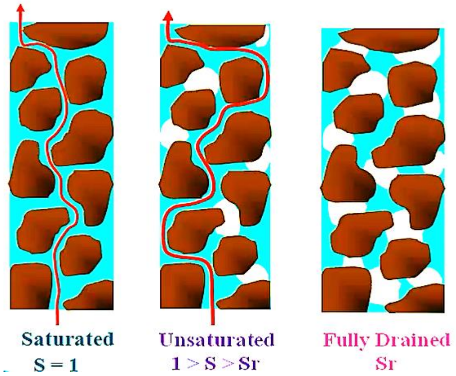


Fig. 1- The flow path in saturated and unsaturated soils

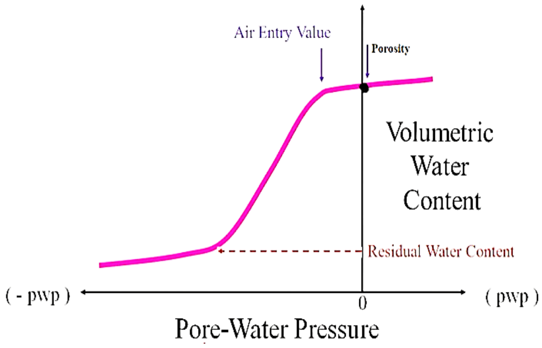


Fig. 2- Function of volumetric water content

Research on the unsaturated condition of soils began in the 1960s, leading to numerous laboratory studies, calculations, and theoretical advancements (Rahardjo and Fredlund, 1995; Van Genuchten, 1980). These theories and experimental results have been assessed in the context of specific conditions in practical projects. The mechanical behavior of soil is characterized by its stress state, which comprises various stress state variables. These variables are independent of the soil's physical properties, and their quantity primarily depends on the number of phases present in 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 came to a conclusion 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:

$$\tau = c' + (\sigma - u)\tan\phi' \qquad (5)$$

Where: τ is the shear strength, c' is the effective cohesion, σ is the normal stress, u is the pore water pressure 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. (1996) took the form of an extension of the Mohr-Coulomb failure criterion.

$$\tau = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\phi_b \qquad (6)$$

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 caused more precise methods to be used to design earth dams.

Specifications and location of the Seydon Dam project

The Seydon Reservoir Dam, a significant engineering project, is currently under construction approximately 40 kilometers southeast of Baghmolek, situated on one of the main branches of the Ala River in Khuzestan province. The catchment area of this dam, which lies within a mountainous region, spans an impressive 496.5 square kilometers. The Seydon Reservoir Dam's construction site is in a V-shaped valley with a relatively symmetrical incomplete arm, as depicted in Figure (3). The summary of the characteristics of Seydon Reservoir Dam is presented in Table (1). Seydon's earth dam is of an earth type with a clay core and two filters located at the bottom and top of the core. The type of clay core material in terms of classification of soils is CL type, whose width reaches 45 meters at the bottom of the dam and 7 meters at the top of the dam. The filter and drain material are of SM type and are placed on both sides of the core. The materials of the dam body are mostly of GP-GM type and have a slope of 1 to 2.5 in the upstream and 1 to 2 in the downstream.

Fig. 3- Location of the valley where Seydon Dam is located (Water and Electricity Organization of Khuzestan Province, 2010)

Table 1- The characteristics of Seydon Reservoir Dam (Water and Electricity Organization of Khuzestan Province, 2010)

Dam Characteristics	Value
The Total Volume Of The Reservoir	65.9 Million Cubic Meters
Useful Volume	50.5 Million Cubic Meters
Normal Level	1290 Meters Above Sea Level
Minimum Exploitation Level	1245 Meters From The Open Sea Level
The Regulatory Water Volume Of The Seydon Dam	6.77 Million Cubic Meters

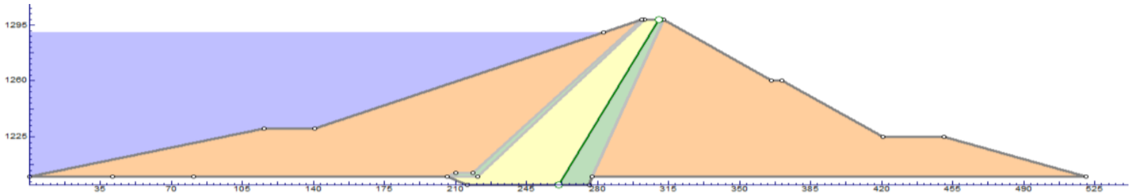


Fig. 4- The hypothetical cross-section of the body of the Seidon dam

Table 2-Specifications of unsaturated model for Seydon dam (Water and Electricity Organization of Khuzestan Province, 2010)

Type of materials	a(kPa)	n	Ksat(m/s)
Core	0.1	1.1	4×10^{-8}
Filter	15.1	7.35	1×10^{-3}
Shell	0.79	10.4	1×10^{-5}

Results and discussion

Seepage analysis results

In this study, we use Slide2 software to conduct seepage analysis of the Seydon Dam under steady-state conditions. Slide2 is a versatile program for assessing slope stability in soil and rock, calculating safety factors and failure probabilities for various slip surfaces with both circular and non-circular geometries. It employs two-dimensional limit equilibrium methods and advanced groundwater seepage analysis using finite element methods, allowing for detailed evaluations of stability and water movement through the dam. This integrated approach aims to assess the Seydon Dam's safety and identify potential risks related to its design and operation. For this purpose, the cross-section of the Seydon Dam is considered in Figure (4), and the height of the water in the reservoir of the dam is 90 meters. The characteristics of the dam materials for the saturated state and the necessary parameters for the unsaturated-saturated soil model state, based on Van Genuchten's model (Van Genuchten, 1980), are given in Table (2). The results of the seepage analysis in the case of assuming the soil model of the dam body in saturated and saturated-unsaturated states are given in Figures (5) and (6).

The results indicate a significant difference in the flow rates passing through the Seydon dam between the saturated model and the saturated-unsaturated model. In the saturated model, the flow rate is reported as $q = 2.83 \times 10^{-5}\ m^3/sec$ hereas in the saturated-unsaturated model, the flow rate is $q = 9.97 \times 10^{-6}\ m^3/sec$his represents a 65% reduction in flow rate when considering the saturated-unsaturated model compared to the saturated model.

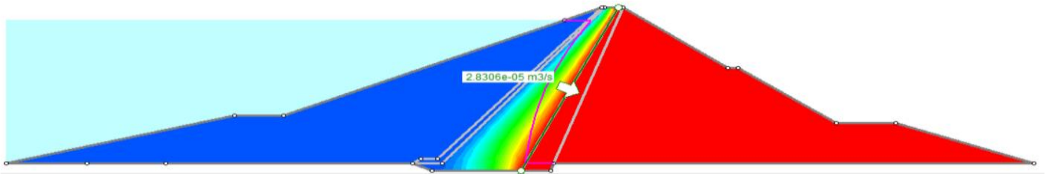


Fig. 5- The result of seepage analysis from the dam body in the full saturated soil model

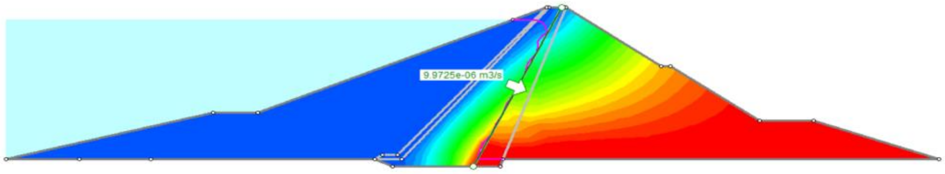


Fig. 6- The result of seepage analysis from the dam body in the saturated-unsaturated soil model

The reduced flow rate in the saturated-unsaturated model is attributed to the incorporation of unsaturated zones within the dam body. While a saturated soil model assumes that the entire soil mass is fully saturated, leading to potential overestimation of seepage flow, the saturated-unsaturated model acknowledges sections of the dam that are not fully saturated. This results in reduced permeability and limited flow, with seepage occurring primarily below the free water line. By accounting for unsaturated conditions, the analysis offers a more accurate depiction of seepage behavior, facilitating a realistic assessment of potential seepage paths and flow rates, which is crucial for dam safety and stability evaluations.

Slope stability analysis results

We have used Slide2 software to check the stability of the downstream slope of the earth dam. Two modes for the dam are considered: static and quasi-static. We have used the results of the previous part for the seepage analysis, and the specifications of the materials for the stability analysis are shown in Table (3). Also, we used the Janbu Generalized limit equilibrium analysis method for the slope stability analysis. the Janbu Generalized method is a rigorous procedure that satisfies both moment and force equilibrium. This method provides a comprehensive approach to slope stability analysis, taking into account the complex interactions between soil strength, pore water pressure, and slope geometry.

The results of slope stability analysis are presented in Figures (7) and (8). The results from the analysis of Seydon Dam reveal a significant improvement in the stability of the downstream slope when the dam materials are modeled as unsaturated. Specifically, the stability factor increased from 1.51 in the fully saturated model to 2.23 in the unsaturated model, resulting in a 52% increase. This increase in the stability factor indicates that the unsaturated condition enhances the dam's ability to resist potential failures, likely due to factors such as increased effective stress and reduced pore water pressure, which contribute to greater overall stability. The stability of the downstream slope is analyzed under quasi-static conditions with a horizontal acceleration of 0.15 to better understand the impact of earthquakes on the dam's stability. The results of quasi-static analysis are presented in Figures (9) and (10).

The analysis presented indicates a notable improvement in the stability of the dam's downstream slope when transitioning from a fully saturated model to an unsaturated model under quasi-static conditions with a horizontal acceleration of 0.15. The increase in the safety factor from 1.11 to 1.68 (a 57% increase) suggests that unsaturated soil conditions provide enhanced stability, possibly due to factors such as increased effective stress and reduced pore water pressure.

The critical slope depth is an important factor in dam stability analysis. In fully saturated models, a smaller critical slope depth indicates a higher susceptibility to failure at shallower depths. In contrast, unsaturated models show greater critical slope depths, suggesting better stability and resistance to sliding and failure mechanisms during seismic events. These findings highlight the need to consider soil saturation levels in stability analyses, especially for dams subject to dynamic forces like earthquakes. Utilizing an unsaturated model could result in more conservative and safer design approaches for assessing dam stability.

Table 3- Resistance properties of dam materials in saturated and unsaturated models (Water and Electricity Organization of Khuzestan Province, 2010)

Type of model	Saturated And Unsaturated	Saturated And Unsaturated	Saturated And Unsaturated	Unsaturated	Unsaturated
Type of material	Cohesion (KN/m^3)	Friction angle (degree)	Unit weight (KN/m^3)	ϕ_b(degree)	AEV(Kpa)
Core	40	23	20.7	11.5	50
Filter	0	35	20	17.5	0.4
Shell	0	44	21.9	22	5

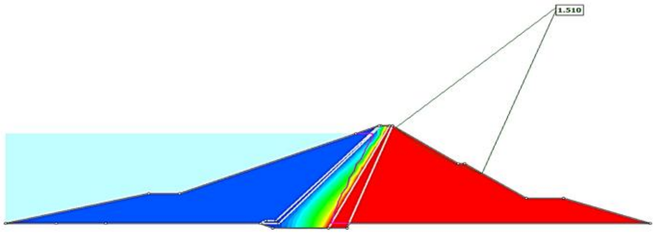


Fig. 7- Stability Analysis of Seydon Dam in steady state condition (saturated Soil)

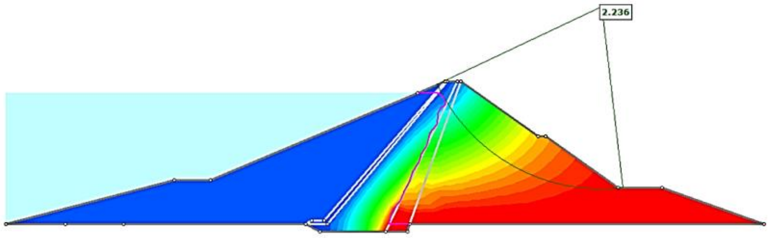


Fig. 8- Stability Analysis of Seydon Dam in steady state condition (unsaturated Soil)

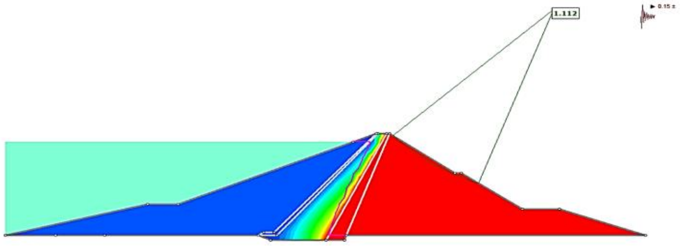


Fig. 9- Stability Analysis of Seydon Dam in steady state condition and quasi-static Mode (saturated Soil)

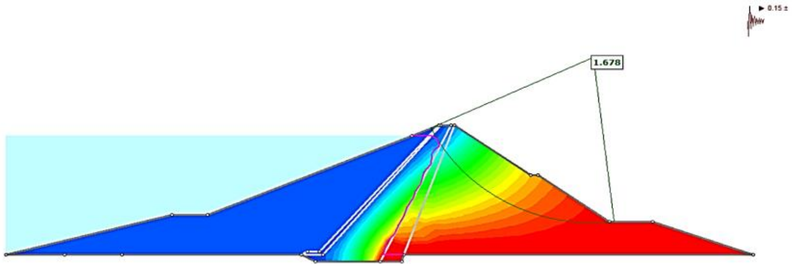


Fig. 10- Stability Analysis of Seydon Dam in steady state condition and quasi-static Mode (unsaturated Soil)

Table 4- Relationships between probability of failure, and reliability index (Phoon and Kulhawy, 2008)

Reliability Index	Probability of failure	Performance level
1	0.16	Hazardous
1.5	0.023	Unsatisfactory
2	0.0027	Poor
2.5	0.0006	Below average
3	0.0001	Above average
4	$3 * 10^{-5}$	Good
5	$3 * 10^{-7}$	High

Probabilistic Analysis

A deterministic Safety Factor assesses the margin of safety in a system by using average or expected values for all variables, providing a basic measure of safety. However, it does not account for variability or uncertainty, which are prevalent in real-world situations. To better understand actual risks, it is important to incorporate probabilistic or stochastic methods in safety assessments, as these approaches reveal insights into the likelihood of failure. A higher probability of failure indicates greater risk, while a lower probability suggests more safety.

The Reliability Index is a key metric in evaluating slope stability following a probabilistic analysis. It quantifies the safety margin by measuring the difference between the Mean Safety Factor and a critical safety factor, typically set at 1. The Reliability Index represents how many standard deviations separate the Mean Safety Factor from this critical threshold, thus indicating the system's reliability or safety level.The Reliability Index (RI), commonly symbolized as β, is a ratio of the mean of the safety margin (mean of FS-1) to the standard deviation of the safety margin (SD of F). This concept was first introduced by Cornell in 1969 and can be mathematically represented by Equation (7).

$$RI = \beta = \frac{(mean\ of\ FS-1)}{SD\ of\ FS} \qquad (7)$$

A higher Reliability Index indicates a greater safety margin and improved reliability in a system, while a lower index suggests a tighter safety margin, potentially elevating the risk of failure. By analyzing the distribution of safety factors relative to the critical value, the Reliability Index quantitatively assesses the overall stability of the system, providing important insights for engineering and risk management decision-making. Relationships between the probability of failure and the Reliability Index are detailed in Table (4). A Reliability Index of at least 3 is commonly recommended as a minimal assurance of a safe slope design (Phoon and Kulhawy, 2008). This value indicates a significant separation between the Mean Safety Factor and the critical safety factor, providing a substantial margin of safety. Achieving a Reliability Index of 3 or higher is often considered a good practice to ensure a high level of reliability and minimize the risk of slope failure in engineering and geotechnical applications.

The variability of the soil can be quantified using the coefficient of variation (COV), which is the ratio of the standard deviation to the most likely parameter value. This measure serves as an indicator of parameter variability and can be expressed mathematically as shown in Equation (8).

$$COV = \frac{\sigma}{\mu} \qquad (8)$$

Several researchers have highlighted the coefficient of variation (COV) as an indicator of variability in soil parameters. For instance, studies by Akbas and Kulhawy (2010) and Pham et al. (2001) propose a COV range of 5–15% for the unit weight of soil. Additionally, Akbas and Kulhawy (2010), and Kulhawy (2017) have demonstrated COV values ranging from 2% to 21% for Effective φ and cohesion parameters. These insights underscore the importance of considering variability in soil parameters when assessing slope stability and geotechnical characteristics.

In this analysis, parameters were considered variables with a Normal distribution and a coefficient of variation (COV) equal to 0.1, as detailed in Table (5). Also, we used Latin Hypercube sampling technique for generating samples of input variables from their probability distribution with 1000 number of samples. One of the advantages of the Latin Hypercube sampling technique is that it provides comparable results to the Monte Carlo technique but with fewer samples.

Table 5- Statistical parameters of dam materials

Name	Property	Distribution	Mean	Std. Dev.	Rel. Min	Rel. Max
Core	Air Entry Value	Normal	50	5	15	15
	Cohesion	Normal	40	4	12	12
	Friction angle	Normal	23	2.3	6.9	6.9
	Unit Weight	Normal	20.7	2.07	6.21	6.21
	ϕ_b	Normal	11.5	1.15	5.25	5.25
Filter	Air Entry Value	Normal	0.4	0.04	0.12	0.12
	Friction angle	Normal	35	3.5	10.5	10.5
	Unit Weight	Normal	20	2	6	6
	ϕ_b	Normal	17.5	1.75	6	6
Shell	Air Entry Value	Normal	5	0.5	1.5	1.5
	Friction angle	Normal	44	4.4	13.2	13.2
	Unit Weight	Normal	21.9	2.19	6.57	6.57
	ϕ_b	Normal	22	2.2	6.6	6.6

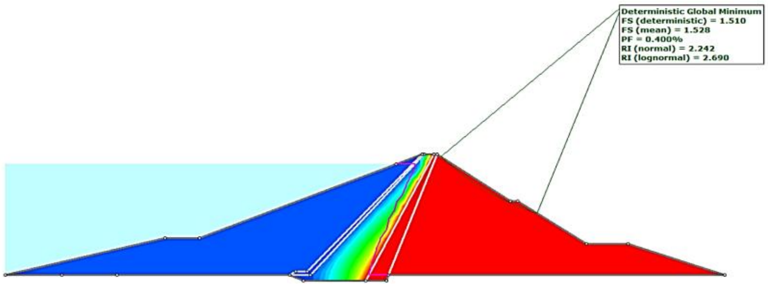


Fig. 11- Probabilistic Stability Analysis of Seydon Dam in steady state condition (saturated Soil)

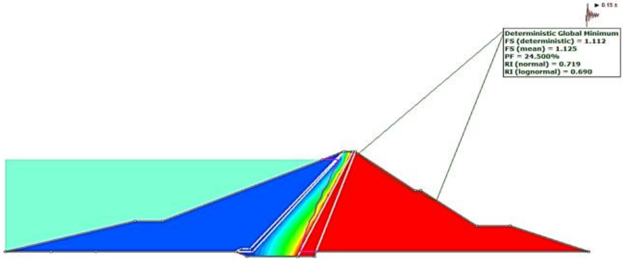


Fig. 12- Probabilistic Stability Analysis of Seydon Dam in steady state condition and quasi-static Mode (saturated Soil)

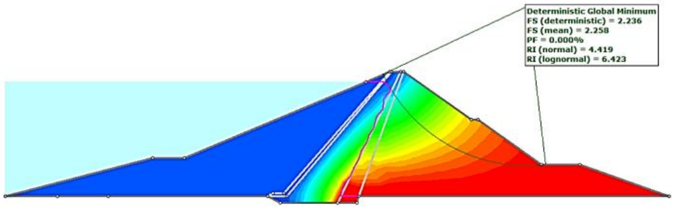


Fig. 13- Probabilistic Stability Analysis of Seydon Dam in steady state condition (unsaturated Soil)

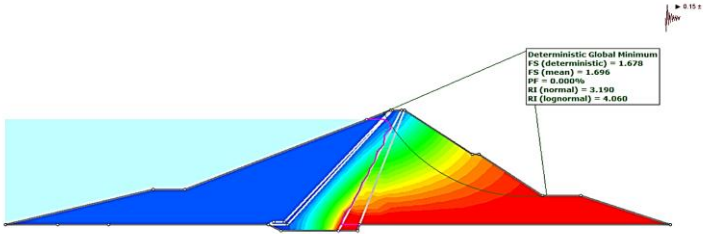
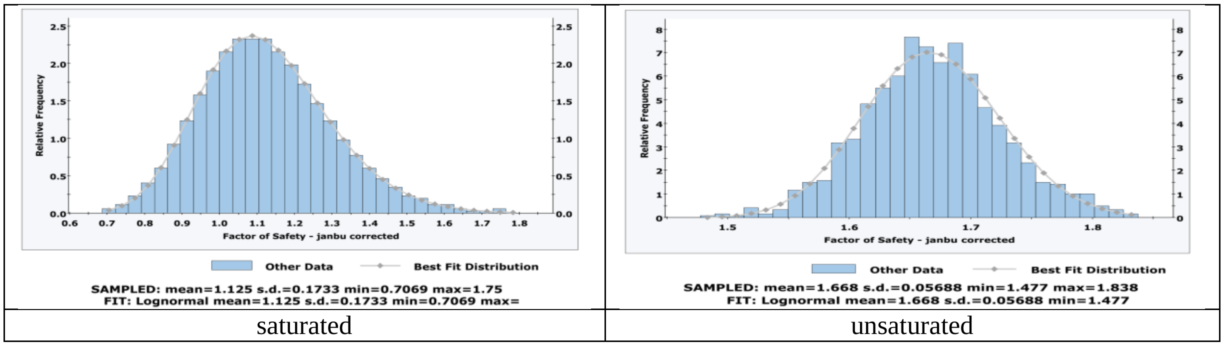


Fig. 14- Probabilistic Stability Analysis of Seydon Dam in steady state condition and quasi-static Mode (unsaturated Soil)



saturated unsaturated

Fig. 15- slope safety factor distribution function for saturated and unsaturated condition

Global Minimum Method

The Global Minimum Probabilistic Analysis Type assumes that the Probability of Failure, derived from the (Deterministic) Global Minimum slip surface, represents the entire slope's risk. In contrast, probabilistic slope stability analysis involves multiple iterations of stability calculations for the Global Minimum slip surface, using various combinations of input variables generated from random sampling methods. This process produces N calculated safety factors, where N corresponds to the number of samples. The Probability of Failure is then calculated by counting how many analyses yield a safety factor less than 1 (indicating instability) and dividing that count by the total number of samples.The results of the probabilistic analysis for both fully saturated and unsaturated states are illustrated in Figures (11-14). These findings indicate that the probability of failure under full saturation conditions is notably low, with a probability of failure of 0.4% (Reliability Index, RI = 2.42) for static conditions and 24.5% (RI = 0.719) for quasi-static conditions. In contrast, for the unsaturated state, the reliability indices are significantly higher, with values of RI = 4.42 for static conditions and RI = 3.19 for quasi-static conditions. Furthermore, Figure (15) depict the distribution functions of slope safety factors under both saturated and unsaturated conditions. The analysis reveals that the safety factor distribution in both scenarios follows a log-normal distribution pattern.

The Overall Slope Probabilistic Analysis

In the Overall Slope method used in Slide2, the search for a Global Minimum slip surface is repeated N times, with N representing the number of samples for the random variables. Each iteration involves loading a new set of random variable samples, allowing for a thorough exploration of potential failure surfaces while considering variability and uncertainty in the input parameters.

This method offers several advantages over the Global Minimum approach in probabilistic slope stability analysis. Notably, it does not assume that the Probability of Failure for the entire slope is the same as that of the Deterministic Global Minimum slip surface. Figures (16) and (17) present the results of the Overall Slope probabilistic analysis for unsaturated conditions, indicating that the probabilistic critical level has decreased compared to the deterministic scenario. This reduction suggests improved confidence and reliability in the slope's stability. By incorporating probabilistic analysis, the assessment accounts for uncertainties and variability, leading to a more robust evaluation of slope safety.

The Mean Safety Factor represents the average margin of safety in a system, calculated through probabilistic analysis, particularly in geotechnical engineering for assessing slope or retaining structure stability. It is derived from the average safety factor of multiple analyses that consider various potential failure surfaces or scenarios. This approach provides a comprehensive understanding of overall safety by accounting for variability and uncertainty in input parameters, offering a more realistic assessment of the system's stability compared to deterministic methods.

Sensitivity analysis

To investigate the effect of different parameters on the results of safety factors, sensitivity analysis based on the statistical distribution of parameters of dam materials is done in Table (3). Also, to investigate the effect of earthquakes on dam stability, the horizontal acceleration distribution function is considered as normal with an average of 0.15 and COV equal to 0.1. According to the results presented in Figure (18), there is a noticeable decline in the safety factor with horizontal acceleration changes, decreasing from 2 to 1.4. Moreover, the analysis of the dam's core materials illustrated in Figure (19) indicates that the unit weight of these materials significantly influences the downstream slope's safety factor, with values ranging between 1.66 and 1.7. In Figure (19), the impact of varying parameters of filter materials reveals that an increase in the friction angle leads to an increase in the safety factor, whereas an increase in unit weight results in a decrease in the slope safety factor. Similarly, the results for shell materials shown in Figure (19) indicate that the friction angle of the dam shell has the most substantial effect on the slope safety factor, with values oscillating between 1.15 and 2.5. Furthermore, a comprehensive examination of all material changes in the dam, as depicted in Figure (19), emphasizes that the friction angle of the shell material exerts the greatest influence on the dam's slope safety factor. This finding is attributable to the fact that the slope rupture arc predominantly passes through the shell material. Consequently, the critical role of shell parameters in slope stability analysis becomes apparent. To investigate this relationship more closely, Figure (20) present an analysis of the correlation between shell parameters and the slope safety factor. The results demonstrate a linear relationship between the friction angle of the shell material and the slope safety factor. In contrast, no significant correlation was found between the slope safety factor and the unit weight or unsaturated friction angle.

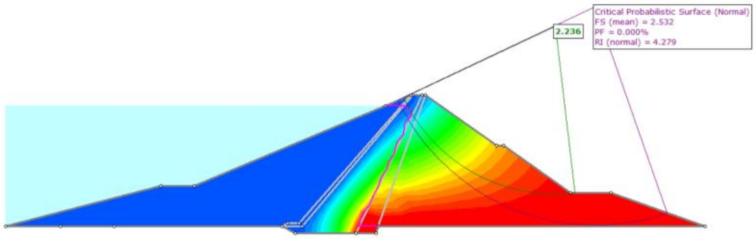


Fig. 16- The Overall Slope Probabilistic Analysis of Seydon Dam in steady state (unsaturated Soil)

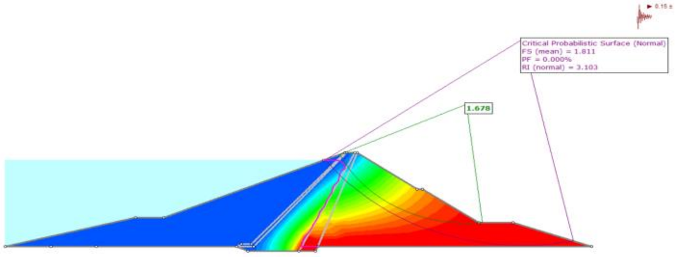


Fig. 17- The Overall Slope Probabilistic Analysis of Seydon Dam in steady state condition and quasi-static Mode (unsaturated Soil)

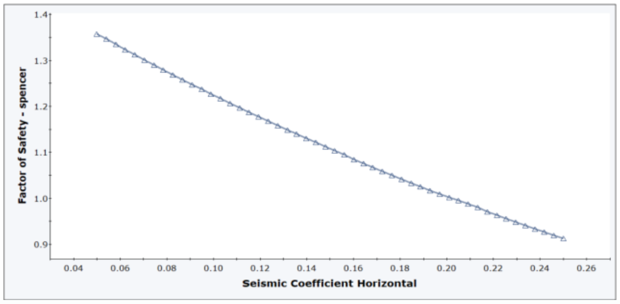


Fig. 18- Changes in safety factor with horizontal earthquake acceleration factor

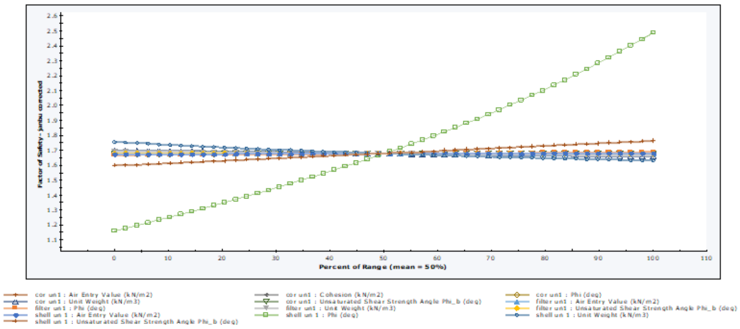
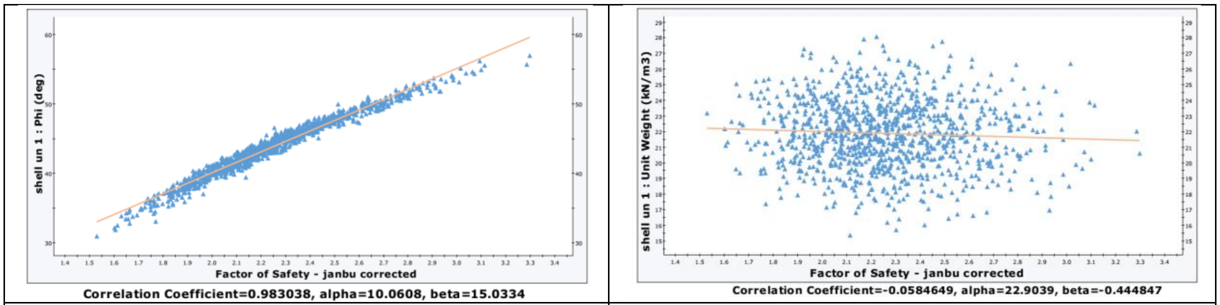


Fig. 19- Changes in safety factor with all dam materials variation



Correlation between factor of safety and friction angle of shell | Correlation between factor of safety and unit weight of shell

Fig. 20- Correlation between factor of safety and shell material

Spatial variation analysis

Most soil materials exhibit varying properties throughout the soil mass, a factor that traditional probabilistic slope stability analyses often overlook. Spatial variability analysis enables the simulation of fluctuations in soil properties, such as strength and unit weight, based on their location within the soil mass. When incorporating spatial variability, the statistical distribution of a material's properties and its correlation length parameters generate a random field of values for each sampling point. Consequently, each sample produces a spatial distribution of values (e.g., cohesion) within the material. Neglecting spatial variability in the analysis can lead to inaccurate and excessively conservative estimates of failure probabilities.

In soils, the correlation length in the X direction is typically much greater—often about 5 to 10 times—than that in the Y direction. This indicates that random fields exhibit lower spatial variability horizontally while showing greater spatial variability vertically. In this research, the correlation length is assumed to be equal to 5 in the Y direction and 25in the X direction. The results of this detailed analysis, which considers spatial variation, are illustrated in Figures (21) to (24). The findings show a decrease in the safety factor alongside an increase in the reliability index for slope stability when spatial variation is taken into account. A summary of the results from the spatial variation analysis compared to prior analyses is provided in Table (6).

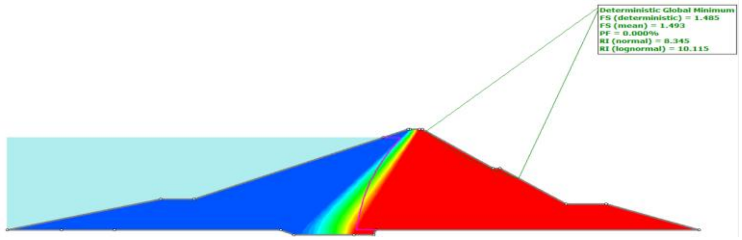


Fig. 21- Spatial variation analysis of Seydon Dam in steady state condition (saturated Soil)

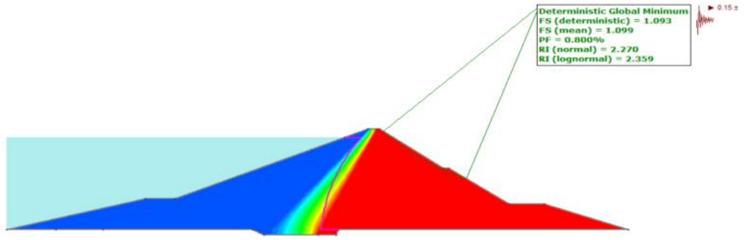


Fig. 22- Spatial variation analysis of Seydon Dam in steady state condition and quasi-static Mode (saturated Soil)

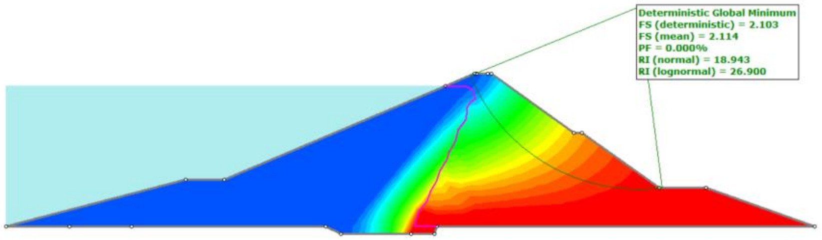


Fig. 23- Spatial variation analysis of Seydon Dam in steady state condition (unsaturated Soil)

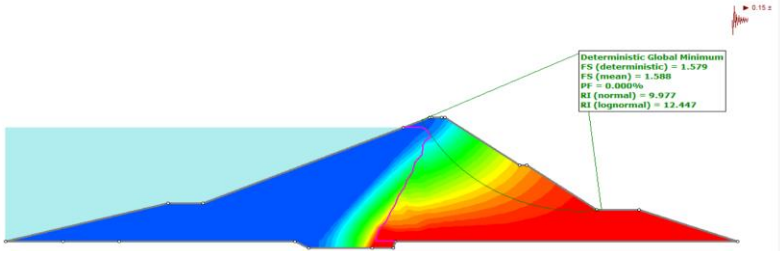


Fig. 24- Spatial variation analysis of Seydon Dam in steady state condition and quasi-static Mode (unsaturated Soil)

Table 6-The result of various slope analyses

Type of Analysis	Probability slope analysis				Spatial variation analysis			
condition	Unsat* (static)	Unsat (quasi-static)	Sat** (static)	Sat (quasi-static)	Unsat (static)	Unsat (quasi-static)	Sat (static)	Sat (quasi-static)
Safety factor	2.236	1.67	1.51	1.11	2.1	1.57	1.49	1.09
Reliability Index	4.42	3.19	2.24	0.72	18.9	9.9	8.34	2.27

*: unsaturated model **: saturated model

Conclusion

1. Unsaturated-Saturated Soil Modeling: Incorporating this modeling improves seepage analysis accuracy in dams. A case study on Seydon Dam showed a 65% reduction in discharge flow when considering unsaturated conditions, highlighting the need for specific soil property assessments and suction tests.

2. Impact of Matric Suction: Matric suction enhances soil stabilization and shear strength. The Seydon Dam study showed a 52% increase in the safety factor for the downstream slope's stability when modeling soil as unsaturated, and a 57% increase under quasi-static conditions with earthquake influence.

3. Reliability Index: A Reliability Index of 3 or higher indicates stable slopes with low failure probability. The unsaturated state analysis yielded a higher index, emphasizing improved stability over saturated conditions.
4. Sensitivity Analysis: The earth dam shell parameters, particularly the friction angle of the shell material, significantly influenced slope stability. A linear relationship was noted between the friction angle and safety factor, while no correlation was found with unit weight or unsaturated friction angle.
5. Spatial Variation Analysis: Considering spatial variations in soil parameters reduced the safety factor for the downstream slope compared to standard assessments, underscoring the importance of incorporating spatial variability for accurate safety evaluations.

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