SUSTAINABLE SOLUTIONS TO ALLEVIATE WATER SEEPAGE FOR ENHANCING SLOPE STABILITY

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ABSTRACT

Seepage, the movement of water through soil or rock, is a crucial factor affecting slope stability, particularly in riverine regions like Bangladesh. The construction of structures near river embankments and the growing population make understanding and addressing slope stability a pressing concern. When water infiltrates a slope, it raises pore water pressure, weakening the soil's shear strength and making the slope more susceptible to failure and landslides. Slope characteristics, soil properties, and groundwater conditions all impact the extent of seepage's influence on slope stability. Certain soil compositions, like those with clay minerals, can lead to the formation of quick clay, which can swiftly turn from solid to liquid when exposed to water, posing a danger to slope stability. To mitigate the detrimental effects of seepage, engineers employ various measures such as drainage systems, retaining walls, and slope reinforcement techniques. In this study, the primary objective was to understand how seepage affects the stability of an embankment slope. We used GeoStudio to create a simulated model of an embankment slope, utilizing 2-D Finite Element Modeling to resolve seepage and stability issues for earth dams. The phreatic seepage surface, the distribution of pore water pressure, and the fluctuation in the earth dams' overall hydraulic head were all examined throughout the examination. The model aimed to predict the potential consequences of seepage and develop solutions to enhance slope stability, which are toe drain, rock toe, and horizontal filter, using safety criteria set by the United States Army Corps of Engineers (USACE) and the British Dam Society (BDS) as benchmarks. The findings we administered in terms of the Factor of Safety (FOS) as 2.614, 2.847, and 2.917 in the solutions which are considerably higher than that of the existing dam. The insights derived from this study are crucial for engineering practices, especially in regions where managing slope stability in challenging geological and environmental conditions is essential for the safety and sustainability of infrastructure.

Keywords: *Seepage, Slope, Dam, FEM, FOS*

1. INTRODUCTION

For centuries, earthen dams have been employed as one of the oldest and most dependable means of water retention, flood management, and hydroelectric power generation. Their fundamental construction concept revolves around confining water within an embankment designed to withstand the relentless forces of water pressure. The mid-20th century saw the bulk of large dams worldwide constructed, and in modern times, two primary categories of dams have emerged: embankment dams and concrete dams. Among embankment dams, there are two primary classes: earth-fill dams and rock-fill dams, which together constitute approximately 85% of all dams across the globe. Selecting the most suitable type of earth dam depends on several factors, encompassing topography, foundation conditions, environmental considerations, construction resources, and socio-economic assessments. Earthen dams, constructed from diverse materials like soil, rock, and other natural elements, are susceptible to water seepage effects. Water seepage materializes due to variations in water pressure on either side of the embankment, leading to the movement and erosion of soil particles, thereby jeopardizing the dam's stability. Consequently, the influence of water seepage on an earthen dam's slope stability is a pivotal concern necessitating meticulous examination and the implementation of countermeasures to guarantee the dam's safety. Engineers and researchers have dedicated themselves to investigating earthen dam behavior under varying conditions and formulating strategies to mitigate associated risks. A good dam should be constructed from materials that are readily accessible in the area, show stability under a range of operating and load situations, effectively manage seepage, and have the right outlet structures to avoid overtopping. (Chadwick et al., 2004). The purpose of this study is to evaluate criteria for determining the stability of reservoir earth dams by considering both seepage and slope stability. The research aims to achieve a lower phreatic line to control seepage, as well as, enhance the slope stability by increasing the factor of safety.

The potential collapse of dams can stem from various factors, including structural instability, hydraulic conditions, seepage within the dam structure, and abrupt water level reductions. It's crucial to calculate the factor of safety for the dam slope stability across diverse operational scenarios to ensure the overall safety of the dam. It's critical to follow established safety guidelines while designing and evaluating embankment dams, as advised by knowledgeable organizations such as the U.S. Army Corps of Engineers (Headquarters U.S. Army Corps of Engineers, n.d.) and the British Dam Society (The British Dam Society (BDS), n.d.). These agencies provide criteria and guidelines that must be met to ascertain the soundness and safety of embankment dam designs. Adhering to these standards is fundamental in mitigating risks associated with potential dam failures, enhancing public safety, and ensuring the reliability and stability of dam structures. Furthermore, these guidelines provide a framework for the proper evaluation and design of embankment dams, promoting best practices and expertise in the field of dam engineering.

This work simulates the combined investigation of seepage and earth dam stability using two-dimensional finite element modeling. GeoStudio is the program used for the simulation. The study's main objectives are to examine the distribution of pore water pressure, the phreatic seepage surface, and the overall fluctuation in the total hydraulic head inside the earth dams. In addition, the slope stability of the dams is verified using four analytical techniques. Acceptable requirements are met by the produced model's validated correctness and dependability.

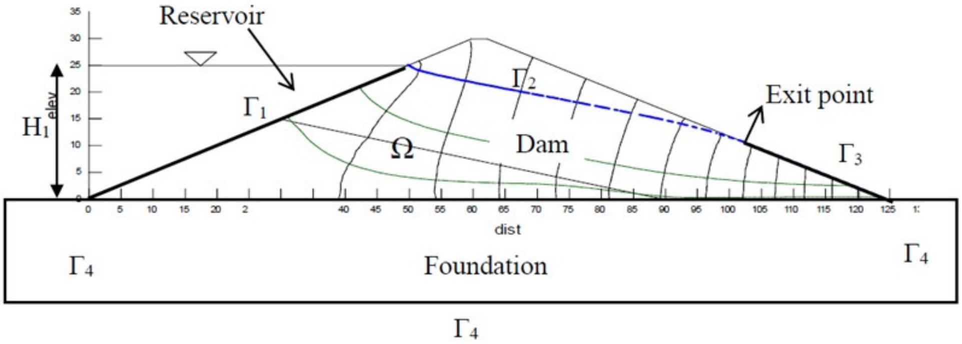


Figure 1.1: Problem statement and boundary conditions

Here the boundary conditions have been set as follows and also illustrated in Figure 1.1;

1. (Γ1) Entrance Surface,
2. (Γ2) Phreatic Surface,
3. (Γ3) Exit Surface (Seepage surface), and
4. (Γ4) Dam Foundation Boundary

In essence, this study focuses on the evaluation of criteria that bolster the stability of dams against combined failures stemming from seepage and slope instability, all with the overarching goal of fortifying dam safety. Earthen dams, deeply entrenched in history, have evolved to address contemporary engineering challenges, underscoring the perpetual quest to enhance their resilience and safeguarding their critical roles in water management and power generation.

The researchers have emphasized the importance of ensuring the safety and functionality of earth dams, particularly those used for reservoirs. They stress the need for a rigorous evaluation of dam design to meet essential criteria, including spillway and outlet capacities, freeboard, and prevention of floodwater overflow. Seepage analysis, in the context of earth dams, serves various purposes, such as predicting the phreatic surface within the embankment, estimating pore water pressures in the embankment or its foundation, and determining exit gradients and uplift pressures at the embankment's toe. It also helps in assessing the volume of seepage flow that might pass through the embankment or its foundation and gauging seepage flows intercepted by drainage features like toe drains or relief wells (Great Britain. Environment Agency., 2011); (Irrigation_and_Water_Power_Engineering (Punmia), n.d.); (Irrigation_and_Water_Resources_Engineering (Asawa), n.d.); (Geotechnical Engineering Principles and Practices by Donald P.Coduto (z-Lib.Org), n.d.); (A Noori Khaleel S Ismaeel Assistant Lecturer, n.d.).

In "Groundwater and Seepage," M.E. Harr explores the idea of utilizing transformations and mapping techniques to relocate the geometric representation of seepage problems from one complex plane to another. This approach enables the migration of the problem's geometry from an unfamiliar plane with elusive solutions to a plane where solutions are readily accessible. It's important to emphasize that this method is exclusively applicable to two-dimensional groundwater issues. While it has been used in the past for general problem-solving, it's not commonly employed for addressing site-specific seepage problems. The main reason for its limited application in such scenarios is the requirement for a deep understanding of complex variable theory and precise selection of transformation functions. Therefore, this method is typically reserved for cases where the mathematical foundations and prerequisites align with the specific nature of the 2-D groundwater concern at hand (Harr, 1991). Shehata proposed a comprehensive solution to address seepage concerns in the context of an overflow spillway located on complex geological formations. Their approach involved the development of an analytical solution to effectively tackle the seepage issue. To enhance the spillway's integrity and mitigate challenges related to uplift and piping effects, they implemented protective measures such as a downstream blanket and strategically positioned end sheet piles. This study underscores the significance of engineering interventions when dealing with complex geological conditions to optimize the performance and stability of overflow spillways. The proposed solution integrates analytical insights and practical structural reinforcements, ensuring a resilient and reliable spillway system that meets safety and efficiency standards. In summary, Shehata's approach offers a holistic solution that combines analytical expertise and structural enhancements to address seepage issues in overflow spillways, particularly in intricate geological settings (Shehata, 2006). Zeidan developed a finite element program to model anisotropy in phreatic seepage problems. Griffiths and Fenton also introduced methods to simulate consistent seepage through three-dimensional soil with varying permeability. They used random field generation and finite element techniques to represent the complex hydraulic process within the soil domain. Permeability, a key factor in seepage, was considered to have a spatial distribution that varies randomly in three-dimensional space. By combining these methods, the researchers aimed to better understand seepage behavior in various geological settings, considering the inherent randomness and variability in permeability. This work aimed to provide a more realistic representation of seepage patterns, offering improved predictions and insights for engineering and environmental applications related to fluid movement in soil structures. In summary, the research focused on accurately modeling seepage with varying permeability, enhancing our understanding of seepage in real-world soil environments (Zeidan et al., 2015), (V Griffiths & Fenton, n.d.).

2. METHODOLOGY

The initial step in constructing a mathematical representation for any system involves defining fundamental governing equations, commonly referred to as general governing equations, which are differential, and stem from the fundamental physical principles that regulate the targeted process for modeling. The study employs diverse methods of analysis to address seepage and slope stability theories across varying operational scenarios. Specifically, three operational cases are examined: the end of construction, a steady state condition, and rapid drawdown aligning with the guidelines set by the US Army Corps of Engineers (USACE) in 2003 (Headquarters U.S. Army Corps of Engineers, n.d.). To simulate seepage within the dam body and its foundation, this study utilizes GeoStudio software. The primary findings encompass the determination of critical aspects like the location of the phreatic surface, seepage velocity, fluctuations in total head, pore water pressure, and factors of safety both upstream and downstream (Slope Stability ENGINEER MANUAL, 2003).

2.1 Theoretical Approach: Darcy’s Law

In 1856, Darcy initiated the study of water flow in uniform sand filters, particularly in Dijon, France. His groundbreaking research established the relationship between flow rate (Q), cross-sectional area (A), and water level disparities. Flow rate increased with larger A and decreased with longer filter length (L). Darcy's findings revolutionized the understanding of water flow in porous media, impacting hydrogeology and fluid dynamics. His work became a cornerstone in filtration systems and fluid transport through permeable materials, influencing subsequent research and engineering applications. Darcy’s formula was presented as:

$$Q = KA\frac{h_1 - h_2}{L} \tag{2.1}$$

Where:
Q is the rate of flow (volume of water per unit time),
K is the coefficient of permeability,
A is the cross-sectional area,
h_1 is the water level in the inflow of the filter,
h_2 is the water level in the outflow of the filter and
L is the filter length.

Table 2.1: Typical Values of the Coefficient of Permeability (Harr, 1991)

Soil type	**Coefficient of permeability K ($\frac{cm}{sec}$)**
Clean gravel	1.0 and grater
Clean sand (coarse)	1.0 – 0.01
Sand (mixture)	0.01 – 0.005
Fine sand	0.005 – 0.001
Silty sand	0.002 – 0.0001
Silt	0.005 – 0.00001
Clay	0.000001 and smaller

2.1.1 Critical Cases for Analysis

Case (1): End of Construction

The main concern with plastic-based embankments is ensuring post-construction stability. After construction, there is an immediate increase in pore pressure due to the consolidation of the fill material beneath the embankment, with water not playing a role. To assess stability, it's crucial to consider the undrained shear strength of the cohesive material within the dam. This involves using the relevant shear strength properties of the cohesive material in the embankment to ensure its long-term stability and structural integrity. Maintaining stability is essential for the safe and successful use of embankments constructed with plastic materials (Headquarters U.S. Army Corps of Engineers, n.d.).

Case (2): Steady State Seepage

Seepage through an embankment adversely impacts its stability by increasing actuating forces and reducing resisting forces. This analysis assumes the reservoir is at its standard level, resulting in a full phreatic line. The upstream slope experiences pressure from the reservoir, while the rest of the dam faces pore pressure from the flow net. The downstream slope is especially vulnerable. Both short-term (undrained) and long-term (drained) perspectives are considered. Short-term analysis employs cohesive material's undrained shear strength parameters, while long-term assessment uses drained shear strength parameters. This assessment is crucial for assessing the embankment's stability under various conditions (Headquarters U.S. Army Corps of Engineers, n.d.).

Case (3): Rapid drawdown condition

During a sudden dam drawdown, the upstream slope undergoes significant stress as water rapidly recedes. Pressure on the slope drops below the drawdown level, while the saturation line remains higher. Resisting forces diminish more slowly than actuating forces due to slower drainage. To ensure stability, calculations consider this difference. Resisting forces are based on the submerged weight of materials below the water surface, using undrained shear strength for cohesive dam materials. Actuating forces use the saturated weight of submerged materials below the water surface. All materials below the drawdown level are submerged, guiding the calculation of resisting and actuating forces. This analysis is crucial for dam stability assessment (Headquarters U.S. Army Corps of Engineers, n.d.).

2.2 GeoStudio Software

GeoStudio software is employed for conducting finite element assessments on dams, primarily utilized across diverse civil engineering applications to analyze problems while considering various factors. Presently, it has extensive use, particularly in finite element analysis, slope stability assessment, seepage analysis, and various other applications within this domain. The steps for utilizing GeoStudio 2004 software are as follows: The model's results encompass identifying the position of the phreatic surface, ascertaining seepage velocity, quantifying seepage volume, assessing total head fluctuations, evaluating pore water pressure, and determining factors of safety both upstream and downstream.

2.3 Slope Stability Inspection

The design and safety of embankment dams are essential and should follow guidelines from respected organizations such as the U.S. Army Corps of Engineers, British Dam Society, U.S. Bureau of Reclamation, Federal Energy Regulatory Commission, U.S. Department of Agriculture, National Resources Conservation Service, and Urban Levee Design Criteria. Complying with their standards is crucial for ensuring the reliability and security of embankment dams. This is vital for managing water resources and reducing risks associated with dam structures, emphasizing the importance of adhering to these authoritative entities' criteria in their design and construction. Table (2.2) presents the minimum required factor of safety values for slope stability of earth dam (F.O.S) based on the recommendations of the previously experienced agencies:

Table 2.2: Safety Criteria (The British Dam Society (BDS), n.d.)

Loading condition	**Stress parameter**	**(F.O.S)**
End of Construction	Total stress (Undrained)	1.3 to 1.5
Steady seepage condition	Effective stress (Drained)	1.3 to 1.5
Rapid drawdown	Total stress (Undrained)	1.2 to 1.3

3. MODEL FORMULATION

3.1 Earthen Dam Model

A viable dam should be constructed from materials that are readily available in the area, stable under all operating and loading situations, waterproof enough to manage seepage, and equipped with the necessary outlet works to prevent crest dam overtopping(Chadwick et al., 2004). In this study, an existing earth dam in Paba Upazila in the Rajshahi district of Bangladesh has been considered. The dam's properties are given below:

Table 2.3: Parameters of the existing dam considered for the case study

Parameters	**Values**
Materials used	Silty Sand
Length	52 meters
Height	12 meters
Water level height	11 meters
Unit weight of reservoir water	10 kN/m^3
Saturated water content	0.5
Saturated hydraulic conductivity	1e-6 m/sec

Figure 3.1: Cross section of Earthen Dam

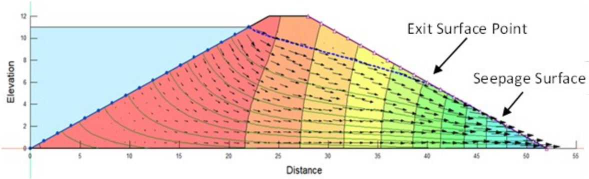
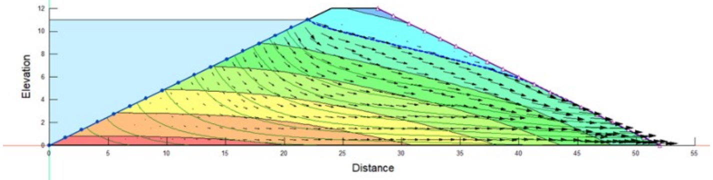


Figure 3.2: Phreatic surface with flow lines



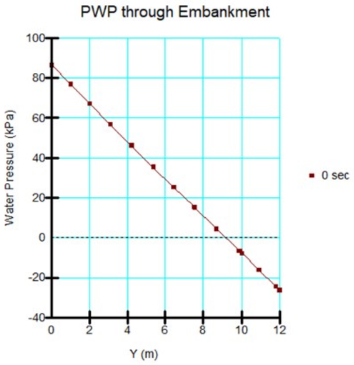


Figure 3.3: Pore water pressure

Figure 3.4: The PWP Vs distance (Y)

Figure 3.1 illustrates a cross-sectional view of the examined dam. For this model, pore fluid boundary conditions were utilized, encompassing water head specifications over both the upstream and downstream faces, specifically tailored for steady-state analysis (Broaddus, 2015).

Figure 3.2, presents the phreatic surface, showcasing flow lines culminating in exit points and the seepage surface. The phreatic surface denotes the upper boundary of water percolating through this stream. Flow lines, illustrating potential pathways for water. Because there is no drainage infrastructure at the junction of the phreatic surface and the downstream face of the dam, flow lines might reach it and perhaps jeopardize the stability of the downstream slope, which is extremely dangerous.

The pore water pressure, or the pressure that water exerts within the pores or interstitial spaces of soil or rock formations, is seen in Figure 3.3. The existence of groundwater or other fluids within the geological material is the cause of this pressure. The distribution of pore water pressure throughout the dam body is shown graphically in Figure 4.6, providing important information about this important component influencing the structural integrity of the dam.

In Figure 3.4, the relationship between PWP within the embankment and the distance (Y) from the dam base is depicted. This graph provides valuable insights into how PWP changes as one moves away from the base of the dam. Understanding this relationship is essential for comprehensive analysis and design in the realm of dam engineering and seepage control.

3.2 Solutions for Seepage Control

There are many solutions, among them, we proposed and analyzed three solutions. They are: i) Toe Drain, ii) Rock Toe, and iii) Horizontal Filter.

i) Toe Drain: In this particular situation, a drainage system is implemented beneath the base of the embankment, known as a toe drain. Its primary purpose is to manage and regulate the seepage and potential piping of water within the dam structure.

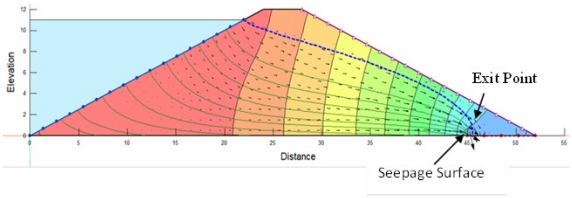
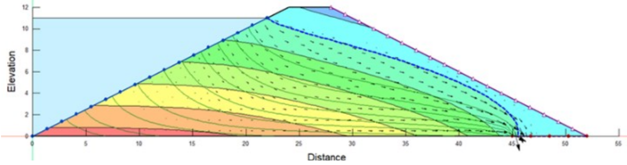


Figure 3.5: Cross section for Toe Drain
Figure 3.6: Phreatic surface with flow lines



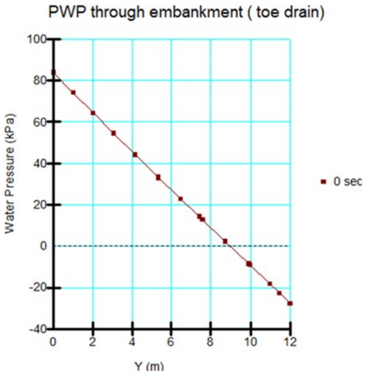
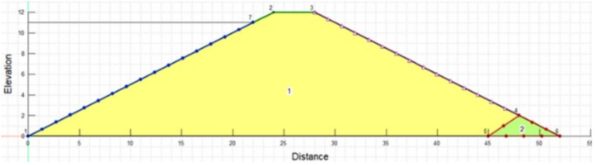


Figure 3.7: Pore water pressure
Figure 3.8: The PWP Vs the distance (Y)

In Figure 3.5, a cross-sectional view of the Toe Drain is presented. Figures 3.6, 3.7, and 3.8 depict key aspects, such as the phreatic surface, pore water pressure distribution, and correlation between pore water pressure and distance from the dam's base. Figure 3.6 highlights the effective reduction of the phreatic line by the toe drain, preventing extension to the downstream face and altering flow patterns. This mitigates excessive pore water pressure generation from the dam's downstream toe.

ii) Rock Toe: In this case, a rock toe is provided beneath the embankment's toe. This is done to manage water seepage or piping inside the dam. Rock toe is made of graded coarse material.



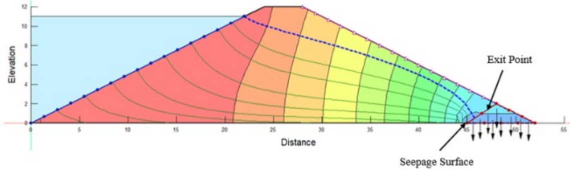
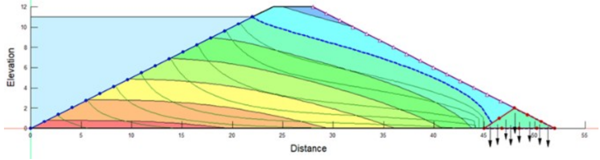


Figure 3.9: Cross section for Rock Toe
Figure 3.10: Phreatic surface with flow lines



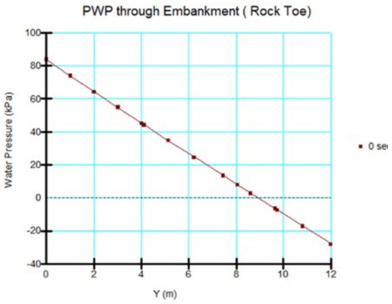
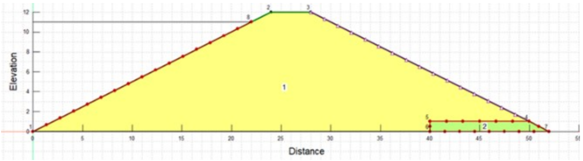


Figure 3.11: Pore water pressure Figure
3.12: The PWP Vs the distance (Y)

Figure 3.9 shows a cross-section consisting of a Rock Toe. Figures 3.10, 3.11, and 3.12 show the relationship between pore water pressure and distance from the dam base, the phreatic surface with flow lines, and the pore water pressure through the dam body, respectively. Figure 3.10 indicates an effective lowering of the phreatic line by the rock toe, preventing extension to the downstream face. The rock toe also reduces excessive pore water pressure, separating flow lines from the downstream toe of the dam.

iii) Horizontal Filter: Here, the base of the embankment is furnished with a horizontal filter to manage potential internal water movement or seepage effectively. The horizontal filter is constructed using coarse-grained materials to optimize its function.



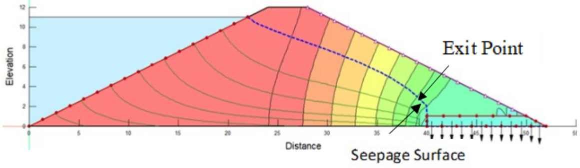
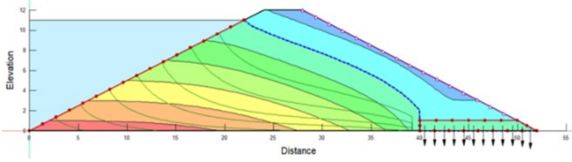


Figure 3.13: Cross section for Horizontal Filter Figure 3.14: Phreatic surface with
flow lines



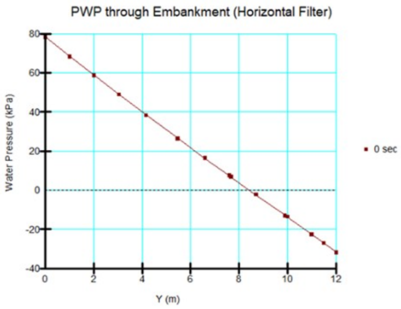


Figure 3.15: Pore water pressure　　　　Figure 3.16: The PWP Vs the distance (Y)

The third solution, the horizontal filter, is illustrated in Figure 3.13, depicting the cross-section. Figures 3.14, 3.15, and 3.16 provide visual representations of the phreatic surface with flow lines, the pore water pressure within the dam body, and the correlation between pore water pressure within the embankment and the distance (Y) from the dam's base.

For the presence of a horizontal filter, the phreatic line has been notably lowered, ensuring it doesn't extend to the downstream face of the embankment, as indicated in Figure 3.13. Moreover, the drain installed helps mitigate the distinct flow lines originating from the dam's downstream toe, thereby reducing excessive pore water pressure. The graph illustrates a decline in pore water pressure due to the efficiency of the horizontal filter.

3.3 Slope Stability Analysis of the Dam

For this study, the authors utilized GeoStudio software to assess slope stability in various extreme operational scenarios over a dam's lifespan. The analysis incorporated the finite element method (FEM) and the Mohr-Coulomb model to characterize soil behavior. Initial inputs were derived from a steady-state seepage study conducted with SEEP/W. The comprehensive evaluation aimed to ensure the safety and reliability of the dam structure, focusing on critical operational conditions. The study's approach, combining FEM and the Mohr-Coulomb model, contributes valuable information for decision-making and design considerations, enhancing understanding of the dam's stability throughout its operational life (GeoStudio, n.d.).

3.3.1 Mohr-Coulomb Model

FEM analysis requires knowledge of the Mohr-Coulomb material model's properties, such as the elastic modulus, poison ratio, and angles of internal friction and cohesion. The first two parameters are used to specify the yield condition. It is required to provide the angle of dilation. The Mohr-Coulomb model's failure surface may be stated as follows:

$$\pi = \sigma \tan \phi + c \tag{3.1}$$

where ϕ is the angle of internal friction (slope of the failure envelope), σ is the normal stress, π is the shear stress, and c is the cohesion (intersection of the failure envelope with the π axis). The Mohr-Coulomb yield surface is shown as a non-uniform hexagonal cone in the primary stress space (Kashef, 1986).

3.3.2 Stability of the Existing Dam and Proposed Solution

Material properties for the Mohr-Coulomb model of the dam are i) Cohesion 12 Kpa, ii) Angle of internal friction 45°, iii) unit weight of soil 18 KN/m^3. Figure 3.17 represents the factor of safety using the steady-state method. In this scenario, a toe drain is provided beneath the embankment's toe. Figure 3.18 represents the factor of safety for the toe drain solution.

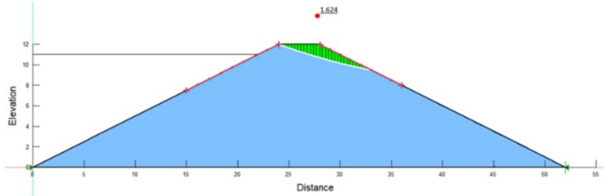


Figure 3.17: FOS of slope for the existing dam

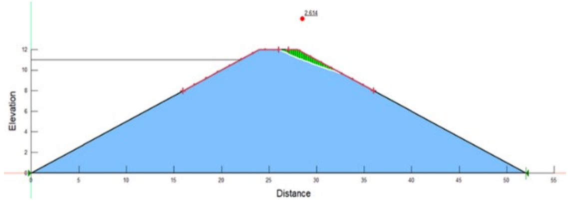


Figure 3.18: FOS of slope for Toe Drain

In the second solution, the embankment's toe is equipped with a rock toe. Geotechnical parameters of rock toe are – Cohesion 0 Kpa, Angle of internal friction 32°, Elastic modulus 30000 Kpa. Figure 3.19 represents the factor of safety for the rock toe structure. Finally, for the third solution, the toe of the embankment is provided with a horizontal filter. Geotechnical parameters of rock toe are – Cohesion 0 Kpa, Angle of internal friction 32°, Elastic modulus 30000 Kpa. Figure 3.20 represents the factor of safety for horizontal filters (Konow T & Mathias S, n.d.).

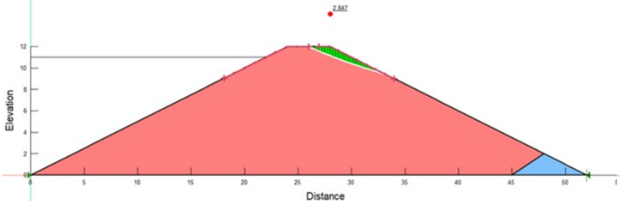


Figure 3.19: FOS of slope for Rock Toe

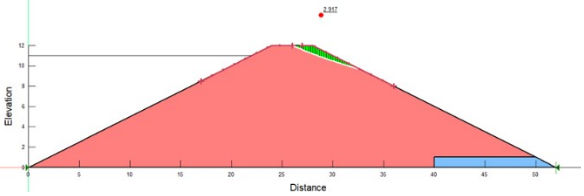


Figure 3.20: FOS of slope for Horizontal Filter

4. RESULTS AND DISCUSSION

Seepage within the dam structure is heavily influenced by the pressure exerted by water within the pores, known as pore water pressure. Elevated seepage rates resulting from heightened pore water pressure pose a significant risk, potentially leading to erosion or destabilization of the dam's embankment and foundation. To effectively manage and mitigate seepage-related issues, various measures such as filters and drainage systems are employed as seepage control techniques. These mechanisms are designed to regulate and reduce pore water pressure, consequently averting potential problems tied to seepage. Depending on the specific circumstances and reasons behind the pressure reduction, alterations in pore water pressure within a dam can yield both advantageous and adverse effects.

Pore water pressure is essentially the pressure exerted by water contained within the pores of rocks or soil, affecting the ground beneath and surrounding a dam. Figure 4.1 illustrates the variations in pore water pressure across the dam at different distances. The blue line represents the existing dam's pore water pressure, while the other three lines depict pore water pressure in different scenarios. Notably, the pore water pressure diminishes in each scenario compared to that of the existing dam. Lower pore water pressure plays an important role in minimizing water seepage through the dam, consequently enhancing its overall stability. By effectively managing and reducing pore water pressure, seepage-related risks can be mitigated, safeguarding the structural integrity of the dam.

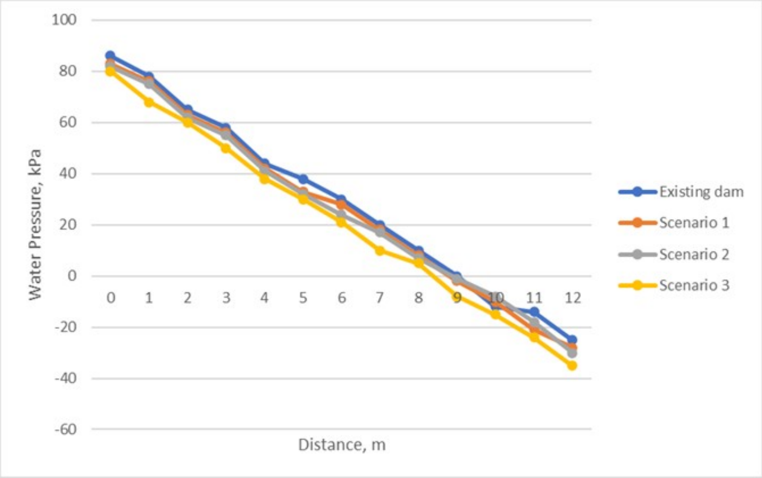


Figure 4.1: Pore Water Pressure through the Dam with Different Scenarios

On the other hand, the phreatic line, often referred to as the water table, groundwater level, or phreatic surface, is crucial in controlling seepage. To avoid excessive seepage and probable dam failure, it is important to make sure the phreatic line is maintained at a safe level. The study discusses the importance of managing the phreatic line within a dam to prevent potential risks and ensure long-term stability. The existing dam's red phreatic line, extending to the downstream face, poses a risk of soil erosion and the formation of conduits, jeopardizing structural integrity.

In Figure 4.2, three scenarios (green, orange, and blue lines) have been proposed for lowering the phreatic line through various measures, such as toe drains, rock toes, and horizontal filters. Lowering the phreatic line reduces seepage and evenly distributes water load, mitigating risks of instability, collapse, and erosion. This is crucial during heavy rain, preventing overtopping and potential dam failure. Implementing these scenarios enhances overall dam safety, prolongs its lifespan, and reduces the need for costly maintenance and repairs.

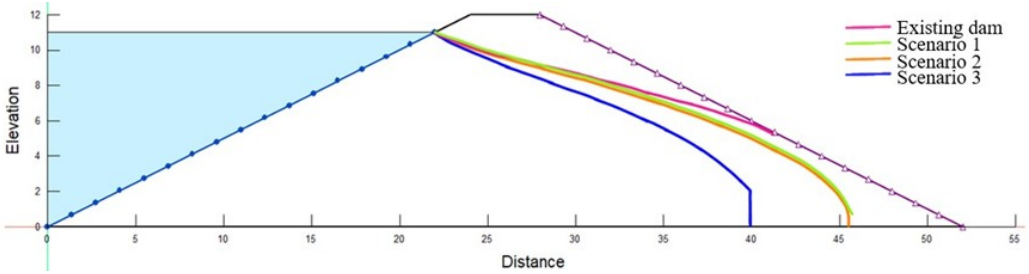


Figure 4.2: The change in phreatic line with different scenarios within the dam

The U.S. Army Corps of Engineers and other engineering authorities evaluate a dam's safety by considering factors such as design, materials used, location, and potential consequences of failure. The dam's factor of safety, a ratio of its maximum load capacity to actual loads experienced, determines the level of conservatism in its design. Higher safety factors, typically ranging between 1.5 and 2.0 or more in the United States, signify a safer design. The existing dam has a factor of safety of 1.624, while three hypothetical scenarios have factors of safety of 2.614, 2.847, and 2.917. A higher factor of safety in these scenarios indicates a design capable of withstanding loads 2.614 to 2.917 times higher than anticipated, emphasizing the safety and resilience of the dam's construction. Figure 4.3 depicts this comparison graphically.

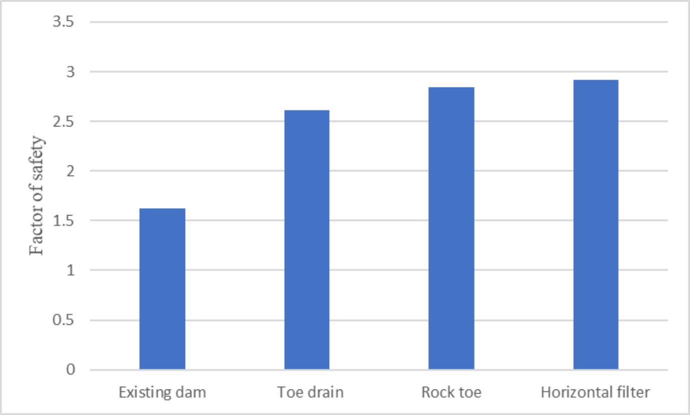


Figure 4.3: Evaluation of Factor of Safety

5. CONCLUSIONS

Embankment dams in geotechnical engineering are often at high risk of instability and catastrophic failure due to seepage, a common issue. Effective management involves lowering the phreatic surface to control pore water pressure through filters and drainage systems and implementing preventive measures to ensure dam integrity and avert disasters related to seepage-induced instability. In Figure 4.1, pore water pressure variations across the dam are illustrated, showing the current dam's pressure in blue and three other scenarios with reduced pressure. Lower pore water pressure is crucial in reducing water seepage through the dam, thus enhancing its stability. Effective management and reduction of pore water pressure are essential for mitigating seepage-related risks and ensuring the dam's structural integrity.

The study focuses on the critical role of the phreatic line, also known as the water table, in managing seepage and preventing dam failure. Maintaining a safe phreatic line level is vital to avoid excessive seepage. Figure 4.2 illustrates the phreatic line changes in various dam scenarios. The existing dam's phreatic line reaching the downstream face can create conduits, allowing swift water passage, and compromising slope stability. Effective drainage and filtration mechanisms at the dam base are necessary to mitigate this risk and ensure structural integrity. Three scenarios illustrate lowering the phreatic line, reducing seepage, and enhancing stability. Keeping the phreatic line within the dam body is crucial to distributing water load uniformly, reducing erosion on the downstream face, and diminishing the risk of overtopping. Implementing these measures enhances safety, prolongs dam lifespan, and reduces maintenance costs. Overall, maintaining a controlled phreatic line is vital for dam safety and long-term effectiveness.

On the other hand, the U.S. Army Corps of Engineers (USACE) and similar engineering bodies evaluate a dam's safety by considering various factors like design, materials used, location, and potential consequences of failure. The factor of safety in dam engineering signifies the ratio between a dam's maximum load-bearing capacity and the actual loads it encounters during its lifespan. A higher factor of safety indicates a more cautious and secure design. In the United States, dam safety factors usually range between 1.5 and 2.0 or even higher, illustrating that dams are constructed to endure stresses 1.5 to 2 times greater than what they are expected to face over their lifetime. A higher factor of safety in these scenarios signifies a safer and more robust design, providing a greater margin of protection against potential stress and load challenges.

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