Eurasian J. Sci. Eng., 2024, 10(1), 1-11
https://doi.org/10.23918/eajse.v10i1p1

Published by Tishk International University
Available at: https://eajse.tiu.edu.iq/submit/

RESEARCH ARTICLE Open Access

Exploring Geometrical and Hydraulic Influences on Frictional and Shear Strength in Earth Dams through Parametric Analysis with Geostudio Software

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Article History
Received: 29.11.2022
Revised: 02.01.2023
Accepted: 18.02.2024
Published: 27.03.2024
Communicated by: Asst. Prof. Dr. Abubakar M. Ashir
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Abstract:
Earth dams, essential hydraulic structures that form the link between water management and power generation, require careful examination of their structural and functional integrity. The essence of its stability lies in the dynamic response of soil structures used in construction to diverse operational stresses. To address this problem, it is necessary to conduct a comprehensive analysis of various geometric and hydraulic factors. This study focuses on unraveling the complex dynamics governing the slope stability (D/S) of the proposed earth dam section. Pivotal indicators for this evaluation are the frictional and shear strength of the soil, which responds to the countless stresses encountered during the operation phases. Taking advantage of advanced Geostudio software, we examined the effect of different filter lengths, permeability coefficients, and operating heads on shear strength and friction. The findings highlight a consistent pattern in the behavior of both frictional and shear forces with respect to distance from the base of the dam. These strengths rise to peak values at a specific distance (65 m), after which a downward trend is observed towards the toe of the dam. Notably, the study emphasizes the critical role of the 30 m filter length, the permeability coefficient K3, and to some extent, K2, in amplifying the friction force values at storage levels ranging from 15 to 40. moreover, the peak friction force at 138.2 kPa and the maximum shear strength value at 158.2 kPa appear at an operating head (H) of 40 m. This optimal performance is intricately linked to the strategic use of a 30 m filter length and a permeability coefficient of $\mathbf{1 \times 10^{-11}}$ m/s. However, this research not only highlights the delicate interplay between hydraulic and geometric factors within the stability of earth dams but also underscores the critical importance of specific configurations in fortifying against potential failure. The insights gained from this study contribute significantly to considerations related to the design, construction, and operation of earth dams, ensuring robust performance in the face of diverse challenges.

Keywords: *Earth Dams Stability; Frictional Strength; Shear Strength; Filter length; Permeability coefficient.*

1. Introduction

Earth dams hold a pivotal and strategic role as hydraulic structures, directly influencing a nation's water and economic security. The importance of these structures comes from their vital role in the efficient water control and energy production. Accordingly, the design, construction and operational aspects of these dams have captured the attention of construction companies and researchers as well. Earthen dams are mostly subjected to various types of structural and hydraulic failure. The of continuous leakage within the dam body represents a major source of failure if its consequences remain unrestricted. In addressing this, the use of finite element analysis for 2D flow was employed to evaluate permeability across the saturated and unsaturated regions of the Fukada Earth Dam. Through a series of iterative computations employing multiple coefficients, an assessment of the issue was conducted, resulting in a minimal disparity between calculated and measured seepage lines. This successful alignment underscores the validation of the adopted mathematical model [4].Abbas [1] utilized SEEP/W software to quantify flow through earth dams featuring an inclined toe filter. The study explored a spectrum of geometrical parameters, encompassing U/S and D/S slopes, top width, freeboard, diverse reservoir heads, and permeability coefficients, to analyze seepage flow quantities. Findings revealed that leakages diminish with steeper filter slopes, increased water heads, and wider dam tops. Conversely, flow augmented alongside heightened angles of upstream and downstream slopes. Statistical analysis via SPSS-19 yielded an empirical equation for estimating internal dam leakages with an inclined filter at the toe. Examining soil properties' impact on earth dam stability, encompassing permeability coefficients, friction angles, and cohesion forces, was carried out through the GeoStudio program [8]. The Al-Adhim Dam served as a case study, culminating in the derivation of an empirical equation to predict safety factors based on the aforementioned parameters. The results verification showed strong agreement with the equation predictions. To demonstrate slope stability approach using finite element analysis, this study [5] presented different cases and compared solutions with alternative methods. The effect of the top flow surface on embankment slope stability is taken into account, with graphical output depicting deformations and failure mechanisms. The study emphasized the competence of the slope stability analysis by finite element method as an effective alternative to classical equilibrium methods and called for its extensive integration into geotechnical practice. In the context of the Iasi Dam in Romania, the operational evaluation included water flow behavior and stability monitoring [6]. Simulation of filtration behavior was carried out using specific software. This study highlighted the indispensable role of monitoring in assessing the structural integrity of dams and collecting data to enhance understanding of the behavior of these structures. The work of Al-Laban [2] investigated the effect of slope conditions on the stability of an earth dam, and attributed settling as a major factor causing infiltration forces to rise and leading to movement and erosion of soil particles. Finite element method is used efficiently to analyze the earth dams for many failur modes and condtions. The research considered core construction coupled with cutoffs to minimize seepage flow and noted the value of upstream filters in managing receding condition-related problems. Assessing the cutoff wall's influence on dam slope stability, a finite element numerical model integrating leakage and pressure distribution was established [7]. Normal storage conditions demonstrated a notable increase in the D/S slope safety factor with only a slight decrease for the U/S dam slope. Ahmed's study [9] researched the effect of horizontal filter length on percolation line behavior and earth dam stability, employing the Geo-Studio program. Variations in storage levels were tested, concluding that augmenting filter length from 15 to 25 meters yielded favorable safety factor results, particularly up to the 20-meter storage level.

2. Methodology

The current study aims to evaluate the stability of earthen dams by evaluating the frictional and shear strength using GeoStudio software, specifically the SEEP/W and SLOPE/W modules. The analysis focused on the D/S slope stability of a practical earthen dam designed with common dimensions relevant to realistic dam scenarios.

2.1 Seepage Analysis (SEEP/W):

The SEEP/W module in GeoStudio is used for steady-state seepage analysis, using Darcy's law to describe groundwater flow through porous media. Laplace's equation is two-dimensional in horizontal terms ($K_x \frac{\partial H}{\partial x}$ and vertical ($K_y \frac{\partial H}{\partial y}$) flow components. The governing equation, incorporating sources/sinks (Q) and a time-dependent term ($\frac{\partial \theta}{\partial t}$), is expressed as:

(1) $$\frac{\partial}{\partial x}\left(K_x \frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial H}{\partial y}\right) + Q = \frac{\partial \theta}{\partial t}$$

2.2 Slope Stability Analysis (SLOPE/W):

The SLOPE/W module based upon major physical properties of different earth dam materials and it is effective to evaluate slope stability. The resisting force is the most critical amount that impaxt the safety of dam due to D/S slope stability. The safety factor is calculated as a ratio of resistance forces summation resistance forces summation and it is generally represent by:

(2) $$FS = \frac{\sum Resisting\ force}{\sum Driving\ force}$$

2.3 Study Hypotheses and Criteria

1. The earth dam section is divided into an outer shell made of silt soil, a dam core with clay soil of three alternatives of permeability coefficients as listed below, and a foundation with specific soil characteristics that have a constant coefficient of permeability as indicated below.
2. All data are reasonably selected to be more compatible with most common earth sections in real sites. The values of top width (10 m), U/S slope (3:1), D/S slope (2:1), freeboard (3 m), and core inclination (8:1) are taken as constant. (Figure 1).
3. The main materials properties are listed in Table 1 shown below.
4. The selected earth dam sections are provided with different filter lengths ($F = 15\ m, F = 20\ m, F = 25\ m, and\ F = 30\ m$).
5. The values of reservoir maximum water levels are identifies as (H=15 m, H=20 m, H=25 m, H=30 m, H=35 m, and H= 40 m).

All the results that were obtained in this study are used to determine the values of friction and shear strength deduced for the critical slip.

Table 1: Materials Properties

Zone	Out shell	core	Foundation
$Permeability\ Coefficient\ m/sec$	$K_O = 1 \times 10^{-6}$	$K_1 = 1 \times 10^{-9}$ $K_2 = 1 \times 10^{-10}$ $K_3 = 1 \times 10^{-11}$	$K_F = 1 \times 10^{-4}$
$Cohesive\ Stress\ kPa$	21	13.5	0
$Friction\ angle$	$\emptyset_{outshell} = 35^{\circ}$	$\emptyset_{core} = 25^{\circ}$	$\emptyset_{core} = 35^{\circ}$

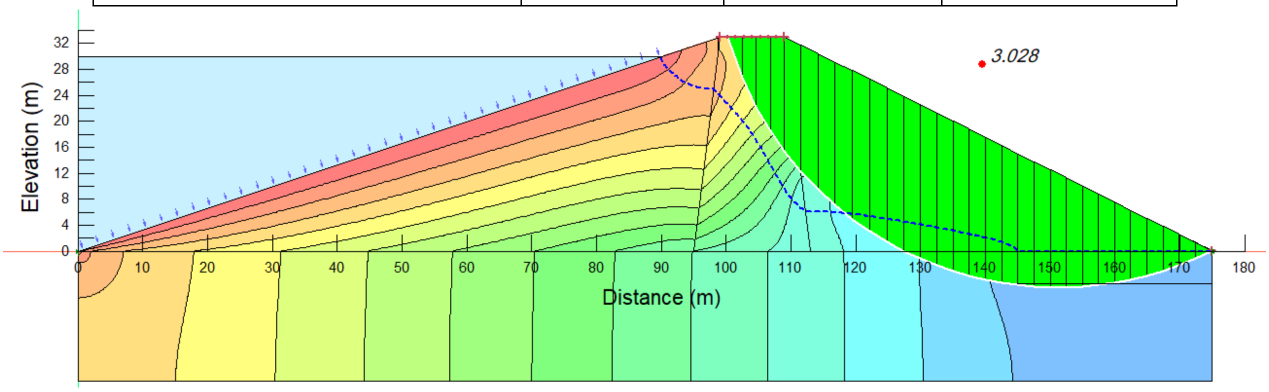

Figure 1: Sample of Earth Dam Section with Slope /W Analysis.

3. Results and Discussion

Earth dams serve as critical hydraulic structures to meet water needs while simultaneously contributing to the economic security of communities. The construction of such dams relies on the use of locally available materials, which necessitates an adaptive design approach that ensures compliance with safety standards against potential failure. This research investigates the effect of variable core permeability coefficients, and different storage water levels and filter lengths on the earth dam stability.

Stability, an essential aspect of earthen embankments, is defined as the ability of a slope to withstand forces that may induce the movement of earth materials down the slope. The basic stability indicators of an earth dam slope are frictional and shear strengths, which form the focus of this study. Shear strength, a measure of a soil's resistance to deformation under tangential compression, plays a pivotal role. Soils with higher shear strength exhibit increased interparticle cohesion, along with enhanced friction or interlocking, which mitigates the risk of particle slippage.

3.1 Frictional Strength

The frictional force appears as a pivotal variable affecting the stability of the riverbed slope (D/S) in the earth dam structure. Their basis lies mostly in soil cohesion properties, with a complex interplay between friction and cohesion evident in field samples, dependent on the size and shape of soil particles. It is worth noting that soil particles that promote high cohesion, such as fine particles, tend to exhibit less friction. In this study, the research investigated the effect of three values of the core dam permeability coefficients. Figures (2) to (7) show the evolution of the friction force concerning distance, taking into account the characteristic core permeability coefficients, water storage heads, and filter lengths.

Figure (2) reveals a significant increase in friction force values up to the dam base distance (65 m) for all permeability coefficients and filter lengths, with peak values ranging from approximately 60 to 140 kPa. In particular, maximum friction force values (105 kPa and 104 kPa) appear in the basic permeability coefficients K1 and K3 with a filter length (F = 30 m), while lower values (70.8 kPa and 70.6 kPa) are observed. When the heart is permeable. K2 factor with filter lengths (F=15 m and F=25 m). Other cases fall within this spectrum.

This observed behavior can be attributed to the use of a 30 m filter, which facilitates early control of the leak line path. Consequently, this results in lower pore pressure, increased cohesion, and thus increased frictional force values throughout the dam structure.

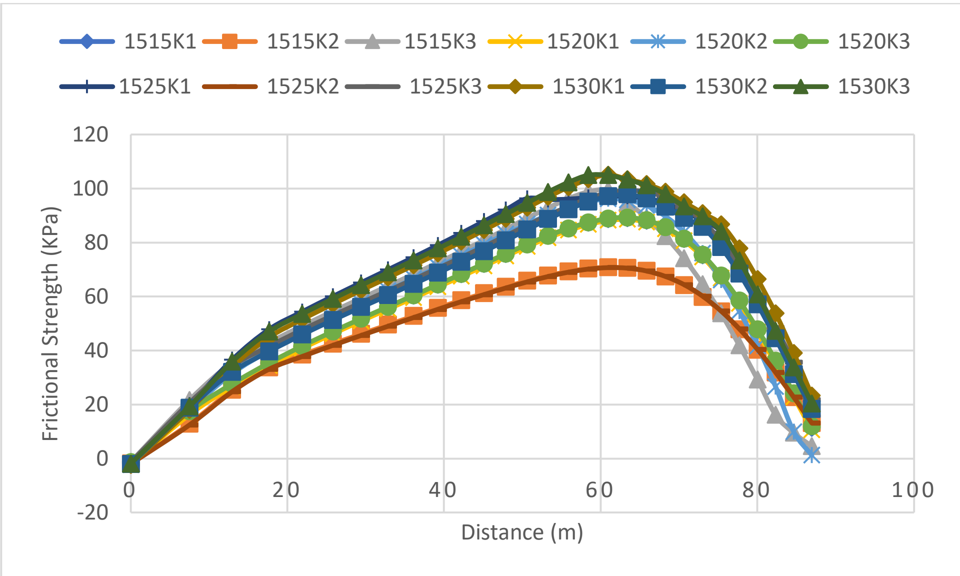

Figure 2: Frictional Strength variation with different (K&F) for H=15.

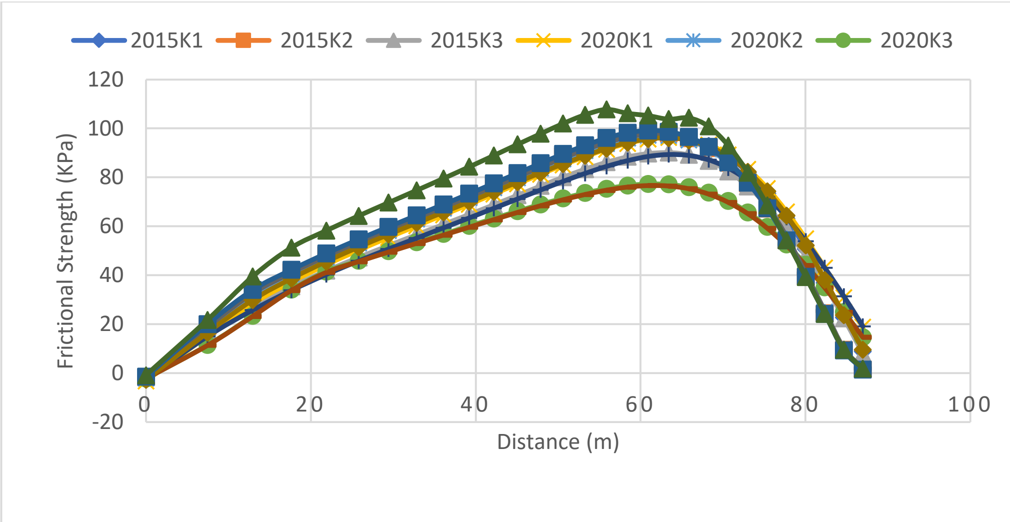

Figure 3: Frictional Strength variation with different (K&F) for H=20.

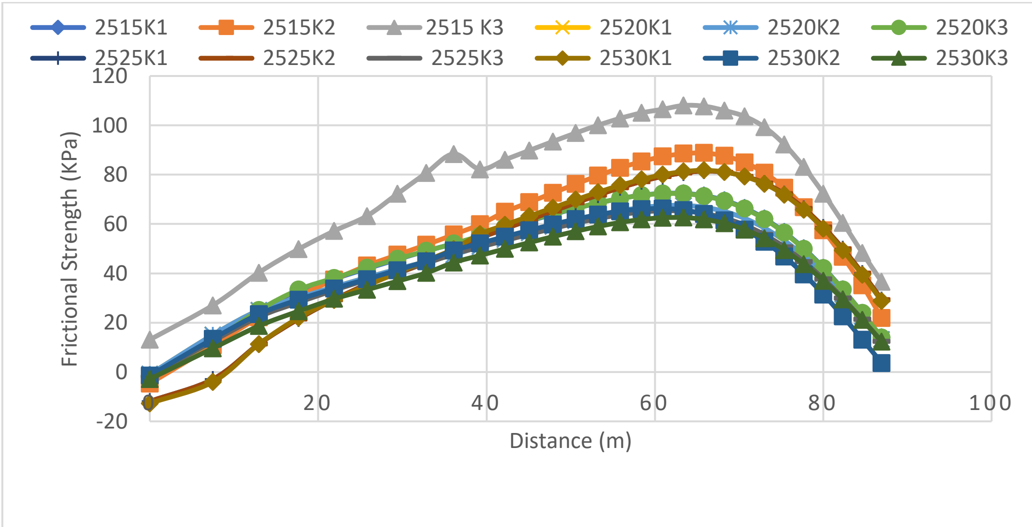

Figure 4: Frictional Strength variation with different (K&F) for H=25.

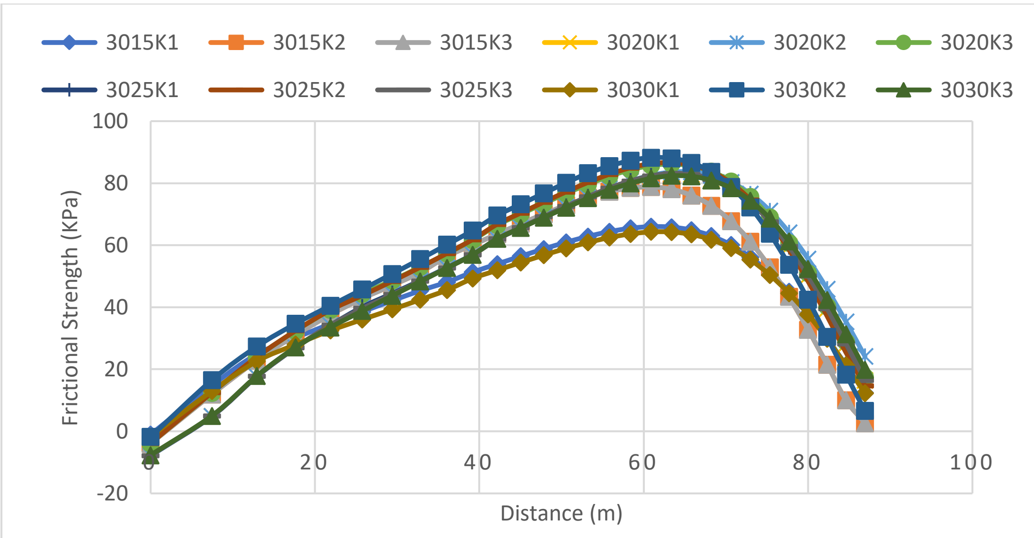

Figure 5: Frictional Strength variation with different (K&F) for H=30.

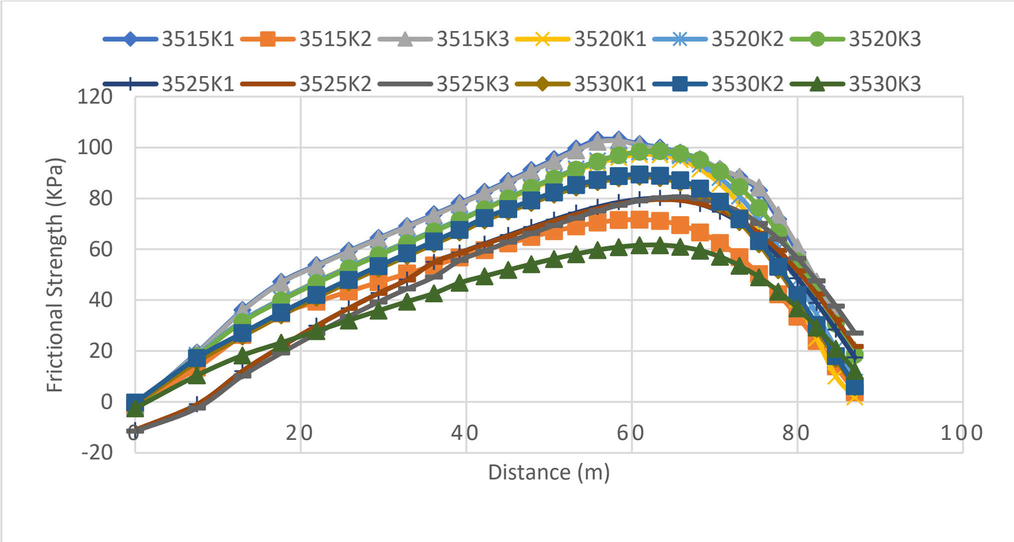

Figure 6: Frictional Strength variation with different (K&F) for H=35.

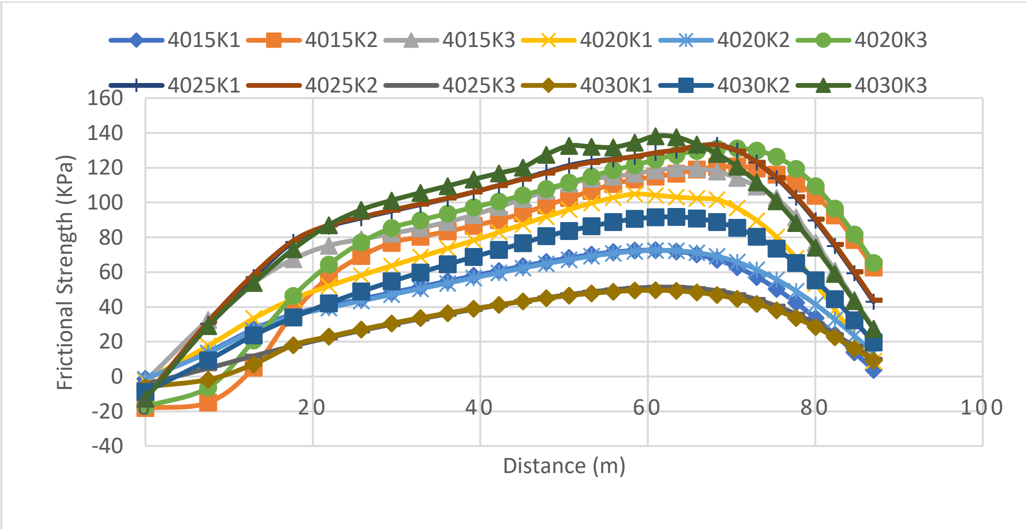

Figure 7: Frictional Strength variation with different (K&F) for H=40.

In Figures 3 to 7, the observed trend seems reminiscent of the previous cases, but it shows a calmer behavior in the peak values. However, the critical core distance of (65 m), compared to the previous cases, reveals a noteworthy friction force of (138.2) kPa at H = 40 m with (F30, K3). These results confirm the influence of a filter length of 30 m and permeability coefficients K3 and, to a lesser extent, K2 in raising friction force values across reservoir levels of 15, 20, 30, and 40 meters.

The results from this analysis do not depict a consistent pattern in the influence of hydraulic and geometric factors considered in this study, highlighting a subtle relationship that is subject to changes. This precise behavior remains constant across specified values of permeability coefficients and filter lengths, as shown in Figures (3) to (7). The complex interplay of these factors underscores the need for a comprehensive understanding of the dynamic effects of friction force in the context of different filter lengths and tank head levels.

3.2 Shear Strength

The soil shear resistance behaves as a resistance decisive determinant against erosion or displacement caused by the effect of shear stress. This property is of paramount importance in the context Stability of earth dams, as they play a crucial role in the design and analysis stages to ensure their safety and integrity Stable operation of these structures. The complex nature of soil shear strength involves two main things Components: cohesion between molecules and the resistance resulting from molecules sliding over each other because of friction. In our study, the shear resistance behavior of the earth dam body revealed a noticeable difference underneath the Effect of different permeability coefficients and filter lengths. This difference in response. The values of the permeability parameters introduce a layer of complexity, which makes interpretation somewhat difficult. Noticeably, with increasing filter length values, especially for tank head (H) levels of 15, 20, 30, and 40 m, shear strength values showed a marked upward path. The peak shear strength values reached (141.4, 123.7, 110.3, 108.3, 139.7, and 158.2 kPa), and they occurred under specific conditions, such as (H=15, F30, K2), (H=20 m, F30, K3), (H = 25 m, F15, K2), (H = 30 m, F30, K2), (H = 35 m, F30, K2), and (H = 40 m, F30, K3).

Furthermore, a consistent pattern emerged in all cases, where shear strength values increased systematically as the base of the dam extended, up to a distance of 65 m. After this point, the values showed a downward trend towards the front of the dam (as indicated by numbers 8 to 13). The figures also confirmed that a rise in water level of 30 meters or more corresponds to a proportional increase in shear force values. This is, to some extent, consistent with the findings of Abbas, J.M. (2017), which emphasize that the increase of soil resistance due to the increase of cohesion and friction angle and water level cause significant increase in safety factor. This is a complete insight of shear force behavior it contributes to a more thorough identification of the dynamic interactions within an earth dam system.

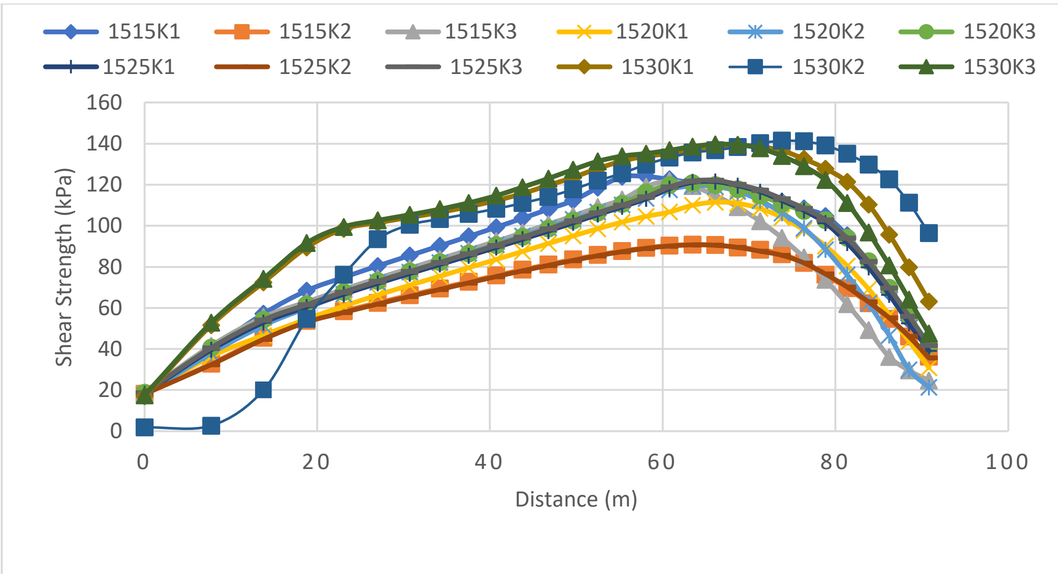

Figure 8: Shear Resistance variation with different (K&F) for H=15 m.

The bahavior of soil is significantly influenced by texture,structure ,water content and degree of comapdction which all together impacted the soil shear strength. However, among these factors, water appears as a common denominator, exerting a profound influence on the shear strength of a given slope. The presence of water within the pores not only changes the weight of the soil but also increases the shear stress, posing a potential threat to slope stability. The interaction between water content and permeability coefficient values becomes particularly crucial in understanding and mitigating these risks. The lower permeability coefficient, combined with the increased filter length, contributes significantly to reducing the water content within the earth dam body. This reduction in turn leads to lessening of the pore water pressure, which enhances the positive effect on shear strength values. The effectiveness of the permeability coefficient is inversely proportional to the length of the filter and its effect on the water content leads to a double benefit. First, as result to low values of permeability coefficients, the seepage is reduced and hence the existence of water in pores are reduced. Secondly, as the filter length increased and the seepage path controlled accordingly, the water content is reduced within the dam structure. Based on the above, decreasing water content will help to stimulate shear resistance, which in turn will lead to enhancing the stability of the dam and increasing the safety factor. This thorough not only offers protections against probable threats caused by increased shear stress, but also contributes to the overall stability of the earth dam structure.

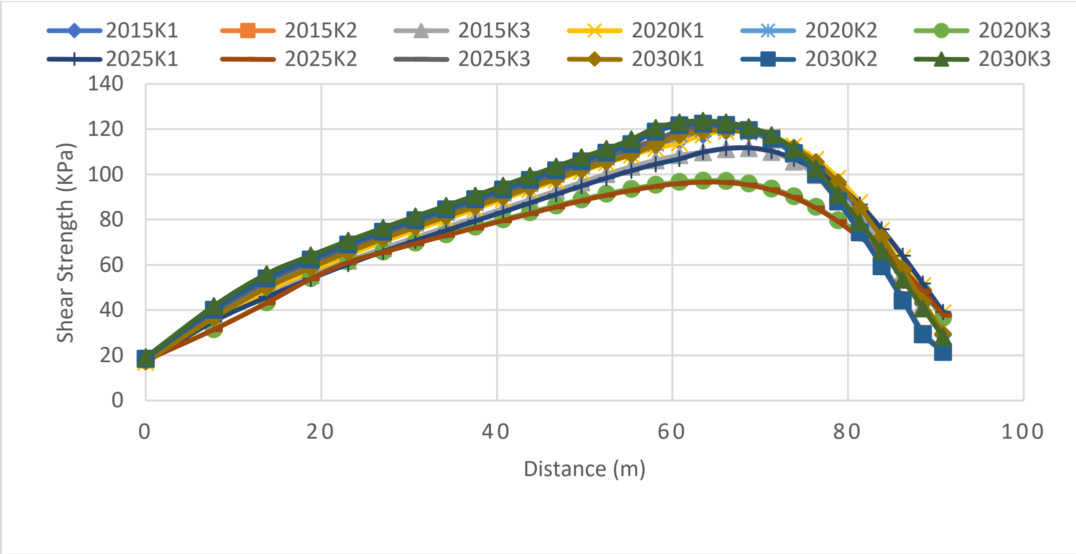

Figure 9: Shear Resistance variation with different (K&F) for H=20 m.

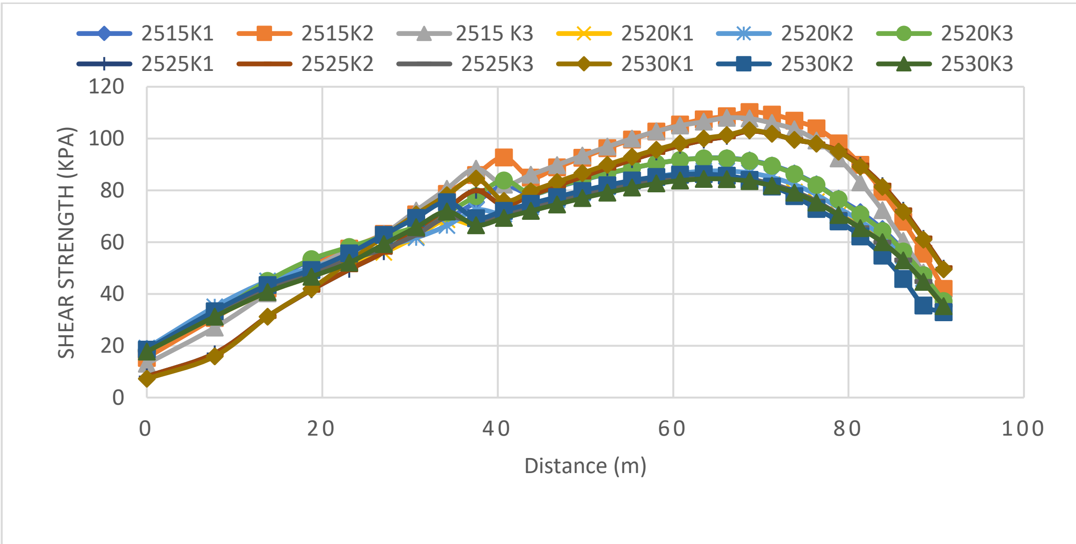

Figure 10: Shear Resistance variation with different (K&F) for H=25 m.

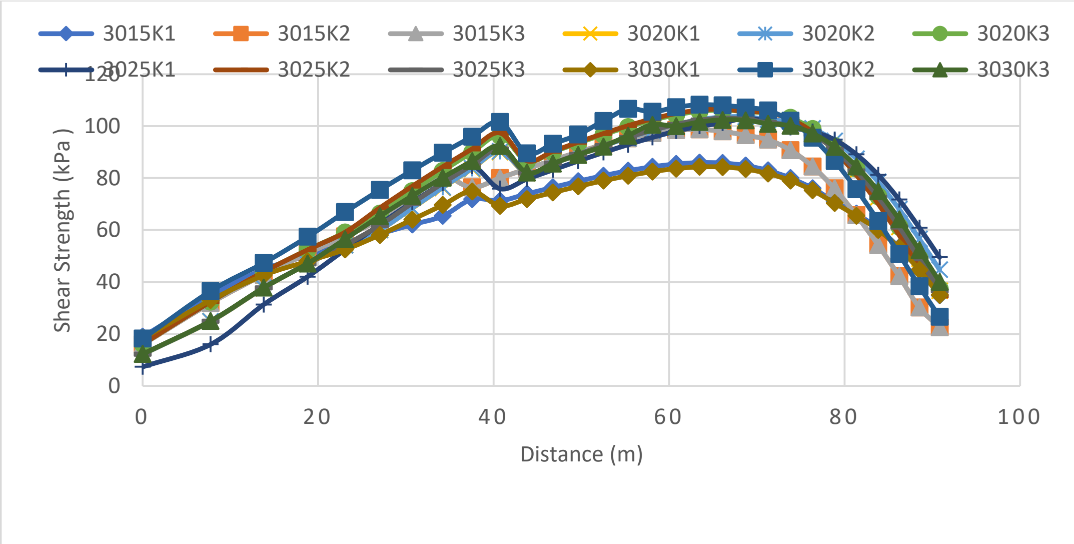

Figure 11: Shear Resistance variation with different (K&F) for H=30 m.

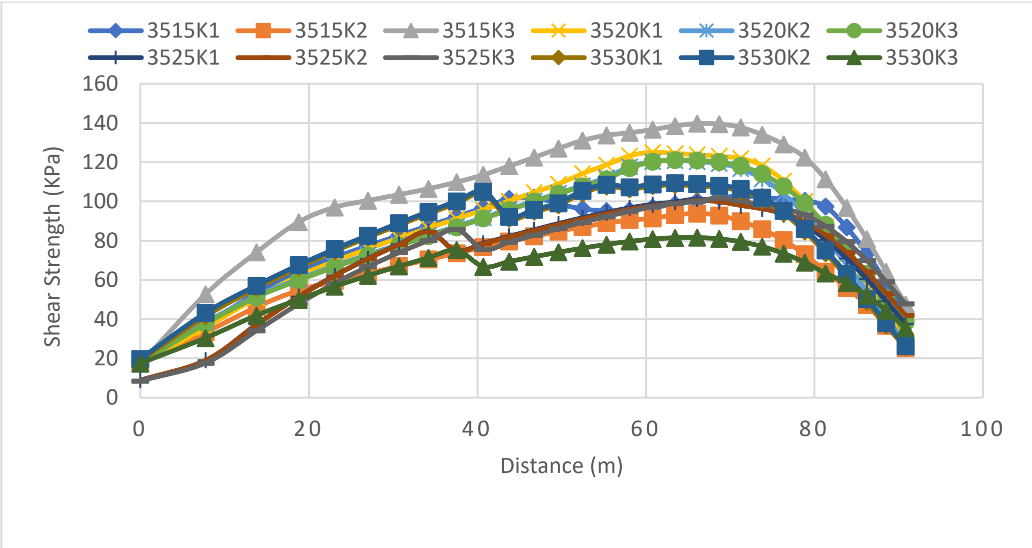

Figure 12: Shear Resistance variation with different (K&F) for H=35 m.

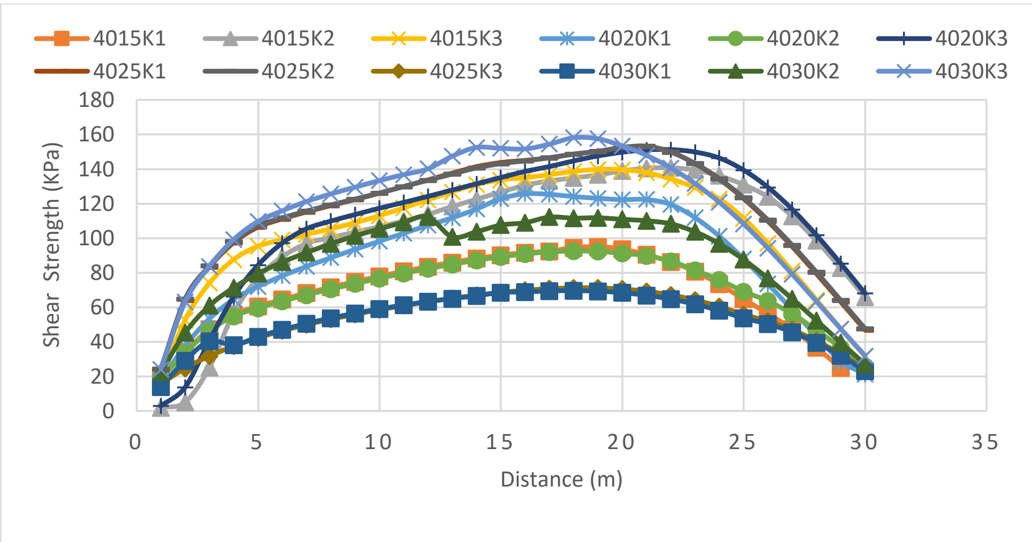

Figure 13: Shear Resistance variation with different (K&F) for H=40 m.

4.Summary and Conclusions

1. Uniform behavior of friction force and shear force: Both friction force and shear force show parallel behavior concerning the core distance of the dam. These strengths rise to peak values at a specific distance (65 m) and then show a decreasing trend towards the toe of the dike.
2. Effectiveness of filter length and permeability coefficient: The results confirm the pivotal role of the 30-meter filter length and the permeability coefficient (K3), and to some extent (K2), in amplifying the values of friction force at different storage levels (15, 20). And 30 and 40 m). This highlights the importance of these geometric and hydraulic variables in enhancing the safety factors of the downstream (D/S) earth dam against potential slide failures.
3. Ideal conditions for peak friction and shear force: Our peak results reveal that the peak friction force (138.2 kPa) and maximum shear force value (158.2 kPa) appear at a tank head (H) of 40 m, using a filter length (F) of 30 m, and a permeability coefficient (K3) 1×10^(-11) m/s. This configuration optimizes the geometric and hydraulic variables, thus enhancing safety factors against failures caused by sliding.
4. Significant increase in shear resistance values: The study showed a significant increase in shear resistance values for specific configurations, including values of (K2, K3), (F=15 m at H=25, 35), and (F=30 m at H= 15, 20, 30, 40 m). This confirms the decisive influence of some hydraulic and geometric factors in enhancing shear strength under specific conditions.
5. Complex dynamics of hydraulic and geometric factors: In contrast to the static trend, our analysis reveals a complex interplay between hydraulic and geometric factors. The differences in behavior underscore the complex nature of interactions within the earth's dam system, posing a challenge to formulating a globally applicable trend.

In conclusion, this study provides a nuanced understanding of the multifaceted dynamics governing the stability of earth dams and provides valuable insights into design and operational considerations to fortify against potential failures.

5. Conflict of Interest:

"There is no conflict of interest for this paper"

6. Author's Contribution:

The authors have contributed significantly to this paper by employing software tools to achieve the main objectives, and enhancing the research process and results through effective use of technological resources.

7. Acknowledgment:

The researchers would like to extend their sincere thanks to Tishk International University for their valuable support in carrying out this study.

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