

Numerical Modelling of Factors Critical to Slope Stability with Plaxis 2D

Muhammad Rehan Hakro ^a, Rabia Soomro ^b, Shehnaz Hakro ^c, Faisal Ahmed Rajper ^{d,e}, Imtiaz Ali Hakro ^f

^a Department of Civil Engineering Mehran University of Engineering & Technology, Sindh Pakistan

^b Department of Civil Engineering, Mehran University of Engineering and Technology Shaheed Zulfiqar Ali Bhutto Campus, Khairpur Mir's, Sindh, Pakistan.

^c PhD Scholar Center for Environmental Sciences, University of Sindh Jamshoro

^d Executive Engineer, Irrigation Department Government of Sindh

^e Sindh Agricultural University Tando Jam, Sindh, Pakistan

^f Institute of Petroleum & Natural Gas Engineering Mehran UET Jamshoro

* Corresponding author: Muhammad Rehan Hakro, Rehan.hakro@faculty.muet.edu.pk

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ABSTRACT

Slope instability is among the primary issues in geotechnical engineering that can result in loss of life and property. This study assessed slope stability by Factor of Safety (FOS) in FEM Plaxis 2D software with different geotechnical and hydrological conditions. The Mohr–Coulomb model is used to predict behaviour of soil and the input parameters determined in the laboratory. Mohr–Coulomb constitutive model is typically more preferred than the Drucker Prager model for slope stability analysis since the soil strength is a key factor controlling slope stability. To determine the geotechnical parameters of soil samples were obtained from each slope segment. In the laboratory, soil samples were evaluated for their strength properties, soil type, size distribution, permeability, etc. The factor of safety (FOS) is determined based on various factors that contribute to slope instability. The parameters for each slope are changed, and the safety factor is determined for each step. The FOS was 2 at the load of 25 kPa and reduced to 1.4 with load of 100 kPa soil. The effect of the footing distance to the edge of the slope is represented by w/x. As the ratio decreased, an increase in the factor of safety value was observed. The FOS decreased from 2.38 to 1.76 with a rainfall duration of 20 days. This study shows that rainfall significantly reduces matric suction in soils at shallow depths, leading to a decrease in shear strength and an increased risk of shallow failures. Additionally, a non-linear relationship between setback distance and FOS was observed, emphasizing the importance of conservative design practices. Finally, the study confirms that pile installation significantly enhances slope stability, with longer piles generally leading to higher FOS. However, optimal pile length and location are highly dependent on site-specific conditions.

1. Introduction

The soils is three phase permeable complex material consists of solid particles, liquids, and gases

in empty spaces than other materials, i.e., concrete, etc. The amount of air and water present in empty spaces varies depending on several variables, such as the surface vegetation, soil's texture, composition, and

climate. The soil behaviour of is primarily influenced by surface characteristics, shape, and size of soil particles as well as by how tightly grains are packed and the amount of water present. There is a significant change in volume, shear strength, and hydraulic parameters in unsaturated soils containing negative pore pressure.

Studies of slope stability aid in the safe and economical construction of slopes, whether they are constructed or natural. These includes landfills, excavations, open-pit mining, road cuts, and slopes. Engineers determine how distant or close a slope is to collapsing using safety calculations. This ratio becomes larger than 1, indicating that the resistive shear strength exceeds the driving shear stress, and the slope is deemed stable. Although the ratio is near to 1, shear strength and shear stress are approximately equal, indicating that slope collapse is possible. If FOS (Factor of Safety) is less than 1, Slope must have failed previously. Serious defects and differential settlements could arise in the buildings in the absence of appropriate methods for evaluating slope stability. Soil settlements can be prevented, foundations can be modified to maximize bearing capacity, and new solutions are continually being developed [1-3]. Consequently, the simplest solution to eliminate these problems is to utilise the appropriate mathematical technique from the beginning during building and structure design and restoration [4].

The FEM (finite element method) has gained popularity in analysis of slope stability due to its assumption-free nature. This allows for analyses to be conducted with any failure surfaces, slice side forces, and orientations. It is possible to quickly and precisely determine equilibrium of shear strengths, displacements, strains, and stresses. This method can provide information regarding deformations at the terrain's surface, allowing us to track progressive failure, including overall shear failure, for more research in this area [1,3]. According to Bishop's theory [5], total stress within soil mass may often be described as the superposition of effective stresses that are transmitted by particle contact with water, depending on saturation S , pore pressure u_w and air-pore pressure u_a

Several research have equated findings of analyses of slope stability conducted using FE and LE methodologies. Lande and Griffiths equated the outcomes of 6- basic slope models derivative by FE (finite element) evaluation to those of further conventional LE techniques. The conclusion was that FE (finite element) is a powerful substitute to conventional LE approaches, and extensive application of it may now get standardised in ge-

otechnical practise. Alternative research [4]. equated FE (finite element) slopes study to a variety of LE approaches for an extensive variety of slope scenarios. Though the researcher of this research advocated implementing FE approach with shear strength RF as effective and extra strong tool for analysis and design, doing additional study utilising this technique is moreover suggested.

To compare the results of the LE methodology and the FE method, Chen et al. [6] analysed the slope stability of non-homogeneous and homogeneous simplified slope. scenarios with varying material properties. The results for homogenous slopes are found to be very similar. When it comes to everyday design and analysis, FE (finite element) technique is not better than LE method. Engineers comparing the outcomes of separate analyses should be aware of the caveats of each method, despite the fact that both provide an estimate of FOS and the most likely mode of failure. The critical slip surface's location and FOS are similar between the two methods when studying a simple, homogenous slope, and the results are same. What's more, the results of this investigation show that there are important distinctions between the FE and LE methods when assessing a slope with a mixture of different types of rocks [7-10].

Geotechnical engineers continue to face significant difficulties when trying to assess slope stability. Many researchers have found this topic intriguing, and their interest in it shows no sign of abating [11-13]. There are numerous possible failure modes for a slope. It was found that the gravitational load did not alter even if soil resistance levels decreased [9][14] .

It is possible to quickly and correctly calculate the equilibrium of displacements, strains, stresses, and corresponding shear strengths in rock or soil masses. Deformations on the landscape's surface can be seen with this technology, allowing us to keep an eye on the spread of failures like global shear failure [15,16].

The most frequently stated FOS explanation for a slope is the ratio between shear strength and shear stress necessary for equilibrium [17,18]. In many cases, a combination of circumstances leads to a slope failing. Slope stability is analysed in relation to FOS value throughout a wide range of essential FOS parameters, such as soil property alteration, excavation along the slope, water depth, duration, rainfall intensity, and unsaturated and saturated soil conditions [19, 20].

The objective of this research paper is to compare the factor of safety (FOS) values under various conditions using the FEM Plaxis 2D software. The study will utilize the Mohr-Coulomb model, with

model parameters derived from in-situ and laboratory tests. This paper aims to provide insights into the potential of computer simulations for understanding slope stability phenomena and to identify the most suitable approaches for slope stabilization and calculating slope stability factors.

2. Research Methodology

The research methodology consists of three phases mentioned below

- Drilling and collection of soil samples from Study Area
- Soil Testing and Parameters calculations
- Numerical Modelling in Plaxis 2D

2.1 Numerical Modelling in Plaxis 2D

The soil was collected from Jamshoro from the slope for geotechnical testing and parameters computations for simulations. Laboratory tests such as: The determination of Atterberg limits (liquid limit, plastic limit, and shrinkage limit), following ASTM D4318 and BS 1377. The Modified Proctor test for maximum dry density and optimum moisture content, in accordance with ASTM D1557. Unconfined compressive strength test following ASTM D2166 Permeability testing using a flexible wall permeameter, according to ASTM D5084.

2.1.1 Finite Element Analysis Using PLAXIS 2D

The increasing use of complex material data and geometries has made analysis both iterative and nonlinear. In such scenarios, inputs (geometry and soil properties) are dependent on the solution itself. While this technique demands significant computational time and data, it is recommended to utilize available Finite Element (FE) software. In the present investigation, the FE software program PLAXIS 2D was employed.

In PLAXIS-2D, the analysis divides the model into discrete elements, each represented by nodes that define the degrees of freedom. The degrees of freedom, along with the discrete values for individual nodes, correspond to the unknowns in the problem under the specified boundary conditions [21]. The displacement components are related to the nodes' degrees of freedom. For triangular elements, PLAXIS uses 6-node or 15-node configurations. These triangular elements, unlike the simplistic "line elements," are fundamental to the analysis and accurately reflect the geometry of the slope.

The material behavior in this FE analysis is governed by the Mohr-Coulomb constitutive model, which is an elastic-perfectly plastic model. This model accounts for both elastic and plastic behavior, with elastic behavior prevailing up to the yield point, beyond which plastic deformation occurs. The Mohr-

Coulomb model simulates the material's irreversible strain growth, forming a yield surface based on the predominant strain and stress conditions. The finite element technique replicates this elastic and plastic behavior through appropriate stress-strain relationships, with Hooke's law used to relate stress and strain elastically. The model separates strains into elastic and plastic components [22-24].

2.1.2 Factor of Safety (FOS) Evaluation Using Strength Reduction

In this study, the factor of safety (FOS) was evaluated using the strength reduction method, commonly known as the phi-c reduction technique. The convergence criterion plays a crucial role in this analysis, and the reduction in strength parameters—specifically the cohesion (c) and friction angle (ϕ)—is achieved through an incremental multiplier (Msf).

For load-controlled calculations, PLAXIS 2D provides accurate collapse load predictions, making it the ideal choice for slope stability analysis using the strength reduction approach. The analysis progresses in stages, where the friction angle and cohesion are gradually reduced until failure occurs, which is identified by the factor of strength reduction (SRF). In PLAXIS, failure is typically detected by non-convergence or large plastic strains that exceed acceptable limits.

PLAXIS-2D is an advanced FE analysis tool designed for 2D geotechnical modeling, including slope stability analysis, plastic deformation evaluation, and other analytical approaches. The input program is divided into several subsections: staged construction, flow conditions, mesh, structures, and soils.

The project properties section specifies the model type (axisymmetric or plane strain), units, and finite element type (6-node or 15-node triangular elements). The material set options allow the definition of different materials and their assignment to the soil regions. Additionally, groundwater conditions, seepage, and drainage types are specified in this section, alongside key soil parameters. The mesh is created by dividing the profile into finite elements, with different mesh fineness levels (e.g., very coarse, coarse, medium, fine, extremely fine). For example, the groundwater level (phreatic level) is defined within the flow conditions section.

Once the input geometry is finalized, the computation can proceed in phases. The initial phase typically sets up the starting conditions of the field, which may include gravity loading or K0 conditions.

The strength reduction analysis follows, where the shear strength parameters are reduced progressively until failure occurs. After defining the geometry model and generating the FE mesh, the configuration and initial stress state must be established. The input program's initial conditions section handles these settings. Initial conditions are divided into two modes: one for generating early pore pressures (moisture conditions) and another for defining the initial effective stress field (geometry configuration). For the purpose of this study, only the phi-c reduction method was used to evaluate the factor of safety (FOS) under varying hydraulic conditions, such as water level fluctuations, rainfall intensity, and excavation near the slope.

The phi-c reduction method in PLAXIS involves reducing the shear strength parameters (cohesion and friction angle) step by step. After each stage of reduction, the safety of the slope is reassessed by observing the resulting displacement or failure behavior. The factor of safety is identified when the system no longer maintains equilibrium under the applied loads and reduced strength parameters. . In this study, PLAXIS 2D was used to simulate unsaturated soil behavior using the Van Genuchten model to define the Soil-Water Characteristic Curve (SWCC). The model accurately captures the relationship between matric suction and water content. Additionally, transient unsaturated seepage was simulated using PLAXIS's capabilities to model the flow of water through the unsaturated zone during rainfall events. This helped to assess changes in pore pressure and the potential impact on slope stability.

2.1.3 Stages in Numerical modelling in Plaxis 2D

Following were the steps employed:

Step 1: Defining of soil stratigraphy and creating a slope geometry.

Step 2: Creating and assigning of material information set.

Step 3: Defining of the structural elements.

Step 4: Early geostatic stresses are created in the mesh by means of lateral earth pressure and gravity.

Step 5: Rearranging displacement value to zero.

Step 6: Activation of load as UDL in staged construction

3. Results and Discussions

This study consists of two assignments: laboratory testing and other simulations and parametric study in Plaxis 2D FEM software.

3.1 Basic Soil Properties

Soil samples were collected from the study areas of Jamshoro. Saturated hydraulic conductivity, unit weight, Atterberg's limits, and grain size distribution (Figure 1) were all measured for each collected sample. The primary soil properties are determined in the laboratory for describing the soil and used as input parameters for the simulation. The liquid limit and plastic limits were 45 and 25 respectively. The collected shale soil sample was classified as CH, according to unified soil classification system (USCS).

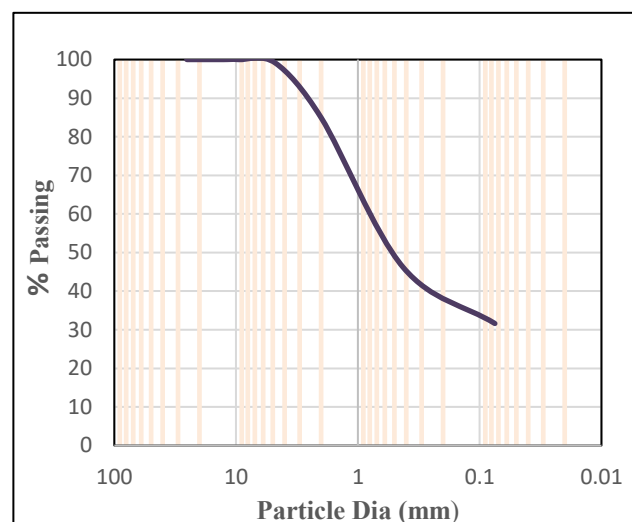


Fig. 1: Particle size distribution curve

Table 1

Soil Parameters

Description	Symbol	Unit	Value
Density	γ	kN/m ³	22
young's modulus	E	[kPa]	24711
poisson's ratio	ν'	[-]	0.30
Cohesion (effective shear strength)	c'	[kPa]	22
Frictional angle	ϕ'	[o]	11
Dilatancy angle	ψ	[o]	0
Soil Classification	CH		

3.2 Numerical Modelling Results

The medium size mesh selected, and mesh is of 252 elements, 2185 nodes, as shown in Figure 2. The top-loading upon slope plays a crucial part in slopes stability in hilly slope zones. While the building load is very huge or point of action from shoulder is very close, slope's shear stress will be much bigger than its shear strength, resulting in im-paired stability of slope. Hence, it is of considerable significance to investigate link be-tween building load and slope stability. The FOS is perceived under different loading conditions. As the load increased, the FOS decreased, the results

are presented between FOS and number of steps of calculation in Figures 5a & 5b.

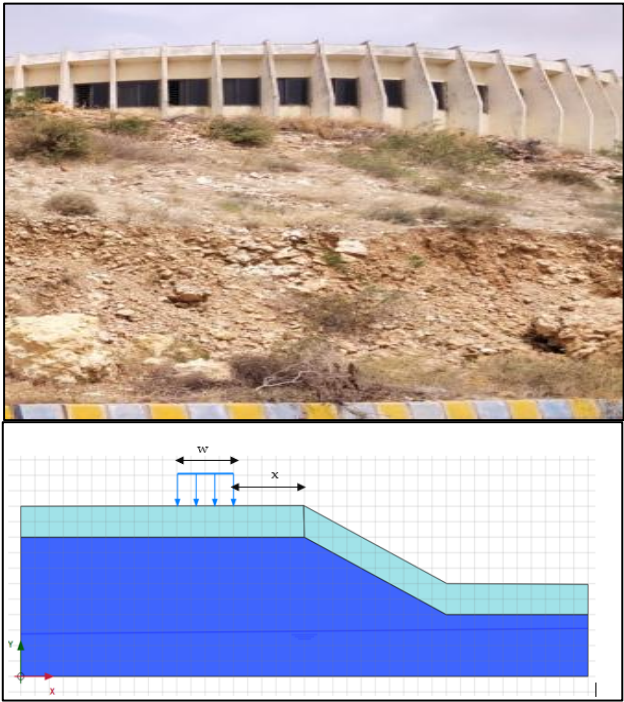


Fig. 2. Slope Geometry

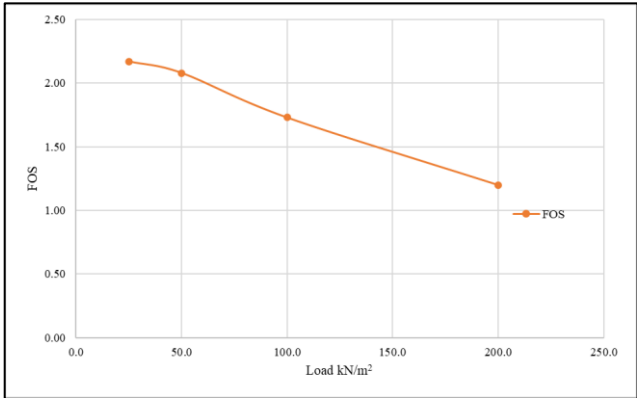


Fig. 3. Load and Factor of Safety (FOS)

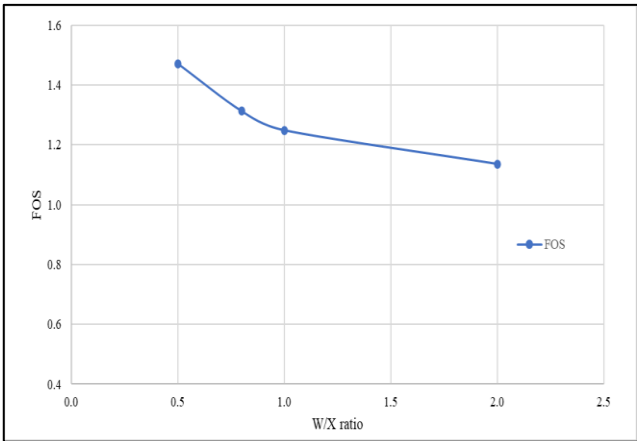


Fig. 4. W/X ratio and Factor of Safety (FOS)

The setback distance is regarded as an essential regulating parameter in assessing the distortion and bearing features of a foundation lying on sloppy ground. The smaller the setback distance, the greater the risk of the failing of foundation and exhibiting distress conditions resulting from slope face

distortion. Consequently, complete parametric re- search was done with setback distance as among simulation's contributing components to emphasize influence of various parameters. The effect of foundation distance to the slope edge is represented by w/x , where w is footing width and x is the distance from the slope's edge as shown in Figure 2. The loading and other soil conditions remained constant in these simulations to observe the influence of ratio w/x on the factor of safety. The impact of w/x ratio to FOS is presented in Figure 4. as the w/x ratio decreases, the FOS decreases, which aligns a smaller setback distance (or a lower w/x ratio) increases the risk of foundation failure and reduces the FOS. The study of Keskin & Laman [25] cited similar results by physical

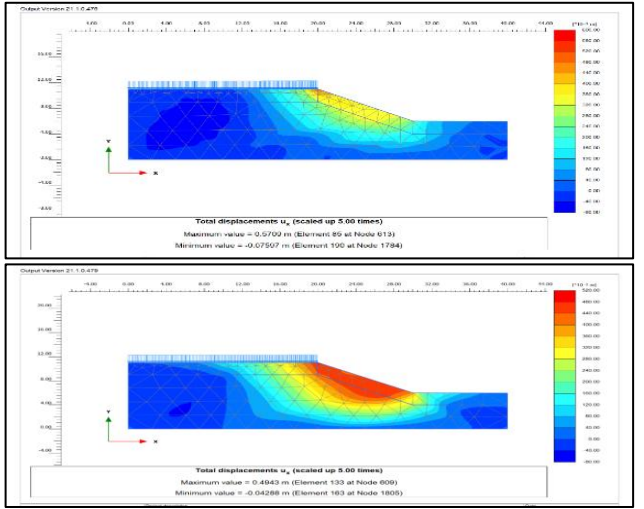


Fig. 5a. Critical slip surface

However, there was a significant disparity between the computational approach and the experimental research. When a foundation is located near a slope, the loading rate and the development of the slip surface throughout the loading operation impact its bearing capacity. The FEM and LEM study of Matsui & San [26] stated that the FOS upsurges as the distance amid the crest of slope and the surcharge upsurges, however, the influence of surcharge remains constant above that level for slopes of homogenous and layered soil.

Footing embedment depth, load distribution, setback distance, and slope angle, and the stiffness and strength properties of the foundation soil, as well as other factors such as earthquake loading, rainfall, and saturation status in foundation soil, all have an impact on the footings performance located nearby the slope. The load carrying capacity of slope was 140 kN/m². Slope failure may occur due to shear strength decrease as a result of rising plastic strains caused by loading. The contours of slip surface due the varying atmospheric circumstances create a flexible boundary condition that affects the distribution of pore pressure

along the entire slope, which in response affects available slope stability and soil strengths. The duration of the rainfall event, factor of safety (FOS) reduced from 2.389 to 1.9 and 1.76 with 10 and 20 days of rainfall duration, respectively as shown in Figure 5 (b). The rainfall intensity was smaller than hydraulic conductivity of soil.

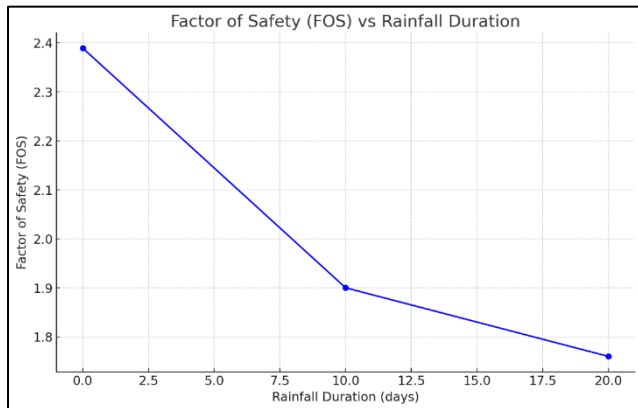


Fig. 5b. FOS and Rainfall duration

3.2.1 Mechanism of reduction of FOS due to rainfall

The equilibrium conditions within slopes, and consequently their degree of stability, are dependent on a number of variables [43], including the boundary conditions at the ground's surface. These generate water exchanges amid top soils and atmosphere through mechanisms such as transpiration, water evaporation from the soil pores, and rainfall infiltration through vegetation; collectively, this phenomenon is known slope–atmosphere interaction'. The evaluation of pore water pressures, in conjunction with infinite slope analysis, has been stressed in order to establish a predictive formulation of the slope failure that frequently results from heavy rains. As a result of this interaction, soil pore pressures, and consequently, the soil stress-to-strain conditions change with time. specifically, pore pressure variations induce, on the one hand, changes of the mobilised shear strengths and, on the other hand, changes of the available shear strengths, and consequently, can cause either commencement or advancement of slope failure, with eventual instability of slope. Failure arises as a result of interaction between the slope and atmosphere, particularly in marginally stable slope parts that might be lost due to even slight upsurges in pore pressure. Else, collapse may occur within shallow slope parts whose stability is intensely reliant on existence of substantial suctions in pores of soil (i.e., above the water table), that are diminished due to rainwater infiltration. Regardless, the slopes stability changes over time as a result of climate The interaction between rainfall and matric suction was analyzed under various conditions, as

shown in Figures 6 and 7. Matric suction was quantified with values from 100 kPa at the surface to lower values deeper within the slope as rainfall intensity increased. In Figure 6, a high-intensity rainfall event of 30 mm/hr caused the matric suction to decrease from 100 kPa to 25 kPa in three days. Figure 7 demonstrates how soil permeability affected matric suction. When permeability was low (1×10^{-6} m/s), the matric suction decreased gradually, while at higher permeability (1×10^{-3} m/s), it decreased more rapidly due to faster water infiltration.

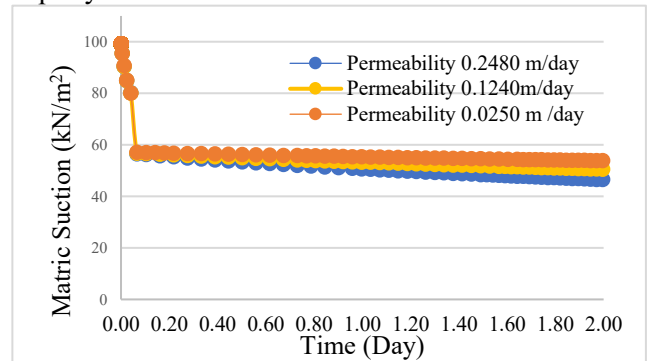


Fig 6: Matric suction with rainfall

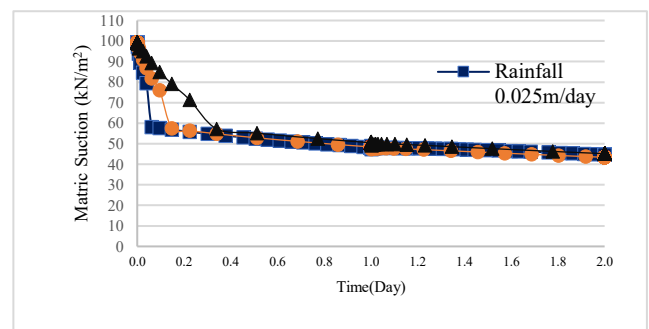


Fig. 7. Matric suction with Permeability

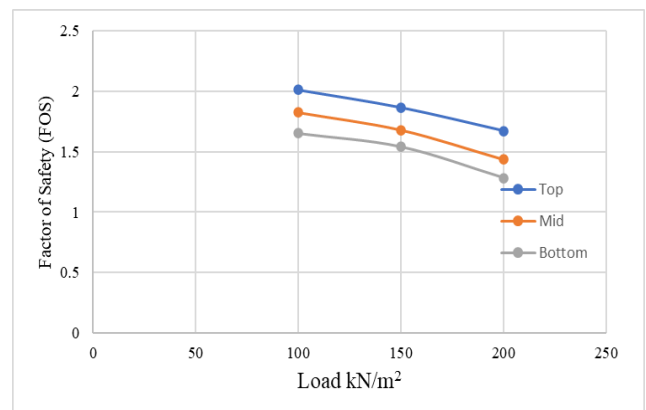


Fig. 8. Provision of piles at various locations and FOS

The piles were modeled using embedded pile elements in PLAXIS, allowing for a realistic representation of the pile-soil interaction. This approach provided a detailed simulation of how the piles influenced the stability of the slope. Elastic support was not used in this analysis, as embedded pile elements offer a more accurate modeling of pile behavior within the soil. The Figure 8 shows the provision of piles at various locations in the slope to observe the effect on FOS.

The diameter of pile was 0.5 m and installed at top, mid and at the bottom of

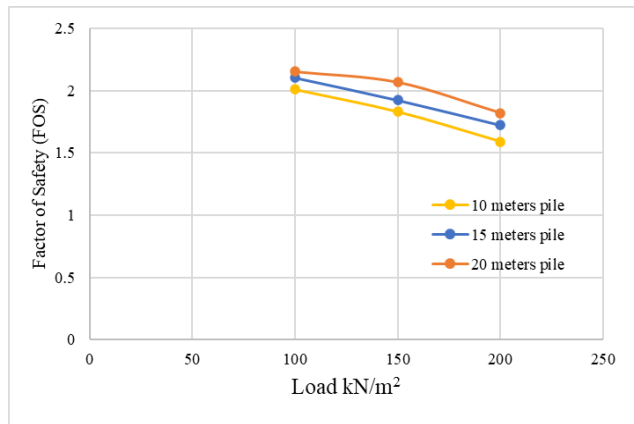


Fig. 9. Provision of piles of different lengths and FOS

the slope. In this analysis the load varied from 50 to 200kN/m². In Figures 8 and 9, the effects of pile location and length on the factor of safety (FOS) were explored. The installation of piles at different locations in the slope (top, mid, and bottom) increased the FOS from 1.2 to 1.7, depending on pile location. When varying pile length between 10 and 20 meters, the FOS increased, from 1.6 to 2.1, indicating the importance of pile length for slope stability. The load varied between 50 and 200 kN/m² to simulate real loading conditions. From it was observed that installation of piles increases the FOS.

The Fig : 9 shows the installation of pile of different lengths effect of the FOS. The results of the study demonstrate that the installation of piles significantly enhances the Factor of Safety (FOS) for slope stability. While varying the pile length within the 10-20 meter range did result in a marginal increase in the FOS, the overall impact of pile installation on slope stability was substantial. This finding highlights the crucial role of pile foundations in mitigating slope failures and improving the long-term stability of slopes.

4. Conclusion

The slope stability analysis was carried out using the FEM technique in PLAXIS 2D under various soil, loading, and rainfall conditions to observe the variation of the Factor of Safety (FOS). Based on the numerical modeling studies using PLAXIS 2D, the following conclusions are drawn:

- The matric suction significantly decreased at shallow depths during rainfall events of varying durations and intensities. This reduction occurred due to the movement of the wetting front from the top to the bottom, which reduced matric suction at greater

depths. This process likely contributed to the reduction in shear strength and, ultimately, shallow soil failure. However, at deeper depths, matric suction was reduced as the water table rose. The primary cause of the reduction in FOS during rainfall events can be attributed to the decrease in matric suction.

- A key observation from this analysis is the non-linear relationship between the w/x ratio and the FOS. As the w/x ratio increases, the rate of FOS reduction accelerates, suggesting that even small decreases in setback distance can have a disproportionately large impact on foundation stability. This emphasizes the importance of adopting conservative design practices and carefully considering even minor variations in slope geometry and foundation dimensions.
- The findings of this study clearly demonstrate that the installation of piles significantly enhances the Factor of Safety (FOS) for slope stability. Furthermore, increasing the length of the installed piles generally results in a corresponding increase in the FOS. However, it is important to recognize that the optimal pile length and location are highly dependent on specific site conditions and the nature of the slope instability.

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