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Original Article

Comparative Stability and Behaviour Assessment of a Hill Slope on Clayey Sand Hill Tracts

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Abstract *- This study assesses the behavior of a roadside natural slope along the economically viable 'Marine Drive' project to protect the lives there as well as the safety and security of the human-made infrastructure. However, roads are often severely affected by landslides, resulting in road blockages, damages and recurrent economic losses in developing countries due to the limitations of engineering geological investigations. In the present study, the stability analysis was conducted using different approaches. Initially, the limit equilibrium methods were employed to analyze the large-scale, deep-seated failure. In addition, the numerical technique based on the two-dimensional Finite Element Method (FEM) was also implemented to analyze similar slope sections. For instance, the computer-aided programs SLIDE for LEM, and PLAXIS 2D for FEM were used to draw this comparison. It has been argued that FEM is a more sophisticated tool in modern practices to analyze and predict slope soil's stability and corresponding displacements. Finally, this comparative study aimed to investigate the surface that is most likely to fail, reporting the critical factor of safety of slope on the clayey sand soil condition of that location. Considering climatic variations that result in it being a rainfall-prone hilly area, this particular slope may be subjected to erosion or an increased water level. Therefore, the slope stability soil condition with higher permeability affecting the strength parameters was also assessed along with the variations in slope geometry.*

Keywords *- Displacements, Finite Element Method, Limit equilibrium, Sensitivity analysis, Slope stability.*

1. Introduction

Over the previous few decades, the challenges of slope stability have increased in accordance with the rapid developments and constructions along hill slopes. Development projects such as road construction, dams etc., trigger the instability of slopes, excruciating their vulnerability to lateral displacements and landslides-like events [1]. Since then, it has been a principal concern as it greatly threatens human lives and infrastructures. To protect lives and property, it is required to investigate the stability of slopes. But, by using investigative tools in laboratory testing and applying proper engineering knowledge, a safe and economical design can be ensured. Here, engineering knowledge refers to conducting proper slope stability analysis.

The Factor of Safety (FOS) generally expresses the stability of slopes, which is evaluated by determining the average shear stress to average shear strength ratio developed. A slope normally fails when this developed shear stress exceeds the soil's available shear strength. Researchers have done numerous works on understanding the complex behavior of slopes and the pattern of failure. The progression of slope-stability analysis methods and techniques ranges from simple analytical techniques to complex numerical solutions. Starting with the quantifications of clay behavior in the middle of the 19th century [2], later on, the approach of assuming circular slip surfaces was introduced in 1916 and presented as a fully described method at the beginning of the 1920s [3,4]. Numerous approaches for the assessment of slope stability using equilibrium equations have been presented so far, and such Limit Equilibrium (LE) methods have been used for a long time [3,5,6] and have been more or less unchanged for decades [7].

Generally, all limit equilibrium approaches are based on the assumption of linear (Mohr-Coulomb) or non-linear relationships between shear strength and the normal stress on the failure surface [8]. However, they also satisfy the equilibrium equations. The Limit Equilibrium methods incorporated in this study are the Ordinary Method of Slices (OMS) and the Modified Bishop Method (MBM), and the Spencer Method (SM). All these approaches involve searching out the critical surface with the lowest factor of safety (FOS).

Failure surfaces, being assumed and divided into specified numbers of vertical slices, were first proposed by W.Fellenius. It is often referred to as the "Method of Slices". Around 10 methods of slices were developed over the last century [9]. Different methods of slices were developed based on different assumptions and inter-slice boundary conditions [8,10]. These variations influence the Factor of Safety results. Among all those methods, Ordinary Method Slices (OMS) is the simplest one, where FOS is derived for the trial failure surface [11].

Moreover, Alan Wilfred Bishop proposed a similar method for assuming to be applied solely to circular surfaces [12]. Later on, to ensure more precise calculations for both circular and non-circular failure surfaces, Spencer's method was developed in 1967 [13].

Similarly, this study was conducted by incorporating these three limit Equilibrium Methods (LEM) to locate the most probable slip surface along the economically viable marine drive project. The primary concern was to investigate the progressive and instantaneous failure of slopes. Here, the details of slope failure were referred to by developing models using both simplified limit equilibrium and numerical approaches that could be used without conducting expensive and complex dynamic analyses. In order to solve mathematical issues, numerical analysis employs approximation approaches while considering the magnitude of potential errors [14,15].

Despite the well-known limitations of LE-analysis methods [2,4,7], they have been widely used, mainly due to their simplicity and usability. In addition, the use of LE approaches in this research, application of the Finite Element Method (FEM) based on deformation analysis and strength reduction technique has been used to analyze the stability of existing hill slopes. They are often numerically handled using finite-element (FE) analysis to automatically locate the critical slip surface [15]. In fact, it doesn't even require any interslice forces to be assumed. Hence, using the accessibility of high computer capacity in these improved advanced analyses, strength parameters are reduced until the failure of the slope [16]. And finally, the factor of safety is defined as the ratio between actual and critical parameters. This enhances the chances of optimizing designs and construction, which are increasingly demanded and often desired.

Generally, for simple geometry and ground conditions, many studies have found that LEM shows good agreement with FEM results [17,18,19]. Still, the use of the FEM portrays detailed information on the stress state in the soil than is available from the LEM, which can assist engineers in the design of slopes and slope retaining structures [20]. These outcomes, however, can occasionally be subject to some degree of uncertainty because of regional variability, financial limitations, or inaccessible model input parameters. Therefore, knowledge of sensitive input parameters results in more accurate model development and design applications, guiding better-estimated values by reducing uncertainty [21]. For slope stability analysis, some of the most sensitive parameters influencing the change in safety factor are the strength parameters (friction angle, cohesion etc.) followed by the geometric attributes of slope [22].

The formations of a hill slope along the famous Marine Drive Road, Cox's Bazar, Chittagong, are specific in kind as it was directly influenced by the rise of the Holocene sea level due to their location on the shore of the Bay of Bengal. Soil of that kind is mainly characterized as poorly graded clayey sand [46]. In fact, these soil characteristics are also predominant in coastal regions and estuaries in different parts of the world [25-28]. Landslide studies with spatial susceptibility zoning [29,30], geospatial mapping [31,32], community vulnerability assessment [33], imagery terrain analysis [29,34,35], risk sensitive land use planning [46], rainfall threshold determination and hydrometeorological early warning system development [48] are so far the notable tasks performed in that particular geological and soil condition. But the shallow failure of landslides occurs due to reduced cohesion between soil or debris, resulting in reduced shear strength of the soil site [37-39]. This is because the engineering properties of slope materials are fundamental for investigating threshold factors favorable to failure [40-42]. For such a type of Bangladeshi soil, many studies have been conducted [24]. Hence, these cliff sections also deserve a detailed slope stability study focusing on their strength-triggering parameters. Many studies have referred to the LEM model in addressing the vulnerability of clayey sand slopes [43], but the widely accepted FEM model has not been incorporated.

The primary aims of this investigation are to identify the potential failure mechanisms and the threshold values of the strength parameters that trigger slope failure on clayey sand. Consequently, the present study compares LEM and FEM techniques for a selected natural slope along the renowned Marine Drive Road in Cox's Bazar, Chittagong. Such a comparison will provide a comprehensive understanding of its stability and other relevant issues. The area under examination is a popular tourist route. Therefore, evaluating the slope stability of the hilly terrain along this route is crucial, which is the primary reason for selecting this location. Moreover, this study incorporates the investigation on the effect of corresponding slope geometry considering slope height and angle with the horizontal (β) and also soil shear strength parameters like soil cohesion (C), angle of internal friction ($\emptyset$) on the factor of safety (FOS) and represents the graphical correlations to calculate the direct factor of safety. Because clayey sand is typically found in coastal locations and estuaries all over the world, this research also illustrates the tentative behavior of landslides happening due to diminished cohesion between soil or debris, resulting in shear strength reduction of the soil site.

2. Materials and Methodology

2.1. Study Area

The whole research work was conducted by collecting soil samples from several portions of the selected natural slope, especially from the failure portion of Himchori hill. This studied area is located at Himchori, Cox's Bazar, in the Chittagong division. It is 6.80 kilometers away from Kolatoli, Cox's Bazar. Geographic coordinates are 21°21'31" N latitude and 92°01'22" E longitude. A view of the study area is highlighted in Fig. 1.

Fig. 1 Study Area

The study area is located along the well-known Marine Drive Road in Cox's Bazar, Chittagong, a popular tourist route that draws many tourists yearly. Therefore, it is crucial to examine the slope stability of the hill tracts along this route, which is why the location for the study was chosen. Here, a particular natural slope has been chosen so that its critical stability and other related issues can be assessed. Initially, the failure surface of the chosen hill was used for sampling in this case. An undisturbed soil sample couldn't be collected as the study area is far away, and the transportation of the samples was not very smooth to be done. Disturbed samples were taken from the failure zone on the cut slope at 62.5 meters above the Mean Sea Level (MSL) elevation. Hence, tests that require undisturbed soil sample data were determined using several well-established correlations with various known properties of the soil to get closer to the result in the field. Initial conditions of the existing slopes and sampling locations are presented in Fig. 2. To perform stability analysis, different laboratory tests (physical, index and engineering properties) were conducted following ASTM standards. ASTM D6913 was followed for the gradation of the soil particles between 75 mm (3 inches) and 75 µm (No. 200) sieves, while ASTM D422 was followed for the soil particles smaller than 4.75 mm (No.4 sieve). Based on the reference to soil condition, necessary soil model parameters were also inferred [44].

2.2. Soil Properties and Parameters

The investigation program included taking samples of the soil at a variety of different sites. A number of different experiments, including grain size analysis of the soil, the Atterberg limit test, the specific gravity (Sp. Gr.) test, the unit weight test, and the permeability test, were performed in the laboratory. The results of these tests were used to identify the features of the subsoil in each of the locations. The values of cohesiveness, friction angle, and other metrics were determined with the help of a few correlations. After the soil samples had been collected, Atterberg limits and soil sample indices were calculated in the lab using the results. In addition, a mechanical study and a determination of the particle size distribution of the coarse-grained soils were carried out. These were conducted using sieve analysis (for particle sizes >0.074 mm in diameter) and hydrometer analysis (for particle sizes <0.074 mm in diameter).

Fig. 2 Location of collection of samples

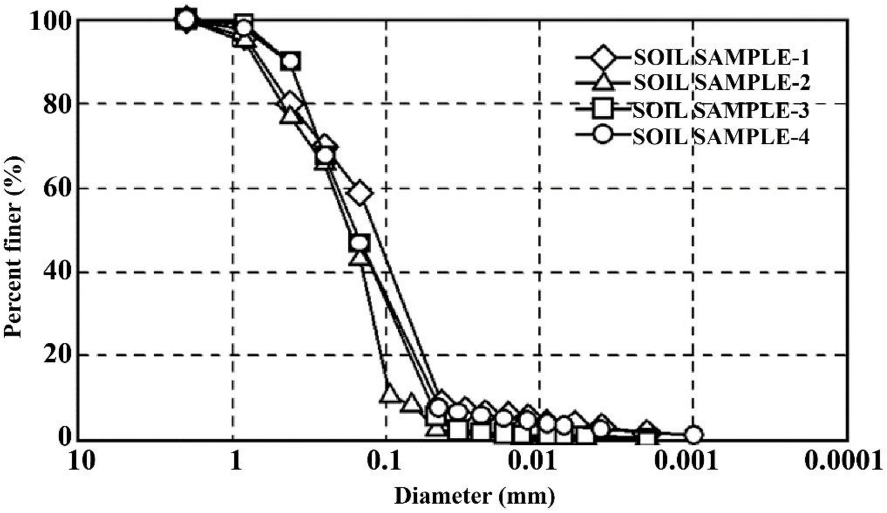


Fig. 3 Grain size distribution curve for different soil samples

The result indicates the soil samples range from very fine to medium grain sand consisting of medium (27%) to fine grain (47%) with moderate amounts of silt and clay (~25%). The soil profile of Sample-1 consists of 200 sieves passing=21% (< 50%). Soil classification using the USCS Chart is SC. The soil types for Samples 02, 03, and 04 are identical when using the flow chart for classifying coarse-grained inorganic soils and are SP-SC poorly graded sand with clay (or silty clay). The tabular representation of the laboratory test results would make it easy to take a quick look at the properties of the soil samples. An overview of the collected data is shown in Table 1, and further inferred soil parameters for numerical modeling are represented in Table 2.

Table 1. Laboratory tests result summary

Sl. No.	Sp. Gr. (G_s)	Unit Weight $\gamma_{sat}(\mathbf{KN/\ m^3})$	Atterberg limits			USCS Soil type
			Liquid limit (%)	Plastic limit (%)	Plasticity Index (%)	
S-1	2.64	19.48	26	14	12	SP-SC
S-2	2.65	19.48	33	17	16	SP-SC
S-3	2.64	19.48	-	-	-	SP-SC
S-4	2.64	19.48	27.86	20	7.86	SP-SC

Table 2. Soil properties for modeling

Sample No.	Unit Weight γ_{sat} (kN/m^3)	Shear Strength Parameters		Permeability, k (m/s)	Modulus of Elasticity, E (kN/m^2)	Poison's ratio, μ
		Cohesion, c (kN/m^2)	Frictional angle, $\varphi°$			
S-1	19.48	11	31	$\mathbf{5.05 \times 10^{-5}}$	$\mathbf{8.0 \times 10^{4}}$	0.35
S-2	19.48	11	31	$\mathbf{5.05 \times 10^{-5}}$	$\mathbf{8.0 \times 10^{4}}$	0.35
S-3	19.48	11	31	$\mathbf{5.05 \times 10^{-5}}$	$\mathbf{8.0 \times 10^{4}}$	0.35
S-4	19.48	11	31	$\mathbf{5.05 \times 10^{-5}}$	$\mathbf{8.0 \times 10^{4}}$	0.35

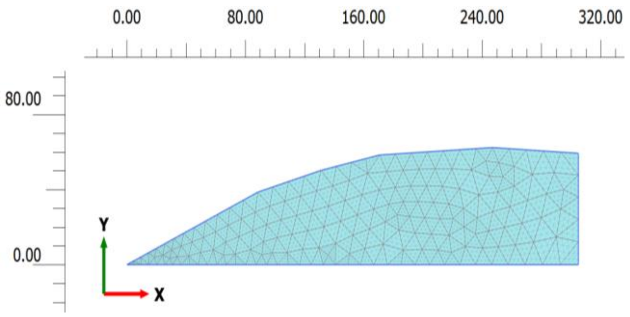


Fig. 4 Geometry of the full slope

3. Modelling

The selected slope was analyzed using both FEM and LEM to determine the most probable failure surface by evaluating the critical factor of safety. The use of computer-aided tools has made slope modelling and analysis faster. Hence, the incorporation of two-dimensional computer-based programs, PLAXIS-2D and Slide v 6.0, was done to perform the stability analysis based on predefined considerations and slope boundaries. Basically, the Slide v 6.0 program, which bases its analysis on the limit equilibrium method, was used for the limit equilibrium analysis of the slope. The ultimate outcome was calculating the factor of safety (FOS). Whereas for FE analysis, PLAXIS-2D was used to perform safety analysis using the strength cases, the construction of the slope geometry and assignment of the material properties, including soil parameters, was initially done for modelling. Origin was set at the slope toe and lower left boundary for LE and FE analysis, respectively. Table 2 provides a list of the engineering characteristics of soil assigned in this model, and Fig. 4 depicts the whole slope's geometry. The model's maximum height was considered 62.5 meters with an average slope angle of 26^{o}.

3.1. Limit Equilibrium Method (LEM)

The limit equilibrium technique is the most widely used conventional slope stability analysis method. This method has various applications with different boundary considerations and underlying assumptions. But all these versions commonly assume the shear strength along failure planes is directed by the linear (Mohr-Coulomb) or non-linear relationship with its normal stress on the failure surface. But one of the most common variations is the use of Terzaghi's theory with further additional consideration of effective stresses with pore water pressures and strength parameters (effective cohesion and angle of internal friction of soil). Among different available methods, the Ordinary Method of Slices (OMS) is one of the widely used methods where the soil masses are discretized into small vertical slices for analysis. Though the variations in slices, interface locations and boundary considerations may result in variations in analysis results, these can be optimized using numerical optimization techniques. For conducting slope behavior analysis, critical slope surfaces are considered for the lowest value of factor of safety (FOS) from a range of values. Hence, for numerical optimization, Slide v 6.0 software adopting the limit equilibrium (perfectly plastic Mohr-Coulomb model) concept with optimized critical slip surface determination can be used to determine the minimum factor of safety (FOS). Besides the Ordinary Method of Slices (OMS), used other different approaches are Bishop Simplified Method and the Spencer method.

To conduct this analysis in Slide v 6.0, the boundary of the model was constructed using the coordinates given previously (Fig. 4.). Once the boundary was made, the model must be imputed with material properties. Since there was no loading above the ground, the field stress must be set as gravity, and the actual ground surface must be selected. The model's boundary could be set in which part it would be deformed or affected by load. Since it was slope analysis where the analysis only occurs on the surface of the slope, all the boundaries should be set in restrained, except the surface of the slope. The slope should be set in free strain. After that, the slip surface was determined manually by the modeler. The number of trials was given until it reached the lowest safety factor.

Table 3. Input Parameters

Parameter	Value	Unit
Unit Weight,γ_{sat}	19.48	$(\boldsymbol{KN/m^3})$
Cohesion, c	11.00	$(\boldsymbol{KN/m^2})$
Frictional angle, $\boldsymbol{\varphi}$°	31.00	°
Permeability, k	$\mathbf{5.05 \times 10^{-5}}$	$(\mathbf{m/s})$
Modulus of Elasticity, E	$\mathbf{80 \times 10^{3}}$	$(\boldsymbol{KN/m^2})$
Poison's ratio, µ	0.35	-

3.2. Finite Element Method (FEM)

Limitations of LE methods of its predefined failure surface were overcome by introducing the finite element (FE) method with an independent consideration of shape and failure positions. This huge advantage over LE methods increased the popularity and acceptance of the finite element (FE) method. This also enables tracking the global stability followed by shear strength reduction towards incremental failure. Geotechnical applications have been widely solved by 2D finite element (FE) analysis rather than 3D FE analysis due to more computational requirements and time consumption. Especially the 2D slope stability analysis is more conservative than 3D [46] since the FOS obtained from 2D is usually smaller than that obtained from the 3D analysis.

By principle, the finite element method calculates each element inside the model. These elements are called mesh. In this study, the adaptive meshing technique with 15-node triangular elements was used based on the observation that it has the fastest convergence yielding the precise location of the failure slip surface and requires a smaller number of elements to achieve the same level of accuracy [45].

The model's geometry was made using the coordinate given previously. The geometry itself is the boundary of the model, which mean all calculation would be done inside the boundary. Input parameters (Table 3) were obtained from laboratory testing and analysis. For material modelling, the Mohr Coulomb model was used because FEM, in conjunction with an elastic-perfectly plastic (Mohr Coulomb) method, has been shown to be a reliable and robust method for assessing the factor of safety of slopes [7].

After generating the mesh, since there was no loading above the ground, the field stress must be set as gravity, and the actual ground surface must be selected. The model's boundary could be set in which part it would be deformed or affected by load. Since it was slope analysis where the analysis only occurs on the surface of the slope, all the boundaries should be restrained except the surface of the slope. The slope should be set in free strain. The model would become as shown in Fig. 4. After all the parameters were set, the calculation was performed.

3.3. Input Parameters

The engineering properties of the soil assigned in this model are listed in Table 3. The same materials were used in both modelling methods. Fig. 4 shows the whole slope's geometry. The model has a maximum height of 62.5 meters and an average slope angle of 26º degrees.

4. Results and Discussion

To delineate the stability calculations and improve the knowledge about stability distributions and their temporal variations, the global Factor-of-Safety (FOS) created the requirement of introducing an expectation value for the slip risk, the global Factor-of-Safety (FOS). The results of both analyses are shown below.

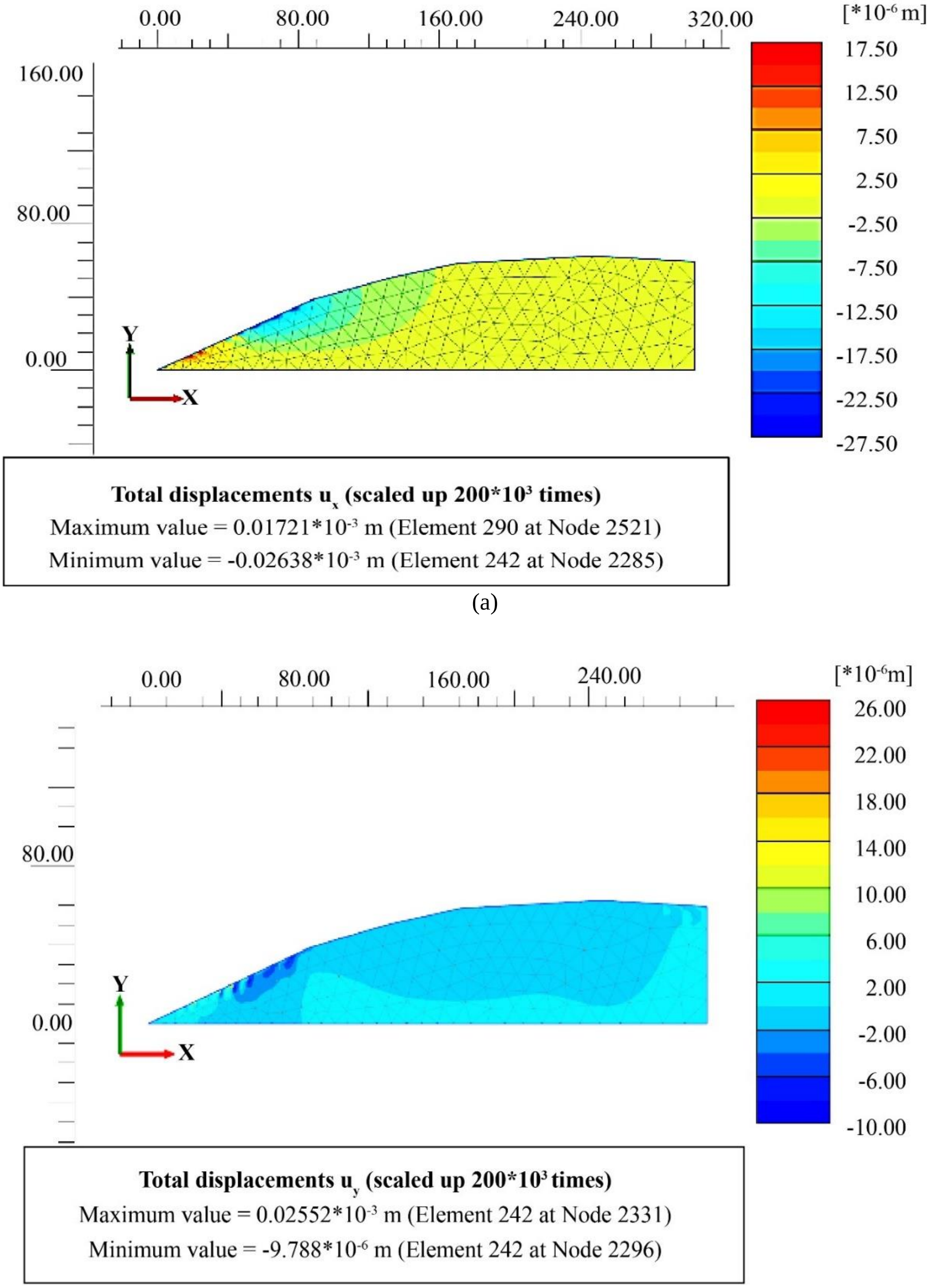
4.1. Finite Element Method

The analysis used a triangular 15-noded fine mesh element from a plane strain model. The critical Strength Reduction Factor (SRF) or Factor of safety using PLAXIS 2D was 1.674 in Fig. 7(b). The result of the modelling showed that the critical surface of failure seems to be located between 10–45 meters. Fig.7(b). shows the critical surface of failure. The horizontal and vertical displacements are shown in Fig. 6(a) and Fig. 6(b). The total displacement of the slope was also negligibly shown in Fig. 7(a) was 3 cm. (Measured perpendicular from the ground surface). So, it can be inferred from the analysis result that greater stability is prevailing in field conditions.

4.2. Limit Equilibrium Method

The principle of the limit equilibrium method was to divide the surface failure into a number of slices. Each slice had a different value of force.

Several trials must be conducted to determine the most significant failure surface with the lowest level of safety. These trials were helped by computer calculation so it could be done faster using SLIDE V.6.0. This analysis provided different results from FEM analysis.



(a)

(b)

Fig. 5 Maximum shear strain of the full slope model (a) Horizontal displacements and (b) Vertical displacements.

Different methods yielded different failure surfaces and factors of safety (Fig. 8). In full slope modelling, the Ordinary method of slices (OMS) showed a factor of safety of 1.64. Bishop's simplified method calculated the factor of safety of 1.64. Spencer's method showed a factor of safety of 1.66.

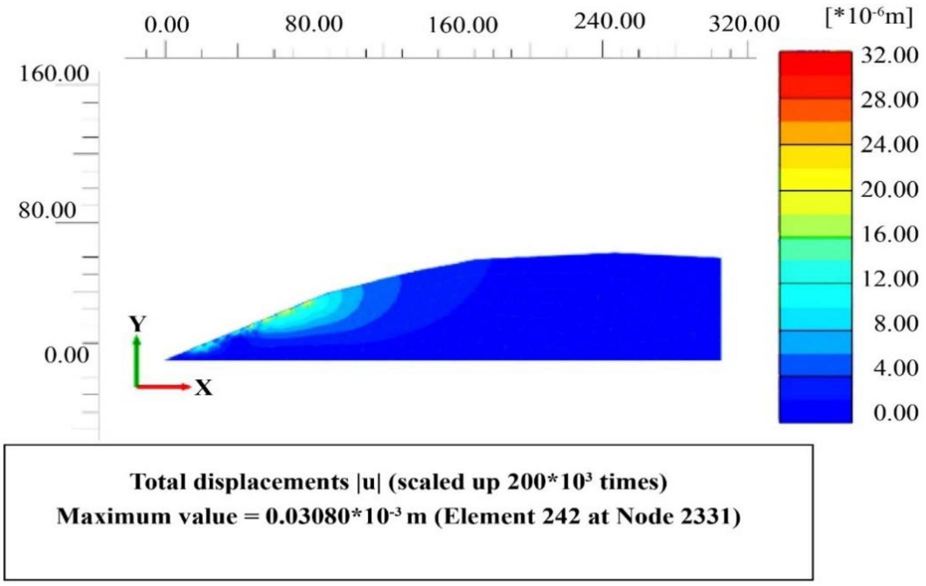


Fig. 6 Total displacement

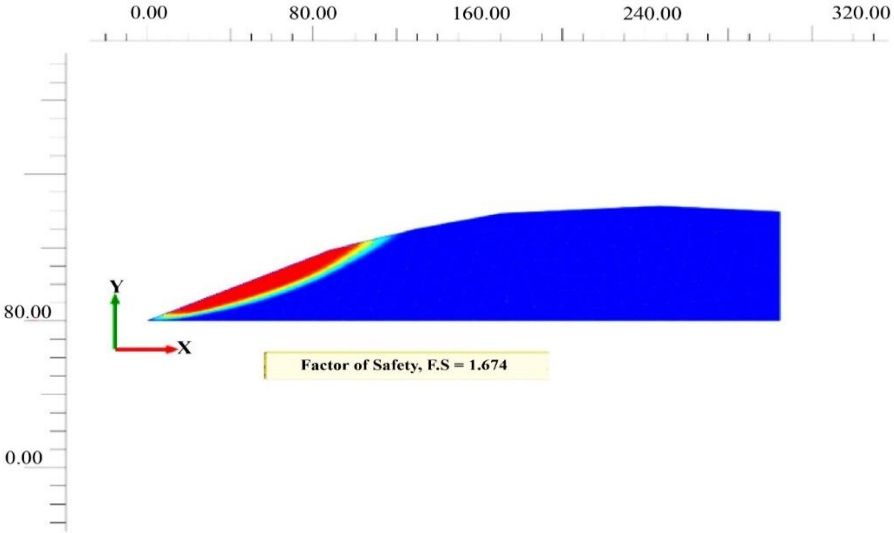
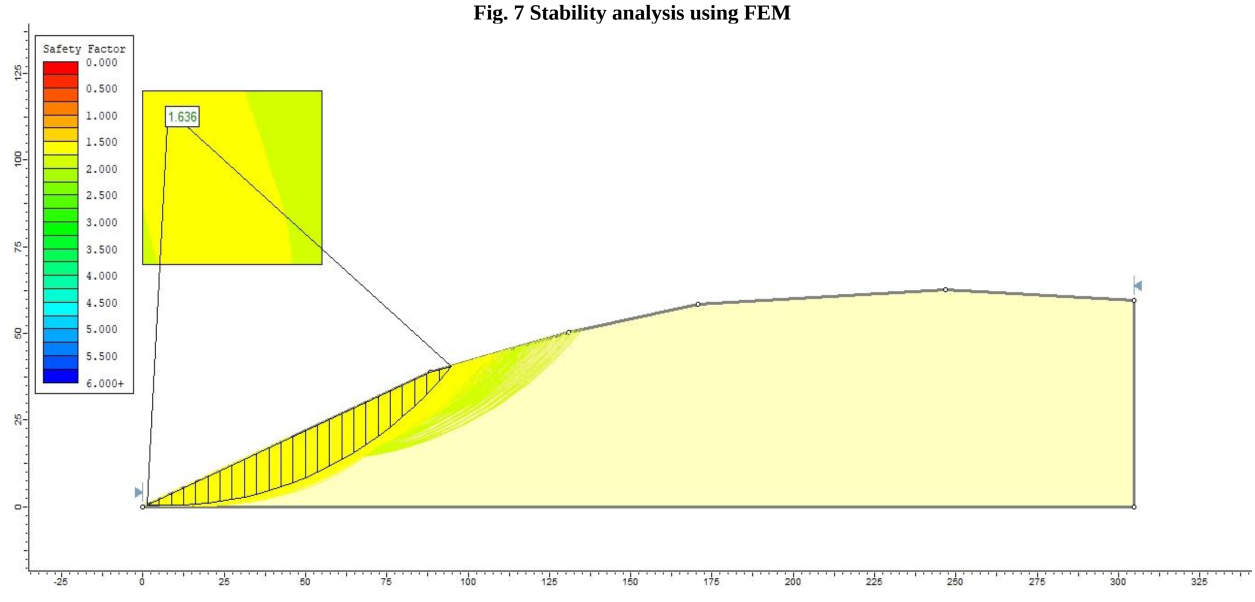
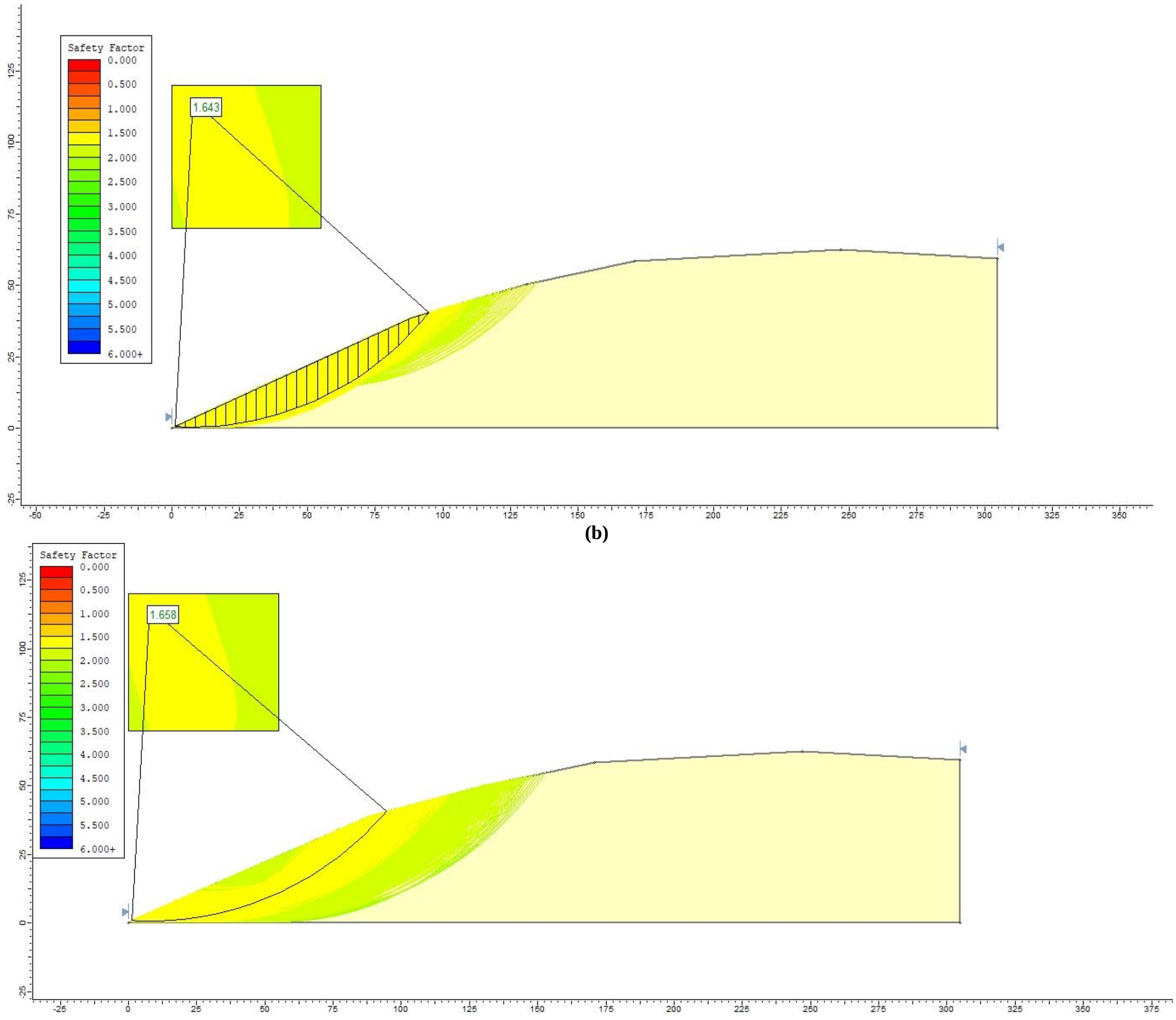


Fig. 7 Stability analysis using FEM



(a)



(b)

(c)

Fig. 8 Limit Equilibrium Analysis of full slope (a) Ordinary Method of Slice and (b) Bishop Simplified Method, (c) Spencer's Method

The result of all analyses is summarized in Table 4. It was found that initially, the slope was stable with dry conditions (FOS > 1.0).

Table 4. The factor of safety of slope analysis

Method of Analysis	Factor of Safety
Finite Element Method	1.674
Ordinary Method of Slices	1.64
Bishop's Simplified Method	1.64
Spencer's Method	1.66

4.3 Sensitivity Analysis

Sensitivity analysis was performed on key slope geometry and soil characteristics for the specified critical slope segment. Alterations to FOS have been analyzed by first adopting different slope geometries. Subsequently, the effect of varying cohesion and angle of internal friction, which is soil's key shear strength properties, was evaluated. Additionally, a single graphic depicting the slope's behavior under varying conditions of slope geometry and soil characteristics has been created. Non-linear fitting of data points resulting from analyses and their tentative gradients has been used to illustrate slope behavior and safety, for example.

The PLAXIS-2D program (a finite element-based application) was utilized to carry out this study's goals. The soil parameters of the uniform slope were taken under consideration, and they were assumed to be in a drained condition. In Table 5, the range of values used to analyze the numerical model:

From a starting height of 14 m, the slope height was progressively reduced to 6 m to examine the slope's stability and failure behavior as a function of the geometry. The toe was considered to be below the water table.

Slope with different inclinations (Table 5) were modelled for finite element analysis in Plaxis-2D and using Limit Equilibrium Method (LEM) in Slide v 6.0

Table 5. Geometric and soil properties used in the numerical model of this study

Slope Geometry		Shear Strength Parameters	
Height (m)	Slope Angle (°)	Cohesion, c($\boldsymbol{KN/m^2}$)	Frictional angle, $\boldsymbol{\varphi}$°
14	45.0	15	35
12	42.5	13	31
10	40.0	11	29
8	37.5	10	27
6	35.0	9	-
-	30.0	8	-

Table 6. Factor of safety (FOS) on different slope heights

Slope Height (m)	FOS for 42.5^0	
	FEM	LEM
14	1.14	1.23
12	1.22	1.44
10	1.30	1.52
8	1.42	1.67
6	1.62	1.88

Table 7. Factor of safety (FOS) on different slope angles.

Slope Angle (°)	FOS for 14m height	
	FEM	LEM
45.0	1.06	1.15
42.5	1.14	1.27
40.0	1.18	1.33
37.5	1.29	1.42
35.0	1.38	1.53
32.5	1.58	1.62
30.0	1.59	1.67

At a rate of 2 meters per iteration, the first model gradually reduces the slope's height from 14 meters to 6 meters (Table 6). In the second model, the height is held constant at 14 m while the slope angle is progressively reduced, changing the horizontal length from 450 to 300 (Table 7). The third and final model simultaneously reduces the slope's height and angle. Figures 9 and 10 depict the model results. The area of the failure mass decreased, and the transition from toe slide to slope slide was found in both analyses as the angle of the slope increased. For slope angles less than 300 ($\beta < 30°$), the effect of slope inclination on slope stability is observed to become nearly saturated.

In addition to the slope geometry, the influence of the slope stability with the variations in strength parameter c was inspected. The corresponding FOS values were calculated, thereby obtaining the influencing mechanism of c on FOS at different height and slope angle variations in Fig. 12, 13, 14, and 15, respectively. With the increase in cohesion, the strength increases, resulting in the overall increment in the stability of the slope at different rates with respect to different heights and slope angles.

Additionally, in every example of slope geometry alteration, the influence of adjustments in another strength parameter called was also evaluated. The result was plainly observable: an improvement in slope stability (Fig. 11.). This is because an increase in the internal friction angle causes the packing to become denser, increasing the shear strength.

Both the results of different cases of variations in soil strength parameters also comply with the relation proposed by [42], an interesting phenomenon of relatively greater influence of the angle of internal friction, φ than cohesion, c, on slope stability at lower slope inclination. Following that, the curves in Fig. 12 represented the higher contributions of cohesion to the Factor of Safety (FOS) than the angle of internal friction, φ, at a slope angle of 35°. Furthermore, it can also be observed from the figures representing greater slopes of the c curve, especially for steep slopes than 35° [Fig. (12–15)]. Hence, the conclusion can be made that the slope difference between the c and φ curves is more significant for slopes with higher inclination angles. In short, following the increment in the slope angle θ, cohesion c has the highest contribution to the shear strength behavior of the clayey sand slope.

Similarly, it can be inferred that the φ-dominated behavior prevails for the smoother gentle slope producing a greater sliding surface.

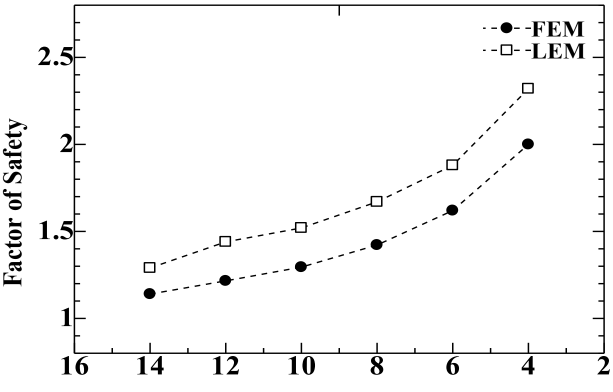


Fig. 9 Factor of safety (FOS) versus slope height using FEM & LEM.

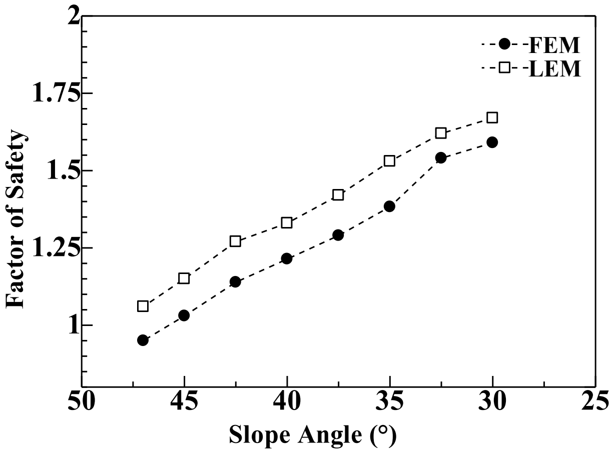


Fig. 10 Variations of a factor of safety (FOS) at different slope angles (β).

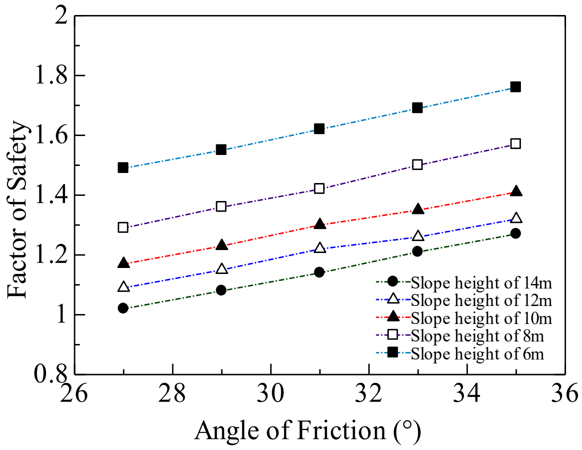


Fig. 11 Variation of a factor of safety (FOS) at a different angle of friction (φ°).

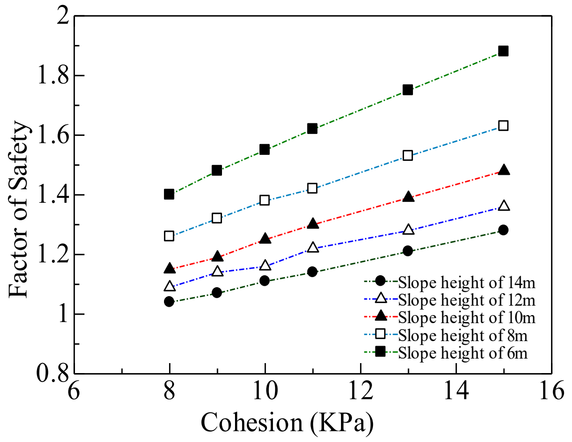


Fig. 12 Variations of the factor of safety (FOS) with cohesion (c) at different heights

Table 8. The factor of safety (FOS) on simultaneous variations of both slope height and angle

Slope Height (m)	Slope Angle (°)	V: H	FOS
12	45.0	1.00	1.14
12	42.5	0.92	1.20
12	40.0	0.84	1.25
12	37.5	0.77	1.36
12	35.0	0.70	1.43
12	32.5	0.64	1.55
12	30.0	0.58	1.67
10	45.0	1.00	1.21
10	42.5	0.92	1.29
10	40.0	0.84	1.37
10	37.5	0.77	1.45
10	35.0	0.70	1.55
10	32.5	0.64	1.66
10	30.0	0.58	1.76
8	45.0	1.00	1.36
8	42.5	0.92	1.42
8	40.0	0.84	1.50
8	37.5	0.77	1.59
8	35.0	0.70	1.68
8	32.5	0.64	1.79
8	30.0	0.58	1.91
6	45.0	1.00	1.55
6	42.5	0.92	1.64
6	40.0	0.84	1.70
6	37.5	0.77	1.78
6	35.0	0.70	1.89
6	32.5	0.64	2.00
6	30.0	0.58	2.15

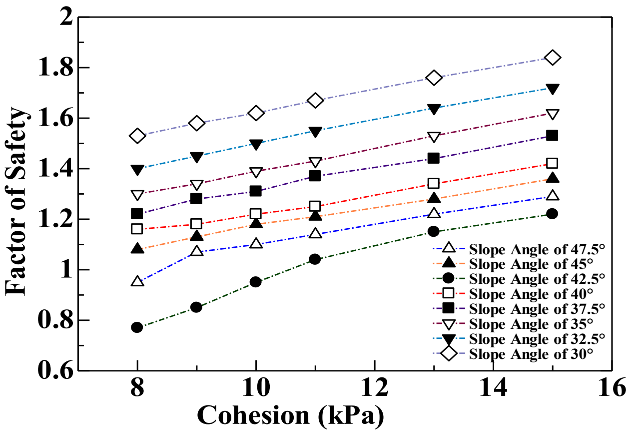


Fig. 13 Variations of the factor of safety (FOS) with cohesion (c) at different slope angles (at height=12 m)

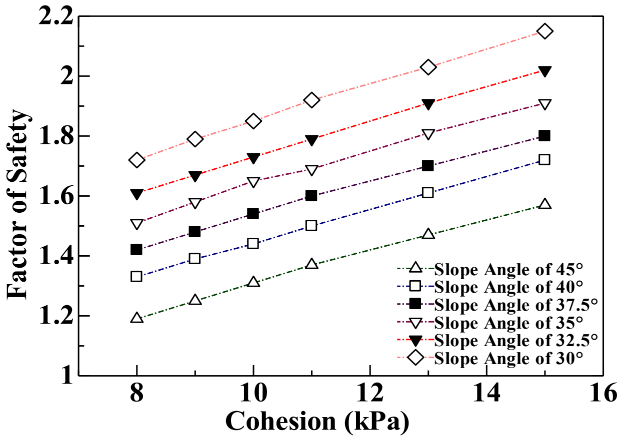


Fig. 14 Variations of the factor of safety (FOS) with cohesion (c) at different slope angles (at height = 8 m)

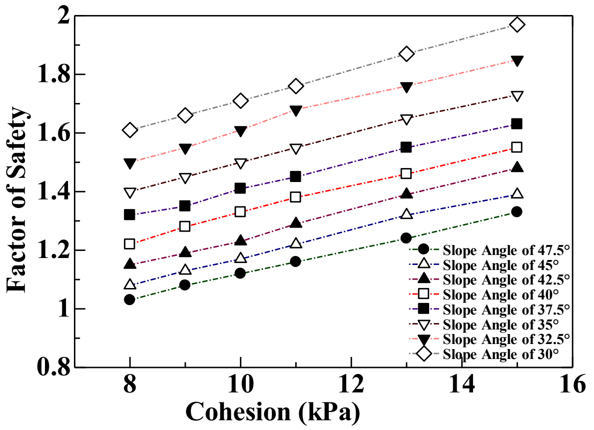


Fig. 15 Variations of the factor of safety (FOS) with cohesion (c) at different slope angles (at height =10 m)

5. Conclusion

This research article's objective was to investigate potential failure mechanisms of clayey sand slope soil and make comparisons between them using LEM and FEM analysis. As a result, the probable failure envelope was investigated, and displacements were measured in response to changes in sensitive strength parameters. The fact that in more general content besides the theory behind governing equations, the constitutive model predominates in the comparison of traditional limit equilibrium and highly accepted finite element method, along with their respective perfections in slope behavior forecasts, is a significant factor. The most important findings from this research have been categorized into the followings:

From the entire slope analysis, it is learned that the minimum safety factor lies between 1.63 and 1.71, with the FOS value obtained from the ordinary slice method being the lowest of the investigated approaches. As a result, under typical conditions, the stability of the chosen slope may be guaranteed by the findings of the calculation.

Results from both analysis techniques fell within a 90% confidence interval; however, the FEM reveals a larger FOS value because of its more precise calculations and realistic assumptions. It holds true even when evaluating the slope of a variety of geometry.

The soil is clayey sand with a permeability of 5.05×10^(-5) m/s. So the earth is not completely clay. When it rains heavily and for an extended period of time, the soil may be able to store enough water in its pores to temporarily alter the strength characteristics, causing the total FOS of the soil mass to decrease. When water level fluctuations affect the strength parameters, the FOS may drop dramatically, revealing a decline in stability or, in extreme circumstances, an impending instability and slope failure.

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