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Study of Slope Stability Using the Bishop Slice Method: An Approach Combining Analytical and Numerical Analyses

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Abstract

The importance of slope stability in civil engineering cannot be underestimated, as failure of these structures can result in significant damage to downstream infrastructure and property. In this study, we used the Bishop slice method, combining both an analytical approach and a numerical approach using the SLOPE/W module of the Geostudio 2018 R2 software. The results obtained from these two methods showed that increasing soil cohesion helps to improve slope stability. The safety coefficients obtained by the analytical method vary between 0.621 and 1.422, while those obtained by the numerical method vary between 0.622 and 1.447, for cohesion values ranging from 4 kPa to 20 kPa. The results obtained by these two methods show a linear relationship between the safety coefficients and soil cohesion. The equation of the analytical method is $y = 0.0496x + 0.4407$, while that of the numerical method is $y = 0.0512x + 0.4357$. The results of the analytical approach indicate that a safety coefficient of 1.5 is reached when the cohesion reaches a value of 22 kPa, while the numerical approach shows a safety coefficient of 1.5 reached at a cohesion of 21 kPa. The difference between these two cohesion values can be explained by the number of slices used, which is smaller in the analytical method. However, the equation derived from the analytical method can be used as a general guide to assess the evolution of the safety coefficient of an overloaded slope in long-term behaviour with an increase in cohesion. However, it is important to stress the importance of verification using specialised software based on the finite element method.

Keywords

Slope, Stability, Safety Factor, Cohesion

1. Introduction

Embankment stability is a crucial issue in civil engineering, as demonstrated by several sources. Slope stability is a topic of great importance in civil engineering, as slope failures can cause considerable damage to infrastructure and downstream properties [1]. Slope stability is a worldwide problem which above all affects people's safety [2]. [3] determines the factor of safety (FOS) of slopes located at Pahang Matriculation College. The slope stability is always considered crucial, as even slight failures can cause monetary losses and harm to human lives [4]. The problem of slope stability is topical not only for evaluating existing slopes but also for implementing new slopes or excavations [5]. Geotechnicians, both practitioners and researchers are concerned about the stability of earth structures such as cuttings, embankments, and dikes [6]. Slope failure has been a major cause of human and material losses, leading to extensive research in this field. Therefore, analyzing slope stability is an important parameter in the design of road embankments to ensure stable and safe construction [7]. Many authors have addressed the issue of embankment stability, as shown by references Chapter 18 of this document [8] is dedicated to the analysis of stability. In 1996, [9] discusses the construction of embankments on organic soils. Some studies demonstrate the potential of satellite interferometric Synthetic Aperture Radar (inSAR) to identify precursors to catastrophic slope failures [10], while others use Pseudostatic analysis to analyze slope stability [11]. The effect of spatial variability of soil properties, slope inclination, and excitation characteristics on the development of permanent displacements is investigated using random fields created by the Local Average Subdivision method [12]. Additionally, studies conclude that the factor of safety (FS) of a slope can also be computed with FLAC by gradually reducing the soil shear strength until failure occurs, using the shear strength reduction technique (SSR) [13]. The purpose of the study was to use both limit equilibrium methods (LEMs) and numerical simulations (finite element method (FEM)) to understand the common factor imposing the selected slope into slope instabilities [14]. A number of studies have been carried out to gain a better understanding of slope stability. These include slope stability analyses using the finite element method [15]. The stability analyses are carried out by the FEM [16], research focusing on slope stability in geotechnical engineering, and a study using geographic information systems (GIS) to map landslide susceptibility [17]. The aim of these studies is to increase knowledge of slope stability and to develop tools and methods for assessing and preventing the risks associated with landslides. It is widely recognised by various sources that engineers need tools for analysing slope stability. For example, [4] emphasise the importance of slope stability analyses to ensure the safety of people and infrastructure. Similarly, [18] indicates that slope stability analysis tools are essential for assessing the risks of ground movement and designing appropriate protection measures, as does [19]. These tools include analytical and numerical methods, such as limit analysis and the finite element method.

Analytical methods play a key role in assessing slope stability. They are based on mathematical equations derived from soil mechanics and are particularly suitable for analysing simple, homogeneous slopes. However, other sources emphasise the importance of numerical methods for dealing with more complex situations, in particular the effects of run-off water and erosion on slope stability [20] [21] conducted slope analsis by using finite-element software. [22] conducted numerically using 2D and 3D limit equilibrium method (LEM) utilising the Slide program by Rocscience. [23] proposed a new method to determine the minimum slope safety factor which is the determination of slope safety factor with analytical solution and searching critical slip surface with Genetic-Traversal Random Method.

Although analytical methods are often used for simple, homogeneous slopes, they have limitations for complex, heterogeneous slopes. According to Bishop *et al.* (2000), in such cases numerical methods are preferred as they use finite element models to simulate soil and rock behaviour under real loading conditions, allowing more accurate analysis of slope stability.

It is important to note that numerical methods can be costly in terms of time and resources, and their reliability can be affected by the uncertainties associated with the modelling parameters and site conditions. Indeed, numerical methods often require a significant amount of data and computation time to be implemented properly. Consequently, it is important for engineers to understand the limitations and assumptions of these methods when analysing slope stability.

The use of simulation software for slope stability analysis can introduce potential errors that must be taken into account. Errors can be caused by incorrect data entry, inappropriate parameter selection or misinterpretation of results. Therefore, users should be aware of these errors and take precautions to minimise their impact on the final results.

It is very important to compare the results of simulation software with those of analytical and numerical methods in order to guarantee the reliability of the results. This comparison allows the detection of manipulation errors such as incorrect data input, incorrect parameter settings or misinterpretation of results, which can lead to erroneous conclusions. By ensuring the reliability of the results, engineers can make more informed decisions to guarantee the stability of embankments and the safety of people and property located downstream.

The overall objective of this study is to add to the existing knowledge of slope stability assessment using Bishop's slice method, building on previous work with the slice method used by [1], [24] in Slope Stability Analysis Using Slice-Wise Factor of Safety, in order to improve the understanding and application of slope stability analysis methods. This study follows on from our study [1].

2. Method of Analysis

To carry out our study on slope stability, we chose to use the Limit Equilibrium Method, which is considered reliable and easy to use by many engineers [25] [26] The limiting equilibrium method is the traditional method used to determine the stability of slopes [27], LEM method is more often used by Engineers because they are more familiar than the FEM method [28]. Currently, both the limit equilibrium method and the strength reduction method are commonly used in slope stability calculations [29]. Modern limit equilibrium software is making it possible to handle ever-increasing complexity within an analysis. In this study, we applied the slice method because of the heterogeneity of the layers in our case study, which is composed of two materials: fill and foundation soil. The slice method involves dividing the embankment into several slices and then analysing the forces acting on each of these slices. Bishop's slice method [30], [7] is one of the most commonly used analytical methods for slope stability analysis, as discussed in [31]-[36]. It consists of dividing the slope into several vertical sections, whose equilibrium is analysed using the equations of soil mechanics. This method is particularly useful for heterogeneous slopes [37] as it allows variations in soil properties along the slope surface to be taken into account. Limit equilibrium method divides the soil in potential sliding surface into several blocks, and calculates stability coefficient by establishing static equilibrium equation and torque equilibrium equation of each block and whole sliding surface based on Mohr-Coulomb yield criterion [38]. To do this, we used Bishop's method, both analytically using MS Excel, and numerically using the specialised software Geostudio 2018 R2 [39] and more particularly its Slope/W module.

The slice method is widely used to analyse slope stability, particularly for complex, heterogeneous slopes, as it takes into account variations in soil properties along the slope surface by dividing it into several slices.

- Bishop's method

Figure 1 shows the slice with forces applied.

The general expression of the safety coefficient for all bands gives:

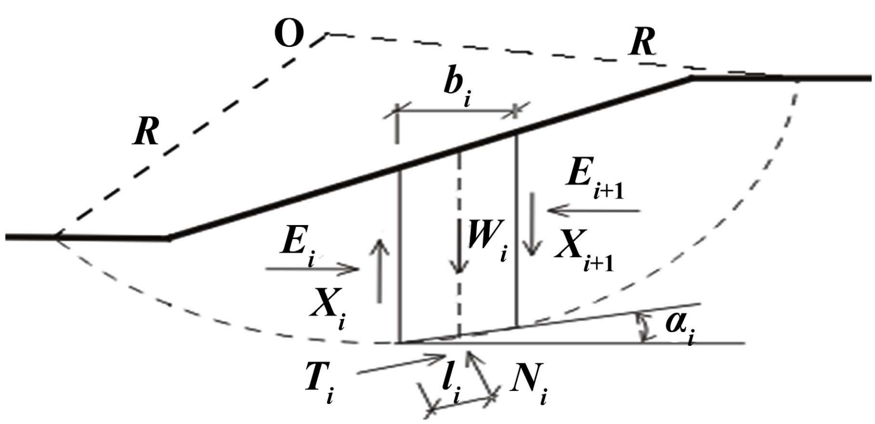

Figure 1. Slice with forces applied [1].

$$FS = \frac{\sum c_i l_i + (W_i - u_i l_i)\tan\varphi_i}{\sum W_i \sin\alpha_i \left[\cos\alpha_i + \frac{\sin\alpha_i \tan\varphi_i}{FS}\right]}$$

where i is the slot number.

This equation was first solved using the analytical method and then the Geostudio 2018 R2 software was used with the SLOPE/W module. A comparison is made between the two methods.

Case Studies

Analytical and numerical analysis techniques were used to assess stability, taking into account additional loads. The geotechnical characteristics and geometric configuration of the embankment were based on studies by [1].

Table 1 illustrates the geotechnical parameters of the soils.

The calculation is based on the following assumptions:

- ✓ Stable foundation 5 m deep;
- ✓ Addition of 6 m high silty sand backfill;
- ✓ The slope of the embankment is 71.57˚;
- ✓ The water level is 1.5 m above the ground level;
- ✓ Uniformly distributed load Q = 25 kpa at the head of the slope with an offset of 1.5 m from the edge.

Figure 2 represents the modelling of the embankment in Geostudio 2018 R2.

3. Results and Discussion

3.1. Analytical Method

Table 2 shows the Summary of preliminary calculations using the analytical method.

Table 3 shows the variation in the safety coefficient as a function of cohesion using the analytical method

Figure 3 shows the evolution of the safety factor as a function of cohesion.

Analysing the results obtained by the analytical method, it can be seen that the function obtained for the variation of the safety coefficient as a function of the cohesion of the slope soil is a linear and increasing function, with a value of =0.9977. This function is expressed by the equation y = 0.0496x + 0.4407. According to this function, to achieve a safety coefficient of 1.5 [40] [41]. For this slope, a cohesion of 21.35 may be 22 kPa, would be required.

Previous studies have shown that the Bishop method is significantly more accurate than the Fellenius method for assessing slope stability. This finding is of

Table 1. Geotechnical parameters [1].

Type of soil	Weight by volume	Cohesion	Friction angle
Silty sand	γ = 18KN/m^3	C = 04 kpa	φ = 25˚
Foundation soil	γ = 19 KN/m^3	C = 09 kpa	φ = 24.5˚

Couleur	Nom	Modèle	Poids volumique (kN/m³)	Cohésion' (kPa)	Phi' (°)	Phi-B (°)	Ligne piézométrique
	Foundation soil	Mohr-Coulomb	19	9	24.5	0	1
	Silty sand	Mohr-Coulomb	18	20	25	0	1

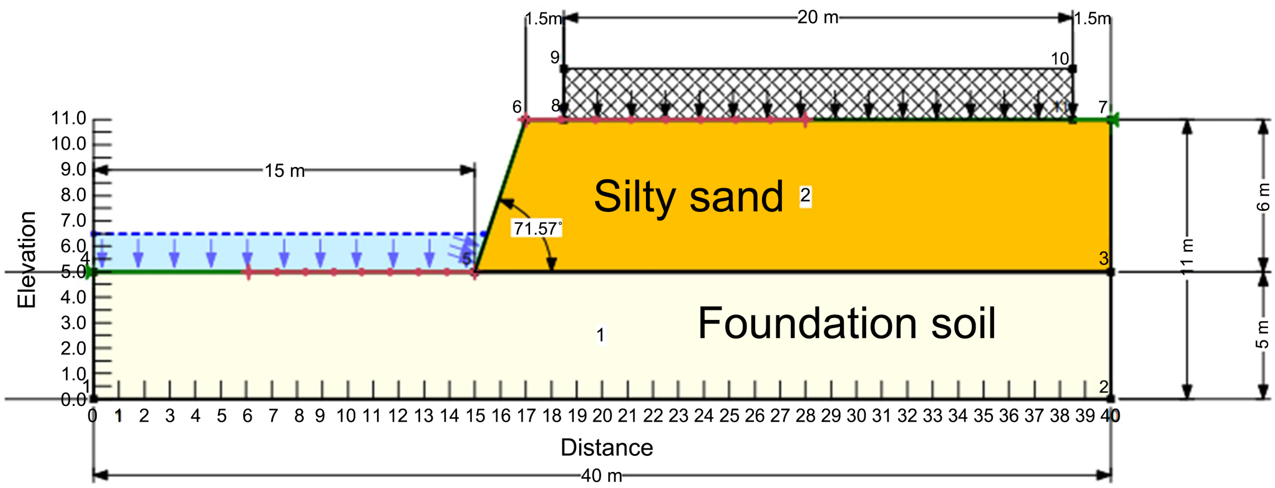

Figure 2. Modelling of the embankment [1].

Table 2. Summary of preliminary calculations.

Slice number	$\sin\alpha$	$\cos\alpha$	$N = w\cos\alpha$	$T = W\sin\alpha$	$c^* b$	$W\cos\alpha$-ul	$\tan\varphi$
1	0.745	−0.67	−18.49	20.65	4.8	−18.49	−0.733
2	−0.43	−0.9	−68.32	−32.37	4.8	−68.32	−0.733
3	−0.01	−1	−80.84	−0.716	4.8	−92.61	−0.733
	−0.01	−1	−6.031	0.053	4.8	1.7375	−0.733
4	−0.75	0.66	20.52	−23.33	4.8	24.288	−0.733
5	−0.75	0.14	1.459	10.57	4.8	−21.43	−0.733
6	0	1	−4.628	0	4.8	−17.36	−0.733
7	−0.65	−0.76	6.616	5.663	4.8	−2.325	−0.733

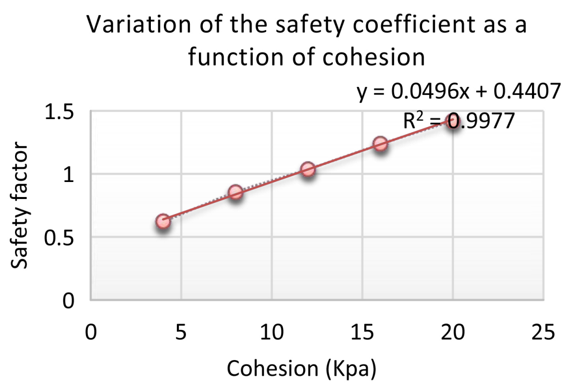

Figure 3. Curve showing the variation of the safety coefficient as a function of cohesion using the analytical method.

great importance as it underlines the advantage of the Bishop method over the Fellenius method in terms of accuracy and reliability of results.

More specifically, the Bishop method offers additional advantages over the Fellenius method in terms of taking more accurate account of the forces and moments of resistance mobilised in a slope. By using advanced analytical and numerical formulations, Bishop's method enables better modelling and a deeper understanding of slope stability mechanisms.

In general, if the factor of safety of a slope is within the interval between 0 and 1.0, the slope is actively unstable. The value over 1.0 indicates that the slope is considered stable [42] [43] [44].

3.2. Numerical Method

Table 4 presents the variation of the safety coefficient as a function of cohesion using the numerical method.

Figure 4 shows the evolution of the safety factor as a function of cohesion.

The function $y = 0.0512x + 0.4357$ obtained from the numerical analysis of the slope shows an increasing linear relationship between the safety coefficient and soil cohesion. This relationship is confirmed by the studies of [45], which show that the safety coefficient increases with increasing soil cohesion. Finally, the study [46] reviewed the effect of vegetation on slope stability and highlighted

Table 3. Variation of the safety coefficient as a function of cohesion using the analytical method.

Cohesion	$C = 4$ kPa	$C = 8$ kPa	$C = 12$ kPa	$C = 16$ kPa	$C = 20$ kPa
Bishop safety factor	0.621	0.858	1.038	1.239	1.422

Table 4. Variation of the safety coefficient as a function of cohesion using the analytical method.

Cohesion	$C = 4$ kPa	$C = 8$ kPa	$C = 12$ kPa	$C = 16$ kPa	$C = 20$ kPa
Bishop safety factor	0.622	0.862	1.059	1.259	1.447

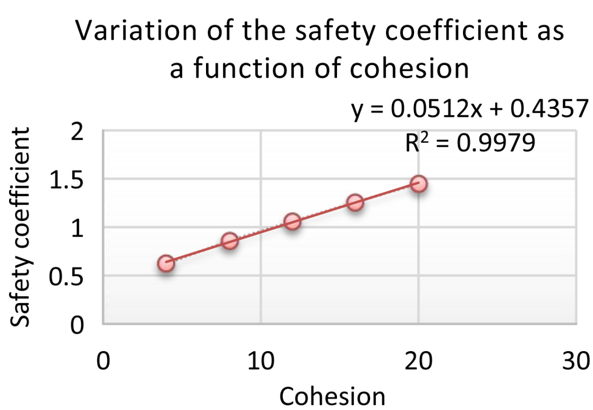

Figure 4. Variation of the safety coefficient as a function of cohesion using the numerical method.

that vegetation can improve soil cohesion and therefore contribute to slope stability.

Based on this function, we can deduce that a safety factor of 1.5 for this slope would require a cohesion of 20.79, or 21 kPa, which is consistent with the results obtained by the analytical method.

The results obtained in this study highlight the crucial importance of soil cohesion in slope stability [47].

4. Conclusions

In conclusion, this study verified the stability of an artificial slope with a surcharge in the presence of a water table using analytical and numerical methods. The safety coefficients obtained showed that soil cohesion has a significant impact on slope stability. The results of the analytical and numerical methods showed a difference due to the number of slices used in the analytical method. The results obtained may be useful for the design and construction of artificial embankments, taking into account surcharge conditions and the water table.

Our future perspectives would be to study the effect of anisotropy of soil mechanical properties on slope stability.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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