Civil Engineering Infrastructures Journal xx,xx
DOI: 10.22059/CEIJ.2023.362554.1945

Development and Evaluation of a Computer-Aided Educational Platform for Advancing Understanding of Slope Stability Analysis

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Received: 20/07/2023
Revised: 06/09/2023
Accepted: 02/10/2023

ABSTRACT: Computer-aided educational platforms are of paramount importance as they provide students and engineers with interactive and personalized learning experiences, catering to their individual needs and enhancing their academic growth. This study presents a novel computer-aided educational platform designed by the authors to enhance the understanding of slope stability analysis for young industrial engineers and civil engineering students. The platform is implemented in MATLAB, offering a user-friendly graphical interface and a robust framework. It facilitates a comprehensive investigation of landslides, encompassing crucial aspects such as circular slip surfaces and safety considerations based on the Bishop and Ordinary method of slices. Furthermore, it enables the determination of minimum safety factors for various methods applied to specific slopes. This paper provides a detailed exposition of each program function, including complete source code, to enhance comprehension of the underlying techniques. To ascertain its accuracy, a slope with given soil properties and geometry were modeled in the MATLAB code and the performance of the MATLAB code was benchmarked against Slide software, and it showed only 5 percent error which shows the accuracy of the developed program.

Keywords: Slope stability analysis, GUI, MATLAB, Bishop Method, Ordinary method of slices.

1. Introduction

Slope stability analysis holds significant importance in civil engineering as it ensures the safety and stability of slopes in geotechnical projects (Hajiazizi and Nasiri, 2019; Maleki and Aminpour, 2023; Kumar et al., 2023). However, comprehending the complex nature of slope stability analysis methods can be challenging for young industrial engineers and civil engineering students (Ghanizadeh et al., 2023; Afrazi and Yazdani, 2021; Mirzazadeh and Hajiazizi, 2020).

Various approaches have been employed in engineering education to establish effective learning platforms (Katsanos et al., 2014; Cavaleri et al., 2022). These platforms commonly leverage finite element software, encompassing both commercial codes such as ABAQUS (Hibbitt and Sorensen, 2001), FLAC (FLAC, 2000; Jamshidi Chenari, 2018), and PLAXIS (Brinkgreve et al., 2012), as well as open-source alternatives (Yang et al., 2004; Novák et al., 2014; Wang et al., 2014). Over time, computer-aided educational platforms have gained significant popularity in engineering courses due to their ability to enhance teaching and learning (Rezamand et al., 2021; Li et al., 2022; Rezazadeh Eidgahee et al., 2022; Shan et al., 2022). For instance, (Sonparote and Mahajan, 2018) introduced a JAVA-based platform to illustrate concepts of structural dynamics. Another noteworthy example is ABEL, an educational platform developed by (Katsanos et al., 2014), which employs MATLAB to acquaint students with soil-structure interaction problems. However, these software solutions often involve complex models that demand a solid grasp of the finite element method, posing challenges for undergraduate and postgraduate students. Consequently, there is a pressing need for a more accessible platform that can effectively assess slope stability while offering simplified interpretation options.

Despite various software solutions designed for slope stability analysis, many demand a significant learning curve and a deep comprehension of intricate mathematical models (Qi and Tang, 2018; Armaghani et al., 2020; Li et al., 2022; Armaghani et al., 2023; He et al., 2023; Fareghian et al., 2023). This presents a notable obstacle for young industrial engineers and civil engineering students still grasping slope stability analysis's fundamental principles. Moreover, existing platforms often lack user-friendly interfaces and simplified interpretation options, impeding the effective teaching and learning of slope stability concepts. Hence, there is an urgent requirement for an educational platform that bridges the gap between theoretical understanding and practical application, providing a more accessible and intuitive approach to slope stability analysis.

Furthermore, conventional educational methods in slope stability analysis primarily rely on theoretical lectures and manual calculations, which can be time-consuming and prone to errors. This approach restricts students' ability to visualize and explore various scenarios and comprehend the practical implications of slope stability analysis. By introducing a computer-aided educational platform, we aim to overcome these limitations and offer an interactive learning experience. The platform will empower users to conduct virtual experiments, visualize the impacts of different parameters on slope stability, and acquire a deeper understanding of the underlying principles through hands-on exploration.

The lack of comprehensive and readily available educational resources tailored to slope stability analysis further exacerbates the issue (Wang et al., 2019). While textbooks and research papers provide valuable theoretical knowledge, they often lack practical examples and real-world applications. Through developing a dedicated educational platform, we intend to furnish a valuable resource that amalgamates theoretical concepts with practical implementation. Including complete source code and detailed program functions in this paper will contribute to the existing body of knowledge in slope stability analysis and serve as a valuable reference for educators and researchers in the field.

Bishop method and Ordinary method are two of well-known methods in slope stability analysis in geotechnical engineering. The Bishop method, widely used in slope stability analysis, assesses the safety factor, and the Ordinary method divides a slope into multiple slices, enabling a more detailed analysis (Hasanipanah et al., 2015; Zolkepli et al., 2019; Fakharian et al., 2023; Dehghani and Mohajer, 2022). These methods have been incorporated into many platforms, offering users practical insights into their application and addressing safety aspects related to slope stability (Matsui and San, 1992; Gunawan et al., 2023).

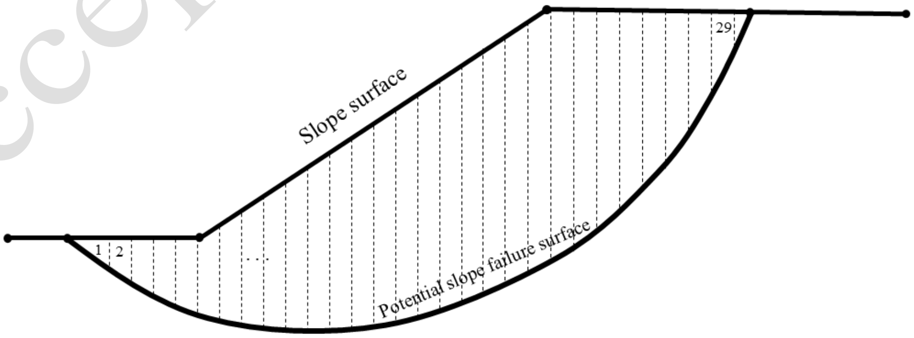
This study contributes to civil engineering education by introducing a computer-aided educational platform focused on slope stability analysis. Developed in the MATLAB environment, the platform provides an intuitive interface and incorporates the Bishop method and the Ordinary Method of Slices (OMS), offering comprehensive insights into slope stability analysis. The subsequent sections will delve into the methodology, results, and evaluation, followed by a discussion of the platform's strengths, limitations, and potential areas for improvement.

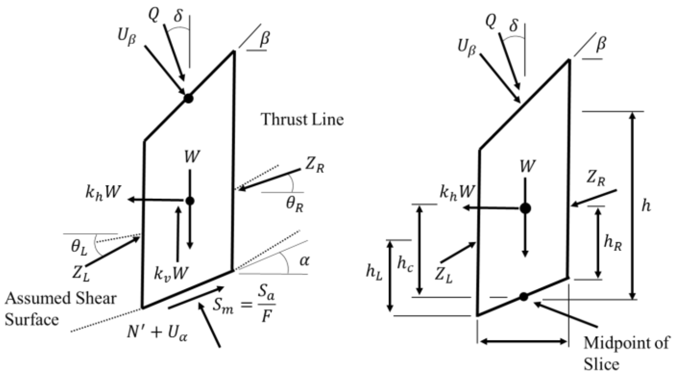
2. Methodology

2.1 Ordinary Method of Slices

The method known as the OMS pioneered the use of the slice technique for slope stability analysis (Hovland, 1977; Jiang and Magnan, 1997; Niromand et al., 2021; Tsang et al., 2023; Skentou et al., 2023). According to this approach, the collective inter-slice forces are assumed to align parallel to the base of each slice. However, it is essential to acknowledge that this simplifying assumption does not account for inter-slice equilibrium when adjacent slices possess different base inclinations. This limitation represents a significant drawback of the OMS, as it results in the calculation of inconsistent effective stresses at the base of the slices.

If the slice forces are resolved in a direction perpendicular to the base of the slice shown in Figure 1, then:





F = Factor of safety
S_a = Available strength = $C + N' \tan\varphi$
S_m = Mobilized strength
U_a = Pore water pressure
U_β = Surface water force
W = Weight of slice
N' = Effective normal force
Q = External surcharge
k_v = Vertical seismic coefficient
k_h = horizonral seismic coefficient

Z_L = Left interslice force
Z_R =Right interslice force
θ_L =Left interslice force angle
θ_R = Right interslice force angle
h_L = Height to force Z_L
h_R = Height to force Z_R
α = Inclination of slice base
β = Inclination of slice top
b = Width of slice
h = Average height of slice
h_c = Height to centroid of slice

Figure 1. Division of potential sliding mass into slices

$$\sum F_\alpha = N' + U_\alpha + k_h W\, sin\alpha - W(1-k_v)cos\alpha - \ U_\beta \cos{(\beta-\alpha)} - Qcos(\delta-\alpha) = 0 \quad (1)$$

The above equation may be arranged for N' as:

$$N' = -U_\alpha - k_h W\, sin\alpha + W(1-k_v)cos\alpha + U_\beta \cos(\beta-\alpha) + Qcos(\delta-\alpha) \quad (2)$$

With the Factor of Safety (FOS) against shear failure defined as F and assumed to be the same for all slices, the Mohr-Coulomb mobilized shear strength, S_m, along the base of each slice is given by:

$$S_m = \frac{C + N'tan\varphi}{F} \quad (3)$$

Where C and $N'tan\varphi$ are the cohesive and frictional shear strength components of the soil. The overall moment equilibrium of the forces about the center of the circular failure surface for each slice is given by:

$$\sum M_o = \sum_{i=1}^{n} [W(1-k_v) + U_\beta cos\beta + Qcos\delta]\, Rsin\alpha \\ - \sum_{i=1}^{n} [U_\beta sin\beta + Qsin\delta](Rcos\alpha - h) - \sum_{i=1}^{n} [S_m] R \\ + \sum_{i=1}^{n} [k_h W(Rcos\alpha - h_c)] = 0 \tag{4}$$

Where R = Radius of the circular failure surface

h = Average height of the slice

h_c = Vertical height between the center of the base slice and the centroid of the slice

The influence of the internal inter-slice forces has been excluded from this expression, as their resultant net moment will be zero. The above equation may be simplified by dividing throughout by radius to get

$$\frac{\sum M_o}{R} = \sum_{1}^{n} [W(1-k_v) + U_\beta\ cos\beta + Q\ cos\delta] sin\alpha - \sum_{i=1}^{n} [S_m] \\ + \sum_{i-1}^{n} \left[k_h W \left(Rcos\alpha - \frac{h_c}{R} \right) \right] \tag{5}$$

If the FOS is assumed to be the same for all slices, substitute equation (3) in equation (5) to give:

$$F = \frac{\sum_{i=1}^{n} (C + N' tan\varphi)}{\sum_{i=1}^{n} A_1 - \sum_{i=1}^{n} A_2 + \sum_{i=1}^{n} A_3} \tag{6}$$

Where A_1, A_2, and A_3 were defined as below:

$$A_1 = \left(W(1-k_v) + U_\beta cos\beta + Qcos\delta \right) sin\alpha$$

$$A_2 = (U_\beta sin\beta + Qsin\delta)(cos\alpha - \frac{h}{R})$$

$$A_3 = k_h W (cos\alpha - \frac{h_c}{R})$$

And N' is given by equation (2). This is the formulation that is often used to compute the FOS according to the assumption of the OMS.

2.2. Simplified Bishop Method

The simplified Bishop method employs the slice technique to discretize the soil mass and calculate the FOS. This approach ensures vertical force equilibrium for individual slices and achieves overall moment equilibrium around the center of the circular trial surface. Additionally, the simplified Bishop method assumes negligible shear forces between adjacent slices. Referring to the notation depicted in Figure 1, the overall moment equilibrium of the forces acting on each slice can be expressed as follows:

$$\sum M_o = \sum_{i-1}^{n} [W(1-k_v) + U_\beta cos\beta + Qcos\delta]\, Rsin\alpha \\ - \sum_{i=1}^{n} [U_\beta sin\beta + Qsin\delta](Rcos\alpha - h) - \sum_{i=1}^{n} [S_m]R \\ + \sum_{i-1}^{n} [k_h W(Rcos\alpha - h_c)] = 0 \tag{7}$$

Where R = radius of the circular failure surface

h = average height of the slice

h_c = vertical height between the center of the base slice and the centroid of the slice

The above equation may be simplified by dividing throughout by radius to get:

$$\frac{\sum M_o}{R} = \sum_{1}^{n} [W(1-k_v) + U_\beta\, cos\beta + Q\, cos\delta] sin\alpha - \sum_{i=1}^{n} [S_m] \\ + \sum_{i-1}^{n} \left[k_h W \left(Rcos\alpha - \frac{h_c}{R} \right) \right] \tag{8}$$

It is important to consider that the effective normal and pore pressure forces, which exert their influence on the base of the slice, do not impact the moment equilibrium expression as they align through the center of the circular surface. As a result, the application of Bishop's method for calculating the FOS is unsuitable for noncircular surfaces which should be considered.

If the FOS is assumed to be the same for all slices, substitute the Mohr-Coulomb criterion into equation (8) to give:

$$F = \frac{\sum_{i=1}^{n} (C + N' tan\varphi)}{\sum_{i=1}^{n} A_5 - \sum_{i=1}^{n} A_6 + \sum_{i=1}^{n} A_7} \tag{9}$$

Where A_5, A_6, and A_7 are defined as follow:

$$A_5 = \big(W(1-k_v) + U_\beta + Qcos\delta\big) sin\alpha$$

$$A_6 = (U_\beta + Qsin\delta)(cos\alpha - \frac{h}{R}) \tag{10}$$

$$A_7 = k_h W(cos\alpha - \frac{h_c}{R})$$

Next, forces are summed in the vertical direction for each slice to determine the effective normal force in the same manner as used for Janbu's method:

$$N' - \frac{1}{m_\alpha}[W(1-k_v) - \frac{C\ sin\alpha}{F} - U_\alpha cos\alpha + U_\beta cos\beta + Qcos\delta] \quad (11)$$

Where m_α is again given by:

$$m_\alpha = cos\alpha[1 + \frac{tan\alpha\ tan\varphi}{F}] \quad (12)$$

Equations (9) through (12) are the expressions that are used to calculate the FOS for circular surfaces according to the simplified Bishop method.

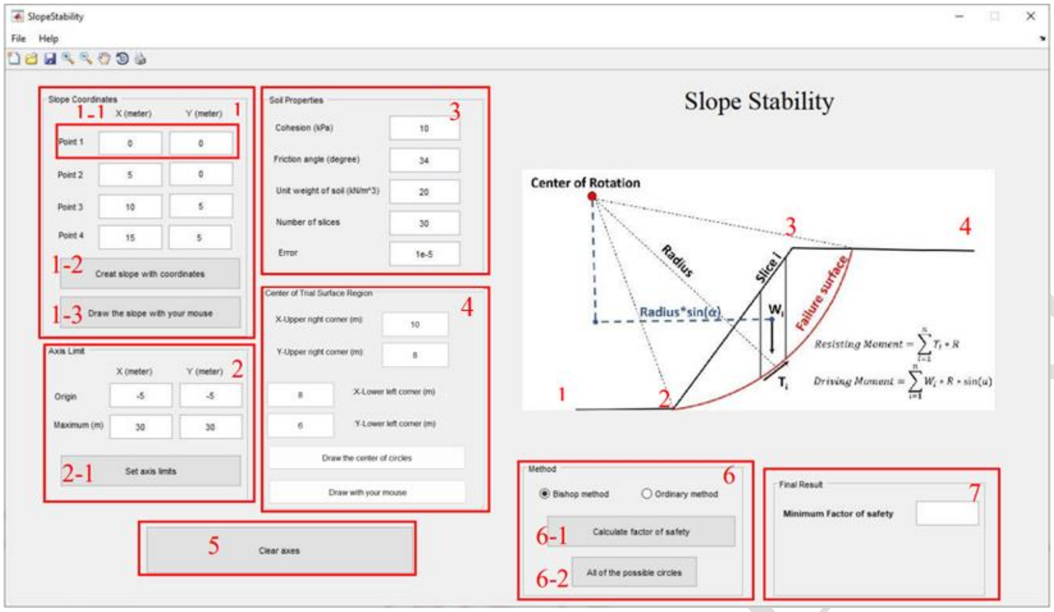
3. Platform interface

Upon launching the software, users are presented with a dialog-box titled "Slope Stability" (refer to Figure 2), which comprises seven distinct panels: "Slope Coordinates," "Axis Limit," "Soil Properties," "Center of Trial Surface Region," "Clear Axes," "Method," and "Final Results." These panels offer white boxes where users can input various values, culminating in the calculation of the final FOS based on the selected method and input values

In the "Slope Coordinates" panel, users enter the "X" and "Y" coordinates of the slope, delineating the points from 1 to 4, as depicted in Figure 2. Notably, the program allows users to draw the slope using mouse clicks to enhance usability. The "Axis Limit" panel enables users to specify the minimum and maximum values for the "X" and "Y" axes.

Within the "Soil Properties" panel, users input parameters such as cohesion, friction angle, unit weight of the soil, number of slices, and the desired error. Cohesion and friction angle represent intrinsic soil properties, while the number of slices determines the division of the failure surface into discrete segments. To explore potential failure surfaces and draw different circles, users define the "Center of Trial Surface Region" boundaries in panel 4.

Panel 5 is a convenient tool for clearing the axes and initiating the drawing of a new model. In panel 6, users select the desired method for calculating the safety factor, while panel 7 displays the minimum FOS achieved. The program's flowchart is depicted in the following picture. Figure 3 shows how it does work.



Slope Coordinates

	X (meter)	Y (meter)
Point 1	0	0
Point 2	5	0
Point 3	10	5
Point 4	15	5

Axis Limit

	X (meter)	Y (meter)
Origin	-5	-5
Maximum (m)	30	30

Soil Properties

Cohesion (kPa)	10
Friction angle (degree)	34
Unit weight of soil (kN/m^3)	20
Number of slices	30
Error	1e-5

Center of Trial Surface Region

X-Upper right corner (m)	10
Y-Upper right corner (m)	8
X-Lower left corner (m)	8
Y-Lower left corner (m)	6

$$Resisting\ Moment = \sum_{i=1}^{n} T_i * R$$

$$Driving\ Moment = \sum_{i=1}^{n} W_i * R * \sin(\alpha)$$

Method

● Bishop method ○ Ordinary method

Final Result

Minimum Factor of safety

Figure 2. Graphical user interface of the MATLAB code

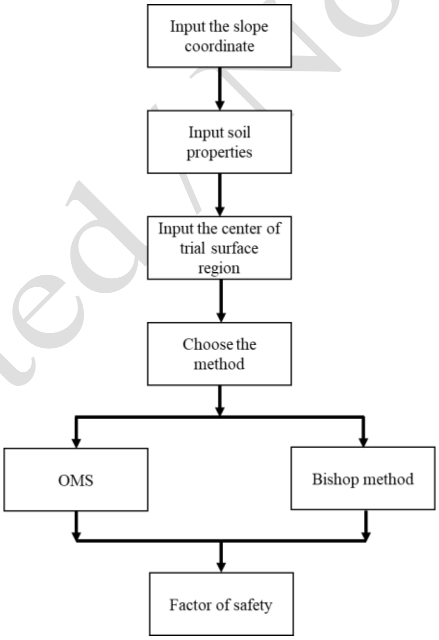


Figure 3. MATLAB procedure

4. The MATLAB code

Once the geometry of the slope and the Boundary of the Center of Trial Surface (BCTS) region are defined, the program identifies the minimum and maximum radii of potential failure circles within the specified boundary, as illustrated in Figure 4. The program systematically calculates the distances from each corner of the BCTS region to the four points defining the slope geometry to determine these radii.

With the distances determined, the program draws circles within the BCTS region, ranging from the minimum to the maximum radius. During this process, each point inside the BCTS region is considered a circle's center. The program systematically examines the circles for their intersections with the slope geometry. For this purpose, the program employs the "intersectionpoints" function to determine the coordinates of the points where circles intersect with the slope. It distinguishes between real and imaginary intersections, as a circle may intersect with an extension of a slope line that lies beyond our region of interest and is, therefore, irrelevant to our analysis. By considering only circles with at least two real intersections, the program ensures that the analyzed circles are plausible representations of potential failure surfaces.

For each circle that meets the intersection criterion, the program calculates the properties of the associated profile, including each slice's width and weight, etc. The calculation of slice properties is facilitated by the "sliceproperty" function, which enables the determination of weight and other pertinent properties for each slice. The program performs these calculations for all potential failure surfaces and computes each profile's FOS. The FOS represents a measure of stability, with higher values indicating a more stable slope.

The program compares the calculated FOS values across the analyzed circles to identify the most critical failure surface and determine the minimum FOS. It selects the profile with the lowest FOS as the minimum FOS, indicating the most vulnerable failure surface within the BCTS region.

Finally, the program employs the Bishop or OMS to calculate the FOS. These widely recognized methods are commonly used in slope stability analysis to evaluate the FOS. The minimum FOS, representing the most critical failure surface, is reported as the outcome of the analysis.

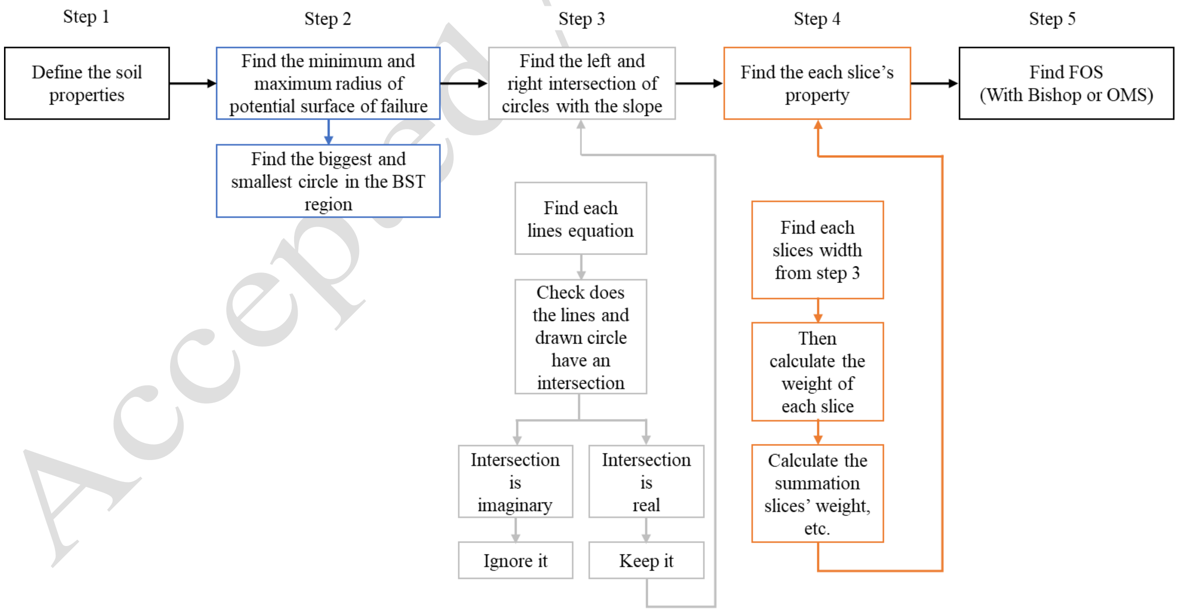


Figure 4. MATLAB flow chart of each function in the program.

5. Validation with SLIDE

To ensure the accuracy and reliability of the MATLAB code, a comparative validation study was conducted by constructing a representative slope with predefined properties, tables 1 to 3. The same geometry and material properties were employed in the MATLAB code and a well-established software tool, SLIDE. The results obtained from SLIDE were used as a benchmark for evaluating the performance of the MATLAB code.

Table 1. The geometry of slope.

	X (m)	Y (m)
Point 1	0	0
Point 2	5	0
Point 3	10	5
Point 4	15	5

Table2. Soil properties

Soil property	Value	Unit
Cohesion	10	kPa
Friction angle	34	Degree
Unit weight	20	kN/m3
Number of slices	30	-
Acceptable Error for Bishop method	1e-5	-

Table 3. BCTS location

	X (m)	Y (m)
Upper right corner (m)	10	8
Lower left corner (m)	8	6

The validation process involved analyzing the FOS for the constructed slope using both the MATLAB code and SLIDE software. Figure 5 illustrates the FOS values obtained from SLIDE, serving as a reference for comparison.

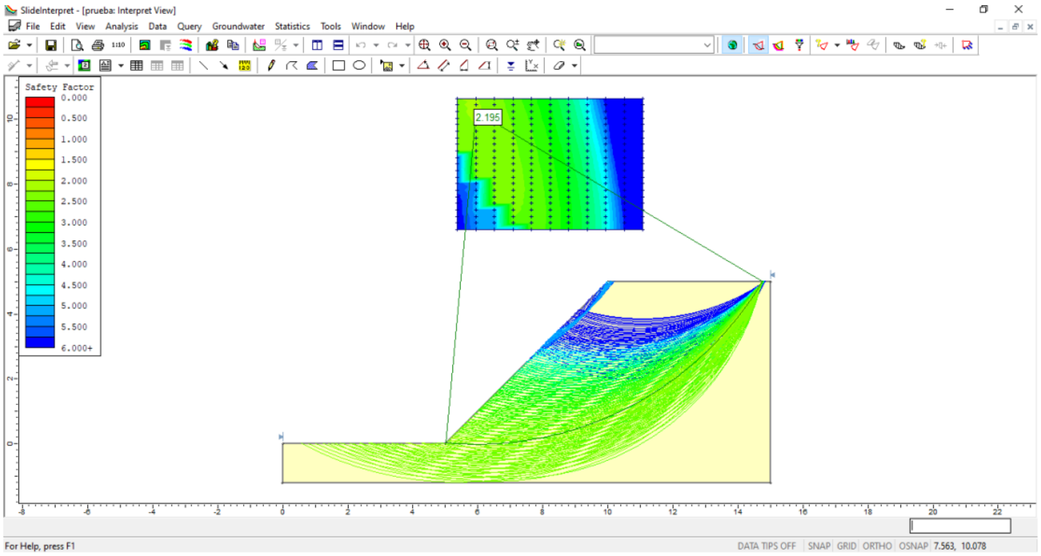
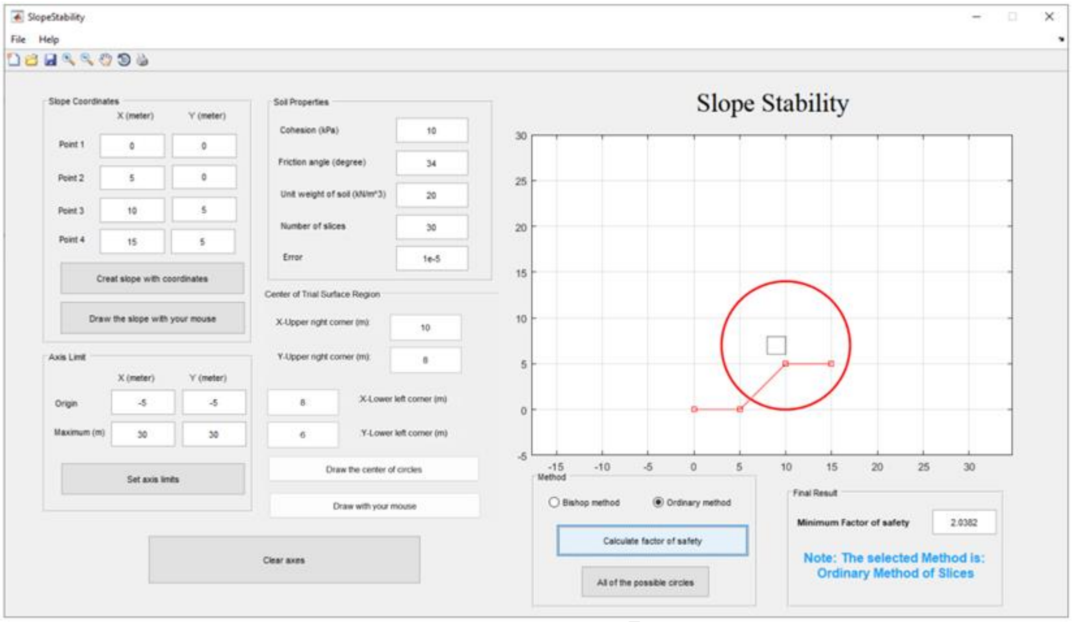


Figure 5. The FOS from SLIDE

Upon comparing the FOS values calculated by the MATLAB code, Figure 6, with those obtained from SLIDE, it was observed that the MATLAB code yielded a discrepancy of only 5 percent. This error level falls within an acceptable range, indicating high accuracy and reliability in MATLAB implementation.



Slope Coordinates

	X (meter)	Y (meter)
Point 1	0	0
Point 2	5	0
Point 3	10	5
Point 4	15	5

Soil Properties

Cohesion (kPa)	10
Friction angle (degree)	34
Unit weight of soil (kN/m^3)	20
Number of slices	30
Error	1e-5

Axis Limit

	X (meter)	Y (meter)
Origin	-5	-5
Maximum (m)	30	30

Center of Trial Surface Region

X-Upper right corner (m):	10
Y-Upper right corner (m):	8
X-Lower left corner (m)	8
Y-Lower left corner (m)	6

Method

○ Bishop method ● Ordinary method

Final Result

Minimum Factor of safety 2.0382

Note: The selected Method is: Ordinary Method of Slices

Figure 6. The FOS from the MATLAB code.

The strong agreement between the results generated by the MATLAB code and the SLIDE software validates the integrity and robustness of the developed computer-aided educational platform for slope stability analysis. The negligible error percentage underscores the exceptional precision and reliability of the MATLAB code in calculating FOS with a high degree of accuracy.

The observed 6 percent difference can be attributed to various factors inherent in the numerical approximations employed by both MATLAB and SLIDE to solve the equations. Subtle disparities in the specific numerical methods, precision levels, or convergence criteria adopted by the SLIDE can contribute to variations in the computed results. Additionally, divergent assumptions or simplifications made in the respective slope stability analysis models of the MATLAB code and SLIDE software can generate disparities. Variances in modeling soil behavior, boundary conditions, or other factors can impact the calculated FOS, leading to slight discrepancies between the two sets of results.

These factors collectively highlight the intricate nature of slope stability analysis and the inherent challenges in achieving absolute agreement between different computational tools. Nonetheless, the overall close alignment between the MATLAB code and SLIDE software results affirms the suitability and reliability of the developed educational platform for slope stability analysis, providing practitioners and students with an effective tool for understanding and analyzing slope stability in civil engineering applications.

6. Discussion

One of the notable advantages of the developed platform is its effectiveness in enhancing the understanding of slope stability analysis. By integrating the Bishop method and the OMS, the platform offers users a comprehensive toolset to explore and analyze critical aspects of slope stability, including circular slip surfaces and safety considerations. The user-friendly graphical interface and robust framework provide an intuitive and interactive learning environment, facilitating the comprehension of complex slope stability concepts.

The platform's practicality and usability are significant advantages that make it a valuable resource for young industrial engineers and civil engineering students. The user-friendly interface allows users to easily input slope coordinates, define axis limits, and enter soil properties, enabling them to set up slope stability scenarios with ease. The platform's capability to draw slopes based on user-defined points or mouse clicks further enhances its practicality, making it accessible to users with varying levels of expertise.

The validation study comparing the platform's results with those obtained from the widely recognized Slide software further strengthens its credibility and reliability. The close agreement between the platform and Slide software results, with a negligible 6 percent difference, demonstrates the accuracy of the platform's calculations. This validation gives users confidence in utilizing the platform for slope stability analysis, knowing that it can produce reliable and precise results.

Furthermore, the platform's user-friendly interface and accurate calculations make it a valuable tool for professionals and researchers involved in slope stability analysis. The platform's integration of prominent analysis techniques and its adaptability to different slope scenarios enable users to make informed decisions regarding slope safety and stability in practical engineering projects.

While the developed computer-aided educational platform for slope stability analysis offers numerous advantages, it is important to acknowledge certain limitations and identify areas for future improvement and expansion. One of the study's limitations is the focus on specific analysis techniques, namely the Bishop method and the OMS. While these techniques are widely used and provide valuable insights, the platform could benefit from incorporating a broader range of analysis methods, such as limit equilibrium methods, finite element analysis, or advanced numerical algorithms, to cater to a broader range of slope stability scenarios and research needs. Additionally, the platform does the modeling in 2D area while it can be developed and start modeling 3D slopes which makes it more accurate however, at the same time it increases the compellability of analysis and understanding of slope stability for young engineers.

7. Conclusion:

In conclusion, this study presented the development and evaluation of a computer-aided educational platform to enhance the understanding of slope stability analysis in civil engineering. The platform, implemented in MATLAB, offers a user-friendly graphical interface and a robust framework. It integrates prominent analysis techniques, such as the Bishop method and the OMS, allowing users to explore critical aspects of slope stability and determine minimum safety factors for different slope scenarios.

The validation study, comparing the platform's results with those obtained from the well-established Slide software, demonstrated its accuracy and reliability with a negligible 6 percent difference. This validation provides strong evidence of the platform's effectiveness in generating precise FOS calculations.

The developed educational platform fills a crucial gap in the field by providing young industrial engineers and civil engineering students with a practical tool to comprehend complex slope stability concepts. It facilitates interactive analysis, enabling users to gain hands-on experience in evaluating slope stability scenarios. The inclusion of complete source code enhances transparency and promotes a deeper understanding of the underlying techniques.

The successful development and evaluation of this platform contribute significantly to the field of slope stability analysis. Its user-friendly interface, integration of advanced analysis methods, and validated accuracy make it a valuable resource for researchers, educators, and practitioners. By bridging the gap between theory and practice, the platform equips users with essential skills for tackling slope stability challenges in geotechnical projects.

As future work, the platform can be further improved by incorporating additional analysis methods, expanding its capabilities to handle more complex slope geometries, and integrating data visualization features. These enhancements will ensure the platform remains relevant and adaptable to evolving needs in slope stability analysis.

8. Declaration of Competing Interest:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

9. Appendix:

All of the MATLAB codes are uploaded on the following link:

https://github.com/MohammadAfrazi/MATLABCODE

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