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A MATLAB-based educational platform for analysis of slope stability

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Abstract: This study presents a computer-aided educational platform namely ErosSSA (Eros-Slope-stability-analysis) developed by the geotechnical group in the Hong Kong Polytechnic University, to provide civil engineering students and young industrial engineers a better understanding for the analysis of slope stability. The platform is developed under the MATLAB environment, with a clear framework and a graphical interface. Using this platform, the rotational landslides can be generally analysed, considering a circular slip surface and the factors of safety defined with respect to basic and advanced methods with different force and/or moment equilibrium. Furthermore, the minimum factors of safety of different methods for a given slope can be determined. From the practical teaching of the ErosSSA in two courses for Bachelor and Master students, they were found to be highly satisfied with the accuracy, the reliability and the convenience of the ErosSSA according to their feedbacks to a questionnaire. These practical teaching experiences support the ErosSSA to be widely used as a suitable teaching platform in geotechnical engineering.

Keywords: slope stability; MATLAB GUI; computer-aided educational platform; geotechnical engineering; optimization.

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1 | INTRODUCTION

Slope stability is an important issue in geotechnical engineering. The reliable analysis of slope stability is significant to prevent geological engineering problems, such as landslides and collapses [1-4]. By determining the safety of the slope project and the thrust of slope instability, a scientific basis for the design of supporting structures can be provided. Since Felenius [5] proposed the Swedish circle method in 1926, numerous methods for slope stability analysis have been reported, including the limit equilibrium method (LEM), finite element/difference method (FEM/FDM), distinct element/rigid element method (DEM), and limit analysis, etc. However, most of the formulas are complicated and not easy for geotechnical engineers and undergraduate/postgraduate students to fully understand the analysis process of slope stability, thus bringing challenges to the engineering practice. Recently, due to the rapid development of computer technology, some computer-aided educational platforms have been proposed to assist teaching students in the engineering field. This novel teaching approach provides an effective way to transit the traditional teaching method with a single form and limited teaching effect. Moreover, since the beginning of 2020, the pandemic of COVID-19 broke out around the world. The COVID-19 brings a significant challenge to the face-to-face teaching for safety reasons. Hence, the online remote teaching associated with a computer-aided educational platform is necessary to deliver the knowledge of the slope analysis for the education of geotechnical engineering.

In general, engineering educational platforms are implemented through finite element software, such as some commercial codes (ABAQUS [6], FLAC [7], PLAXIS [8], and COMSOL [9]), or open-source codes [10-13]. To date, computer-aided educational platforms have been widely implemented in engineering courses to facilitate the teaching and learning process. Sonparote and Mahajan [14] developed a platform to demonstrate structural dynamics using JAVA [15]. A platform software prepared in the DELPHI environment was developed

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by Gencer and Gedikpinar [16] to be utilized in laboratories of electric machinery courses. A MATLAB-based educational platform like ABEL developed by Katsanosp [17] was used to familiarize students with the problems of soil-structure interaction. Nevertheless, the complicated models provided by these software require users to understand the finite element method, which is not easy for undergraduate and postgraduate students. Therefore, a platform with easier interpretation is needed to evaluate the slope stability.

In the last decade, Graphical User Interfaces (GUI) are attracting interest from many scholars and engineers. GUI is a user interface that contains graphical objects, such as windows, icons, menus, and text. When these objects are selected or activated in a certain way, they cause actions. The MATLAB GUI [18] provides developers an environment integrated with MATLAB. This allows the developers to simplify the program and to easily develop a graphical interface at the same time, helping readers understand specific problems during the training process. Hence, the MATLAB GUI can be used to develop an educational platform for more convenient analysis of slope stability.

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In this study, a computer-aided learning and simulation platform ErosSSA (Eros-Slope-stability-analysis) is developed. Two factors (the "Parameters of Soil" and the "Geometry of Slope") are considered, showing the most significant impact on the factor of safety of slope stability. The limit equilibrium method is adopted during the analysis. Using this platform, the factor of safety under a given slip surface can be determined by five different methods. In addition, unlike other slope software, ErosSSA can quickly find the minimum factor of safety under a specific slope geometry.

In addition, in slope stability analysis, we need to find the global minimum/critical solution for design. A general method in class is to analyze a number of trial circles in the same way but with different circle centers and different points where the circle cuts the slope to determine the minimum safety factor. Another traditional method is the "stability chart" method, which is only suitable for the homogeneous slope and very simple geometry. Other methods like FEM, DEM and FDM, require a complicated modeling process. ErosSSA can quickly find the minimum factor of safety under a specific slope geometry, and the analyze process of searching the critical solution is also displayed in this tool.

Finally, some learning examples and the student feedbacks are also presented to demonstrate the applicability of ErosSSA in the education of geotechnical engineering.

2 | DEVELOPMENT OF ErosSSA

The ErosSSA was developed using MATLAB GUI by the geotechnical group in the Hong Kong Polytechnic University. It can be uploaded to personal homepages, and students can install it directly on the computer for use without licenses. Students can easily learn to use this tool because of its simple operation and clear interface. Compared with other slope softwares, this tool highlights the function of finding the minimum safety factor. The Nelder-Mead simplex based differential evolution algorithm (NMDE) is adopted to identify the minimum safety factor. The detailed development process is demonstrated as follows.

2.1 | Basic theory

In this educational platform, the factor of safety (F_s) is used as an indicator to evaluate the slope stability [19]. If $F_s \leq 1.2$ [20], the slope is considered unstable. The most common approaches for defining F_s in the limit equilibrium method are based on the force equilibrium, moment equilibrium, and shear strength method [21]. Moment equilibrium is used in the analysis of rotational landslides. Considering a circular slip surface, the factor of safety equals to the sum of the resisting moments (M_r) divided by the sum of the driving moment (M_d). Force equilibrium is applied to translational or rotational failures composed of a plane or polygonal slip surfaces, while the factor of safety is defined by dividing the sum of the resisting forces (F_r) by the sum of the driving forces (F_d). For the shear strength method, the actual shear stress can be mobilized along the failure surface against the ultimate shear strength.

Limit equilibrium method [22] solves a statically indeterminate problem. Assumptions on the interslice shear forces are needed to render the statically determinate problem. The failure is assumed to occur by rotating a rigid block of soil on a cylindrical failure surface, along which the undrained shear strength of the soil is moved. Based on the assumptions on the internal force and/or moment equilibrium, there are many methods developed for the evaluation of slope stability, including Fellenius [23], Bishop [24], Lowe and Karafiath [25], Janbu [26-28], Morgenstern-Price [29], Spencer [30], etc. Since most of the existing methods are very similar in their basic formulations with only different assumptions on the interslices shear forces, it is possible to group most of the existing methods under a unified formulation. Fredlund [31], Espinoza [32], Cheng [33] and Chang [34] have proposed slightly different unified formulation to the more commonly used slope stability analysis methods.

According to different analysis methods, several factors of safety can be obtained for a given slope, but the design requirements for the factor of safety are generally not limited to a specific analysis method in most design codes from different countries. So, five classic analysis methods, Swedish, Fellenius, Janbu's Simplified, Janbu's Modified, Bishop methods, are adopted in this platform to calculate the factor of safety. The corresponding formulas are shown as follows:

$$F_{s,Swedish} = \frac{M_{\text{resistance}}}{M_{\text{renversement}}} = \frac{\sum (l_i c' + b_i h_i \gamma \cos\alpha_i \tan\phi') R}{\sum b_i h_i \gamma \sin\alpha_i R} \tag{1}$$

$$F_{s,Fellenis} = \frac{\sum \left[l_i c' + (b_i h_i \gamma \cos\alpha_i - \gamma_w b_i h_i \sec\alpha_i) \tan\phi' \right]}{\sum b_i h_i \gamma \sin\alpha_i} \tag{2}$$

$$F_{s,Janbu's\ Simplified} = \frac{\sum \left[c'b + (b_i h_i \gamma - u_i b_i) \tan\phi' \right] / \eta_{\alpha_i}}{\sum b_i h_i \gamma \tan\alpha_i} \quad \text{with} \quad \eta_{\alpha_i} = \left(1 + \frac{\tan\alpha_i \tan\phi'}{F_s} \right) \tag{3}$$

$$F_{s,Bishop} = \frac{\sum \left(l_i c' \cos\alpha_i + b_i h_i \gamma \tan\phi' \right) / m_\alpha}{\sum b_i h_i \gamma \sin\alpha_i} \quad \text{avec} \quad m_\alpha = \cos\alpha_i + \frac{\sin\alpha_i \tan\phi'}{F_s} \tag{4}$$

where $u_i = \gamma_w h_w$; γ_w is the unit weight of water; h_w is the height to the water table above the base of the slice; l_i, b_i, h_i, R and α_i are used to describe the geometry of the slope; γ, ϕ' and c' are the unit weight, effective internal friction angle and cohesion of soil, respectively; m_α and η_α are the correction coefficients in Janbu's Simplified Method and Bishop Method, respectively. The detailed interpretation of the parameters in these five formulas can also be seen in Figure 1.

In Janbu's modified method, a correction factor f_0 is applied to the factor of safety from the simplified analysis. The correction factor f_0 is determined by the following formula.

$$\begin{aligned} &\text{For } c',\ \phi' > 0, \quad f_0 = 1 + 0.5\left[\frac{D}{l} - 1.4\left(\frac{D}{l}\right)^2\right] \\ &\text{For } c' = 0, \quad f_0 = 1 + 0.3\left[\frac{D}{l} - 1.4\left(\frac{D}{l}\right)^2\right] \\ &\text{For } \phi' = 0, \quad f_0 = 1 + 0.6\left[\frac{D}{l} - 1.4\left(\frac{D}{l}\right)^2\right] \end{aligned} \tag{5}$$

where l refers to the length of the slope; D is the maximum thickness of the slope.

2.2 | Platform interface

After opening ErosSSA, a dialog-box entitled "Slope Stability Analysis Platform" (Figure 2) is displayed, including seven panels: "Parameters of Soil", "Slip Surface", "Geometry of Slope", "Option of Calculation", "Number of Slice", "Figure of a slope", and "Results of Calculation". Different values can be filled in these white boxes. Then, the calculated results are displayed in these blank (grey) boxes. The detailed operation method is shown in Figure 3.

Five parameters are considered in the panel of "Parameters of Soil": unit weight of slope soil (γ), cohesive strength (c), and friction angle (ϕ). In this platform, three different drainage conditions can be applied, i.e., saturated, dry and drained conditions. These three cases can be calculated by selecting γ_sat, γ_dry and γ'_eff, respectively. Note that the default unit weight

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of water γ_w is 9.8 kN/m^3.

The coordinates of the determined circular failure surface can be filled in the panel of "Slip Surface". In "Geometry of Slope", three parameters are used: height of slope (H), angle of slope (α), and angle of the top face of the slope (β). ErosSSA can automatically check the values of the user's inputs. An error message appears when inappropriate parameters are filled, as shown in Figure 4. In addition, the more number of slices, the higher the accuracy and the longer the calculation time.

A typical schematic figure is displayed in the top right corner of the platform interface (Figure 2), indicating all the parameters. When clicking the "RUN" button, this figure changes to the calculation results according to the input parameters, as shown in Figure 5. When clicking the "CLEAN" button, Figure 5 changes back to the origin schematic figure as shown in Figure 2.

After each calculation, a TXT file namely solution (as shown in Figure 6) can be automatically generated in the folder where the educational platform is saved. The TXT file records the coefficients of each slice and the results of the factors of safety, which can be directly imported into an EXCEL file for future processing and analysis.

2.3 | Minimum factor of safety

In ErosSSA, to define the minimum factor of safety, the "Minimum Factor of Safety" in the "Option of Calculation" panel can be selected. The Nelder-Mead simplex based differential evolution algorithm (NMDE) proposed by Yin et al. [35] is adopted to accelerate the convergence speed, as shown in Figure 7. Before performing the differential evolution (DE) mutation, all the individuals are sorted on the basis of their fitness values. The best n+1 (n is the number of variables) individuals are selected to perform the Nelder-Mead simplex [36]. According to the results of the Nelder-Mead simplex, the best individual is updated. Then, the best individual is recombined with the N-(n+1) remaining individuals to perform the DE

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mutation. This process is executed N times, followed by obtaining a new population with N individuals. After this process, the obtained population is applied to the crossover operation. In order to avoid a rapid loss of diversity, an elitism strategy is adopted to perform the selection. In the selection, 10% of individuals with the highest fitness value are selected from the parents and children to survive to the next generation. The remainders are chosen by tournament selection from the mating pool composed of parents and children other than the 10% individuals. The completion mechanism can help the NMDE determine better solutions. More details about NMDE can be seen in Yin et al. [35]. Except for the NMDE, any optimization method with a high searching performance can be used to identify the minimum factor of safety, such as MBSA [37].

A minimum factor of safety can be obtained in a reasonable time period. In this platform, only the Swedish method is adopted to find the minimum factor of safety. Figure 8 shows the process of searching for the minimum factor of safety displayed in the figure panel. After identifying the circular failure surface with the minimum factor of safety, a message box is displayed by ErosSSA.

3 | PRACTICAL TEACHING APPLICATION

Since the COVID-19 brings a significant challenge to the face-to-face teaching for safety reasons, the ErosSSA can be used as an educational platform to improve theteaching and learning efficiency of slope engineering course for both undergraduate and postgraduate students. In the previous teaching without this platform, instructors only showed the related formulas and used Excel (Figure 9) to calculate the safety factor of the slope. Only a "Stability chart" was used to calculate the minimum safety factor. Currently, they can use ErosSSA to demonstrate the slope stability analysis through various examples and explain the calculation steps through the generated "solution" file. The process of identifying the circular failure

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surface with the minimum safety factor can also be presented. In addition, students can visualize and learn the evaluation process of slope stability by using ErosSSA. During the operation, they can understand the slope parameters comprehensively. A detailed demonstration of three cases is introduced as follows.

3.1 | Case 1: Different geometries of slopes

Figure 10 shows a template that the top face of the slope is inclined. Students need to input the values of height, the angle of the top face and the toe of the slope. The coordinates of the circular failure surface such as the first point and the center point are also needed for the calculation. This suggests that ErosSSA can be used to investigate the slope stability with different geometries under various failure surfaces.

3.2 | Case 2: Different reservoir conditions

The reservoir conditions for a slope can be simply divided into three categories: the reservoir full of water, the empty reservoir and the case of rapid emptying. The differences between these three conditions are the unit weights (γ) of soil. When the reservoir is full of water, the saturated unit weight (γ_sat) is used in the calculation. The dry unit weight (γ_dry) is used under the empty condition, while the effective unit weight (γ'_eff) is used under the rapid emptying condition. These three conditions can be calculated by selecting γ_sat, γ_dry and γ'_eff in the "Parameters of Soil" panel, respectively (Note: the default γ_w = 9.8 kN/m^3). Table 1 summarizes the values of γ in M_r and M_d under different drainage conditions.

The schematic view of the reservoir full of water is plotted in Figure 11 for calculation. The saturated unit weight of soil (γ_sat) is used. Figure 12 (a) shows the calculated results using the ErosSSA. If the reservoir is in a rapid drainage state, the effective unit weight of soil (γ'_eff) should be selected, presenting the calculated results as shown in Figure 12 (b). By comparing the results of these two cases, the factors of safety of the same slope are quite different under various drainage conditions. On the whole, the factor of safety is much lower for the reservoir

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full of water than that for the case of rapid drainage, suggesting that a good drainage path for the reservoir is favorable for more stable slope maintanence.

Figure 13 shows the results of these two conditions calculated by the EXCEL program (LME), indicating a good agreement with the results of ErosSSA.

3.3 | Case 3: Validation - the minimum factor of safety

In the evaluation of slope stability, users need to determine the global minimum/critical solution for design. To validate the calculated results from ErosSSA, a similar slope stability analysis is conducted by the PLAXIS 2D (Figure 14).

1. The height of the slope is 14 m.
2. The angle of the slope is 45°.
3. The reservoir condition is empty.
4. The parameters of soil are as follows: $\gamma_1 = 11$ kN/m^3, $\gamma_2 = 11$ kN/m^3, $c = 10$ kN/m^2, $\phi =$ 35°.

The factor of safety calculated by PLAXIS 2D is 1.452. Accordingly, the calculated factors of safety are 1.42853, 1.42853, 1.50575, 1.41489, and 1.49885 using the Swedish method, Fellenius method, Bishop method, Janbu's Simplified method and Janbu's Modified method, respectively in the ErosSSA (Figure 15), indicating a good agreement with the result from PLAXIS 2D. The results obtained from the two softwares have a minor difference, because they use different calculation methods. The comparison between the results from ErosSSA and PLAXIS 2D shows that the proposed computer-aided educational platform is reliable and accurate.

3.4 | Student feedbacks

In the semester of 2020-2021, online teaching is required for all courses in the Hong Kong Polytechnic University due to the pandemic of COVID-19. Hence, the online teaching joint with the self-developed computer-aided educational platform ErosSSA was used to deliver the

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knowledge of slope stability for the courses of "Geotechnical Design (course code: CSE 40403; for Bachelor students)" and "Soil Behaviour and Geotechnical Engineering (course code: CSE578; for Master students)". Several calculation examples about the previous three cases were shown to students for teaching and training. For the learning example in Section 3.3, some parameters were changed for students to complete as assignments after class. The students were required to use ErosSSA and PLAXIS to perform the analysis and compare the results. Finally, they were asked to complete a questionnaire to evaluate the contribution of ErosSSA platform to their study of slope stability analysis. The questions in the questionnaire are shown in Table 2, including: 1) What is your overall feeling about ErosSSA? 2) Do you think this platform is easy to operate? 3) What do you think of the layout of this platform? 4) Will you recommend this platform to your friends? 5) Have you encountered any bugs when using it? 6) Any advice to improve this platform?

After collecting the feedbacks from the students, we summarized the results of the first five questions, as listed in Table 3. From the first two questions, most students (more than 85%) thought the ErosSSA was useful, easy and convenient for the analysis of slope stability. In terms of the layout of the platform, more than 80% of them were highly satisfied (Grade 4 and 5). After the learning and training process of the platform, more than 80% them expected to recommend ErosSSA to their friends (Grade 4 and 5). Moreover, 25 students (9.77%) encountered bugs while using the platform. In addition, some students also provided suggestions to improve the platform as follows:

1) Consider the soil nail condition in slope engineering, and

2) Provide a process display with formula calculation.

These two suggestions are very helpful, although they would affect the current layout and the calculation efficiency. Nevetheless, these suggestions will be considered to further improve the platform in the future. On the whole, the current ErosSSA platform is generally satisfying

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for the teaching on the analysis of slope stability.

4 | CONCLUSIONS

The ErosSSA is developed as an educational platform to promote the teaching and learning efficiency, for the analysis of slope stability. It can be uploaded to personal homepages, and students can install it directly on the computer for use. Five classic analysis methods, Swedish, Fellenius, Janbu's Simplified, Janbu's Modified, Bishop methods, are adopted in this platform to calculate the factors of safety. In addition, compared with other slope software, this tool adds the function of finding the minimum safety factor. The Nelder-Mead simplex based differential evolution algorithm (NMDE) is adopted to identify the minimum safety factor.

The ErosSSA can be used for Bachelor and Master geotechnical courses. Through the operation process, the ErosSSA helps students understand the evaluation process of slope stability. The graphical interface variation with the calculation is useful to understand the process of searching for the minimum factor of safety.

Due to the COVID-19, the online teaching method associated with the ErosSSA teaching platform was used to deliver the knowledge of slope stability in the courses of "Geotechnical Design" for Bachelor students and "Soil Behaviour and Geotechnical Engineering" for Master students of the Hong Kong Polytechnic University in the semester of 2020-2021. Students' feedbacks were collected, from completing the assignment using the ErosSSA. The feedbacks showed that the majority of the students were highly satisfied with ErosSSA. They though this platform is helful, easy and convenient for the analysis of slope stability, although a minor proportion of them encountered bugs. From their specific suggestions and the collected bugs, this platform would be further improved for a wider application in the teaching and learning of geotechnical engineering.

Currently, ErosSSA has only been used in two courses. Case studies on slope analysis

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carried out by this tool are not enough. The effectiveness of the tool needs to be verified in more courses.

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TABLE 1 Summary of different reservoir conditions

Reservoir conditions	γ in M_r	γ in M_d
Saturated (γ_sat)	γ_sat − γ_w	γ_sat − γ_w
Dry (γ_dry)	γ_dry	γ_dry
Drained (γ'_eff)	γ'_eff	γ'_eff + γ_w

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TABLE 2 Questionnaire for the ErosSSA evaluation

1) What is your overall feeling about ErosSSA?	**Useless**	**1**	**2**	**3**	**4**	**5**	**Very helpful**
2) Do you think this platform is easy to operate?	Hard to understand	1	2	3	4	5	Very easy
3) What do you think of the layout of this platform?	Very dissatisified	1	2	3	4	5	Very satisfied
4) Will you recommend this platform to your friends?	Nope	1	2	3	4	5	Absolutly
5) Have you encountered any bugs when using it?	○ Nope, it runs smoothly. ○ Some characters cannot be displayed. ○ It failed to give an answer. ○ The website broke down. Others:____________________.						
6) Any advice to improve this platform?	____________________ ____________________						

For Peer Review

TABLE 3 Summary of student feedback on the ErosSSA questionnaire.

Questions	Grade				
	1	2	3	4	5
What is your overall feeling about ErosSSA?	2 (0.78%)	1 (0.39%)	33 (12.89%)	91 (35.55%)	129 (50.39%)
Do you think this platform is easy to operate?	4 (1.56%)	8 (3.13%)	42 (16.41%)	85 (33.20%)	117 (45.70%)
What do you think of the layout of this platform?	3 (1.17%)	3 (1.17%)	39 (15.23%)	94 (36.72%)	117 (45.70%)
Will you recommend this platform to your friends?	5 (1.95%)	2 (0.78%)	38 (14.84%)	91 (35.55%)	120 (46.88%)
Have you encountered any bugs when using it?	○ Nope, it runs smoothly. 231 (90.23 %)] ○ Some characters cannot be displayed. [4 (1.56%)] ○ It failed to give an answer. [12 (4.69%)] ○ The website broke down. [2 (0.78%)] Others:_________________________. [7 (2.73%)]				

For Peer Review

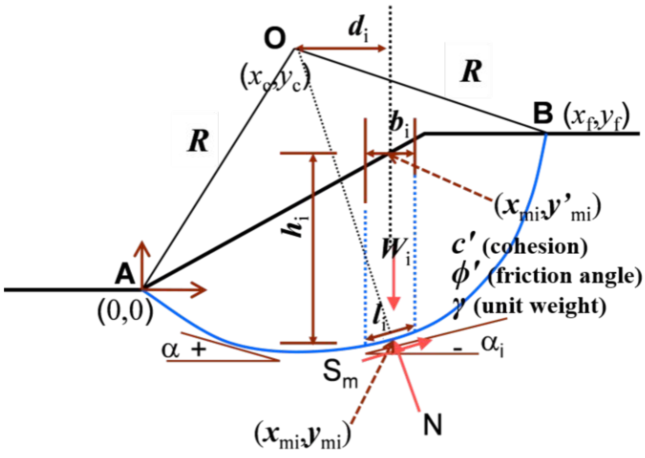


FIGURE 1 Reference diagram of parameters in the formulas for slope stability

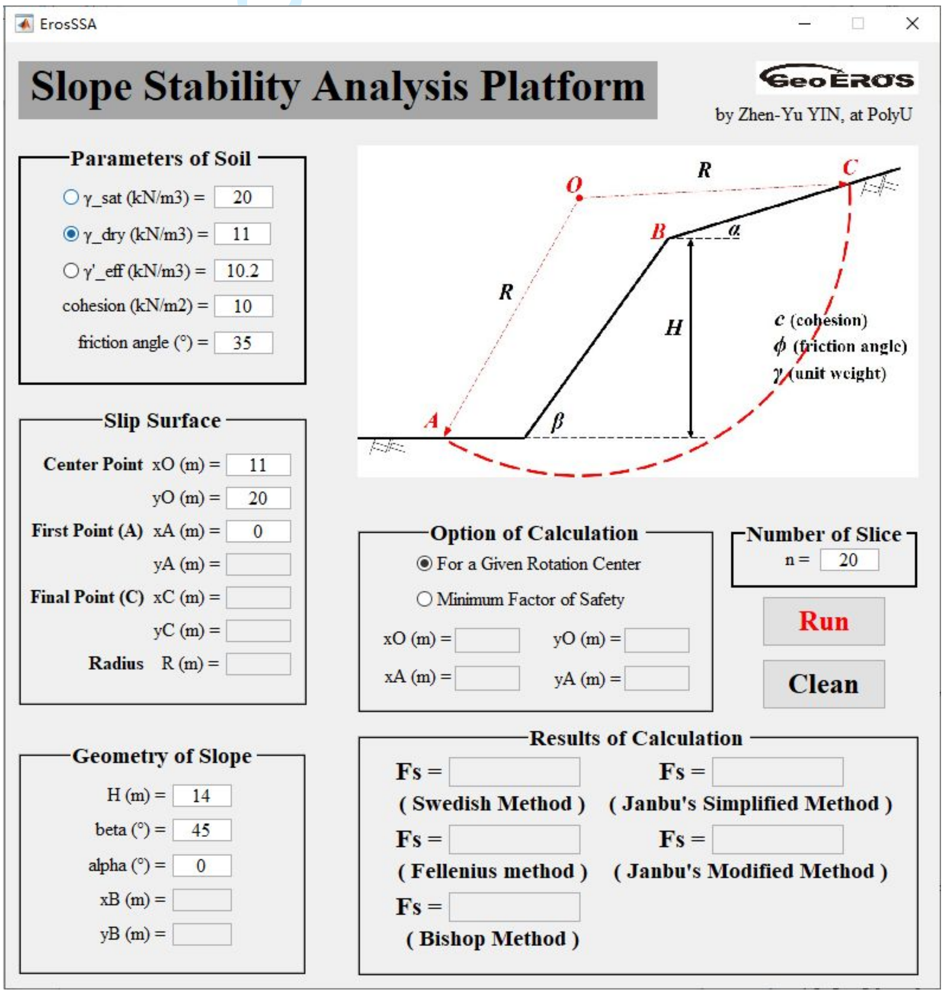


FIGURE 2 Screenshot of ErosSSA default window

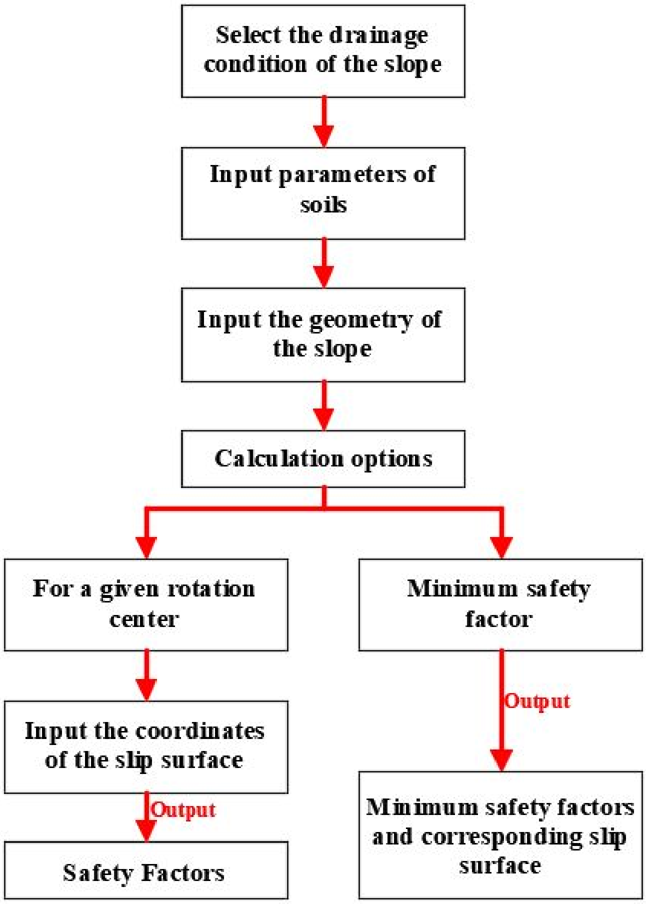


FIGURE 3 Operation Method

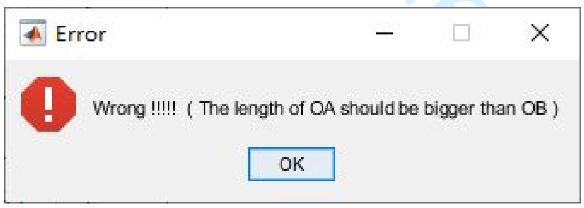


FIGURE 4 Screenshot of “error message” for improper input

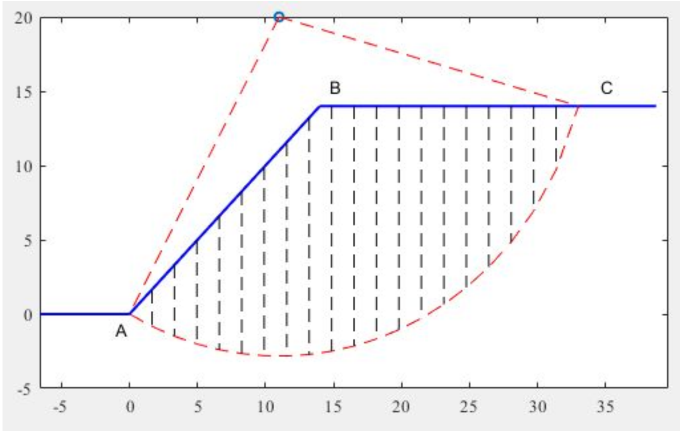


FIGURE 5 Screenshot of a typical calculation result figure

For Peer Review

solution.txt 2021/1/24 23:15

No.	x	y	yy	xmi	ymi	yymi	hi(m)
001	+0.00e+00	+0.00e+00	+0.00e+00	+0.00e+00	+0.00e+00	+0.00e+00	+0.00e+00
002	+1.65e+00	-8.23e-01	+1.65e+00	+8.26e-01	+8.26e-01	-4.12e-01	+1.24e+00
003	+3.30e+00	-1.49e+00	+3.30e+00	+2.48e+00	+2.48e+00	-1.16e+00	+3.63e+00
004	+4.95e+00	-2.01e+00	+4.95e+00	+4.13e+00	+4.13e+00	-1.75e+00	+5.88e+00
005	+6.60e+00	-2.40e+00	+6.60e+00	+5.78e+00	+5.78e+00	-2.20e+00	+7.98e+00
006	+8.26e+00	-2.66e+00	+8.26e+00	+7.43e+00	+7.43e+00	-2.53e+00	+9.96e+00
007	+9.91e+00	-2.80e+00	+9.91e+00	+9.08e+00	+9.08e+00	-2.73e+00	+1.18e+01
008	+1.16e+01	-2.82e+00	+1.16e+01	+1.07e+01	+1.07e+01	-2.81e+00	+1.35e+01
009	+1.32e+01	-2.72e+00	+1.32e+01	+1.24e+01	+1.24e+01	-2.77e+00	+1.52e+01
010	+1.49e+01	-2.50e+00	+1.40e+01	+1.40e+01	+1.40e+01	-2.61e+00	+1.66e+01
011	+1.65e+01	-2.15e+00	+1.40e+01	+1.57e+01	+1.40e+01	-2.32e+00	+1.63e+01
012	+1.82e+01	-1.67e+00	+1.40e+01	+1.73e+01	+1.40e+01	-1.91e+00	+1.59e+01
013	+1.98e+01	-1.06e+00	+1.40e+01	+1.90e+01	+1.40e+01	-1.36e+00	+1.54e+01
014	+2.15e+01	-2.85e-01	+1.40e+01	+2.06e+01	+1.40e+01	-6.70e-01	+1.47e+01
015	+2.31e+01	+6.56e-01	+1.40e+01	+2.23e+01	+1.40e+01	+1.85e-01	+1.38e+01
016	+2.48e+01	+1.79e+00	+1.40e+01	+2.39e+01	+1.40e+01	+1.22e+00	+1.28e+01
017	+2.64e+01	+3.17e+00	+1.40e+01	+2.56e+01	+1.40e+01	+2.48e+00	+1.15e+01
018	+2.81e+01	+4.85e+00	+1.40e+01	+2.72e+01	+1.40e+01	+4.01e+00	+9.99e+00
019	+2.97e+01	+6.94e+00	+1.40e+01	+2.89e+01	+1.40e+01	+5.89e+00	+8.11e+00
020	+3.14e+01	+9.70e+00	+1.40e+01	+3.05e+01	+1.40e+01	+8.32e+00	+5.68e+00
021	+3.30e+01	+1.40e+01	+1.40e+01	+3.22e+01	+1.40e+01	+1.19e+01	+2.15e+00

Mr	Md	Fs_Swedish	Mr_Bishop	Fs_Bishop
2.84e+03	1.02e+03	2.787	3.18e+03	3.129

FIGURE 6 Screenshot of “solution” file

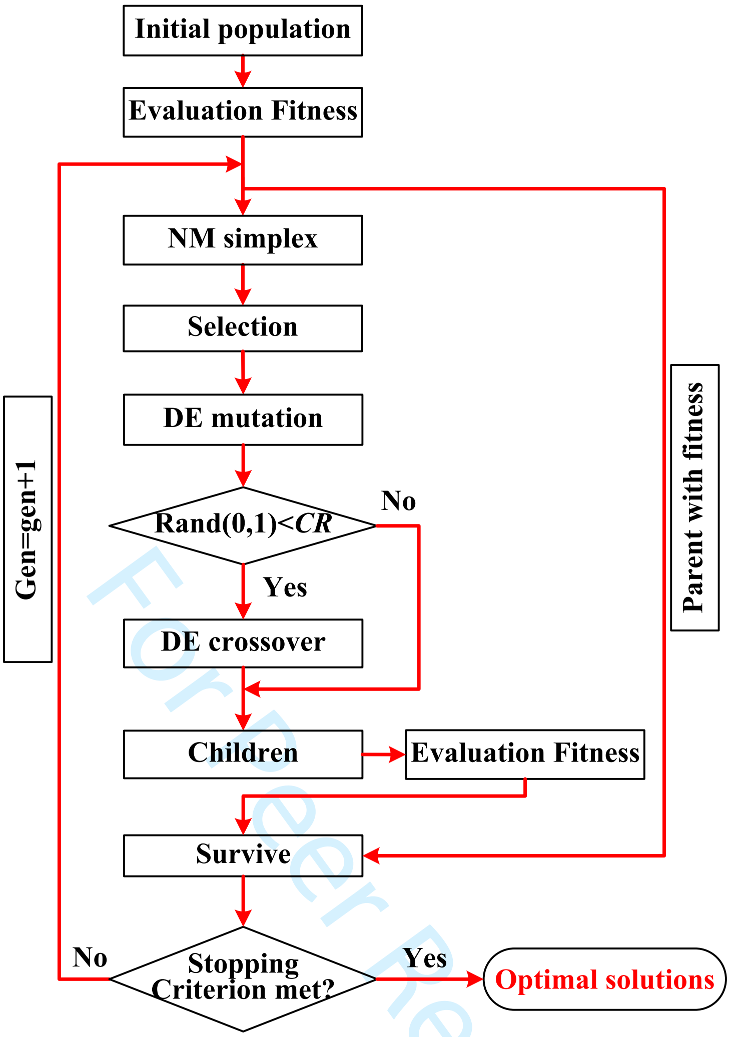


FIGURE 7 Flowchart of NMDE

For Peer Review

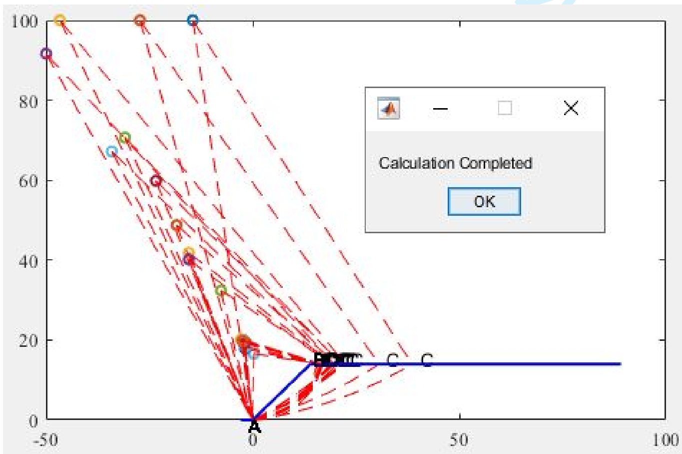


FIGURE 8 Screenshot of a typical result of the minimum factor of safety

Intersection points

No_i	xi	yi	y'i
1	0.00	0.00	0
2	2.00	-0.98	2
3	4.00	-1.73	4
4	6.00	-2.27	6
5	8.00	-2.63	8
6	10.00	-2.80	10
7	12.00	-2.80	12
8	14.00	-2.63	14
9	16.00	-2.27	14
10	18.00	-1.73	14
11	20.00	-0.98	14
12	22.00	0.00	14
13	24.00	1.24	14
14	26.00	2.80	14
15	28.00	4.77	14
16	30.00	7.35	14
17	32.00	11.06	14
18	33.02	14.00	14

Middle points

No_mi	xmi	ymi	y'mi
1	1.00	-0.49	1.00
2	3.00	-1.35	3.00
3	5.00	-2.00	5.00
4	7.00	-2.45	7.00
5	9.00	-2.72	9.00
6	11.00	-2.80	11.00
7	13.00	-2.72	13.00
8	15.00	-2.45	14.00
9	17.00	-2.00	14.00
10	19.00	-1.35	14.00
11	21.00	-0.49	14.00
12	23.00	0.62	14.00
13	25.00	2.02	14.00
14	27.00	3.78	14.00
15	29.00	6.06	14.00
16	31.00	9.20	14.00
17	32.51	12.53	14.00

					For dry slope	
Slice No.	hi (m)	bi (m)	αi (degree)	li (m)	M_r	M_d
1	1.49	2.00	-25.98	2.22	978.1876875	-327.379466
2	4.35	2.00	-20.52	2.14	1920.220425	-765.752939
3	7.00	2.00	-15.24	2.07	2847.326829	-923.776817
4	9.45	2.00	-10.09	2.03	3734.769475	-831.532876
5	11.72	2.00	-5.03	2.01	4561.768658	-515.480361
6	13.80	2.00	0.00	2.00	5310.039529	0
7	15.72	2.00	5.03	2.01	5962.822178	691.480361
8	16.45	2.00	10.09	2.03	6157.991411	1447.532876
9	16.00	2.00	15.24	2.07	5900.580174	2111.776817
10	15.35	2.00	20.52	2.14	5542.652477	2701.752939
11	14.49	2.00	25.98	2.22	5087.166132	3187.379466
12	13.38	2.00	31.72	2.35	4538.898337	3532.539521
13	11.98	2.00	37.83	2.53	3905.837201	3690.81229
14	10.22	2.00	44.51	2.80	3202.469277	3596.770627
15	7.94	2.00	52.05	3.25	2459.199547	3144.370057
16	4.80	2.00	61.19	4.15	1760.07314	2110.544161
17	1.47	1.02	70.46	3.06	786.5887562	356.2569011
				sum	64656.591	23207.294
					FS	2.786

FIGURE 9 Traditional Excel method.

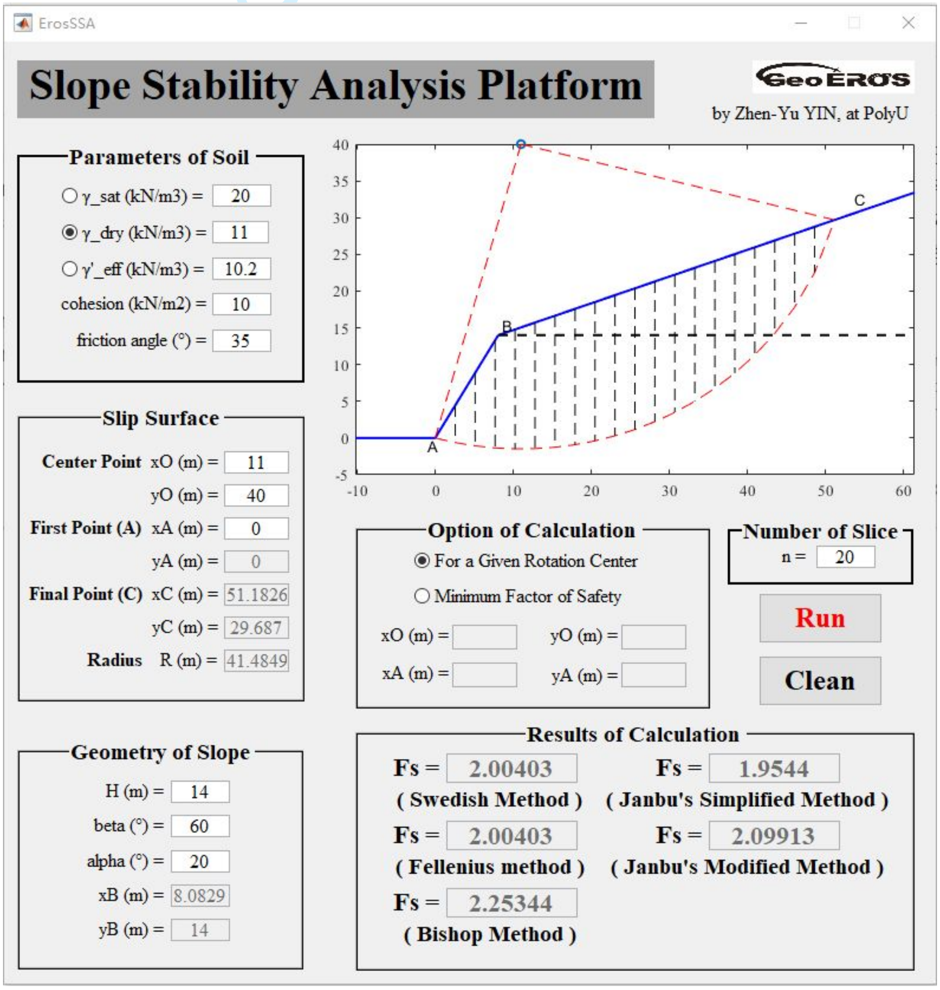


FIGURE 10 Screenshot of ErosSSA showing the analysis result of Case 1

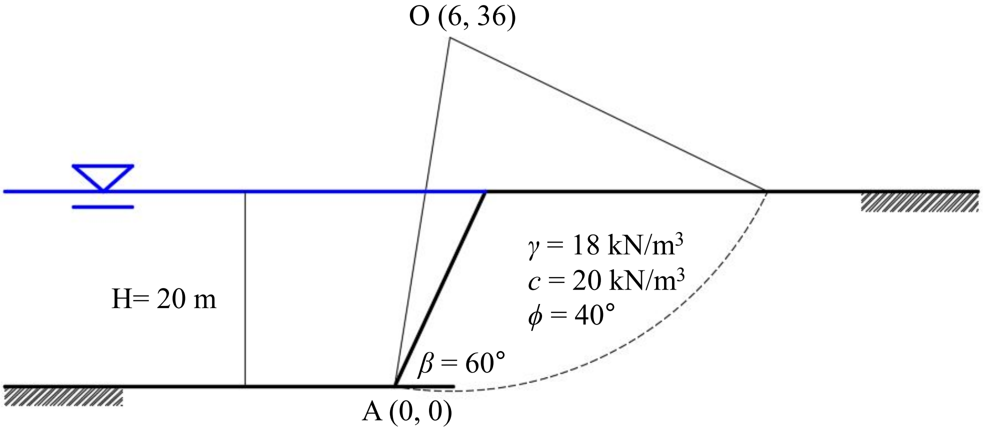
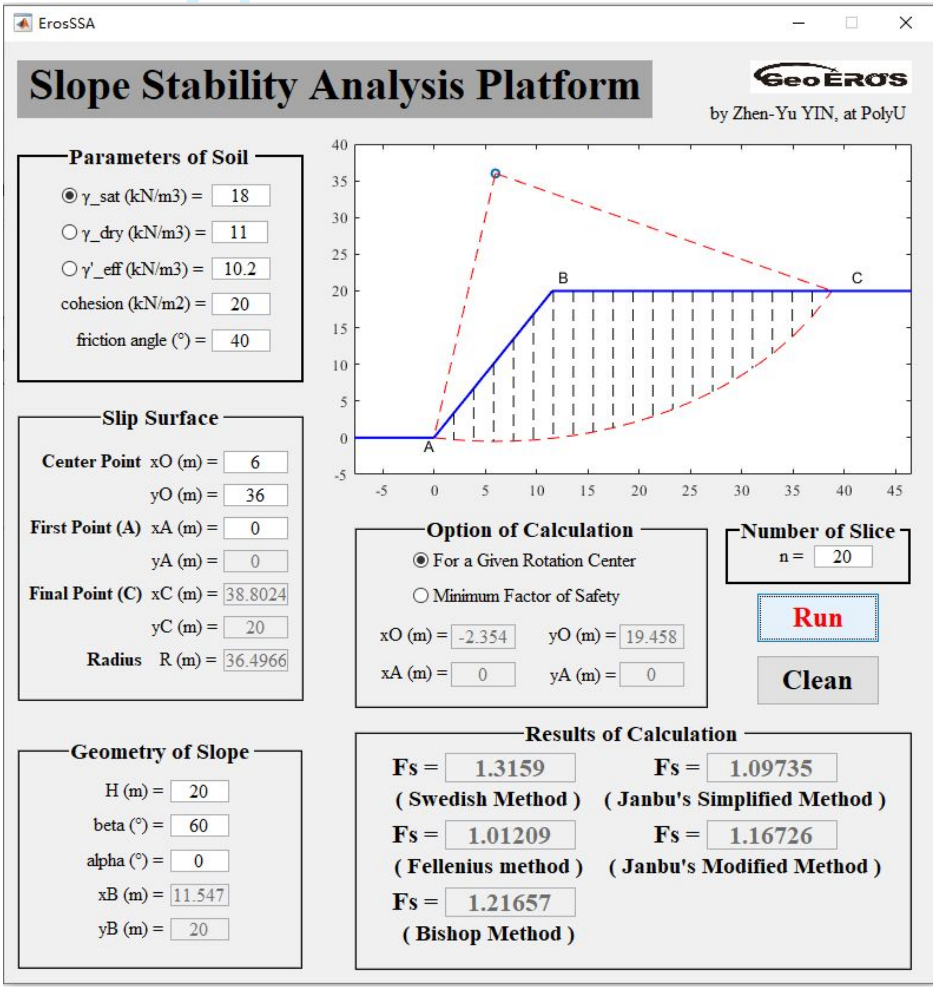
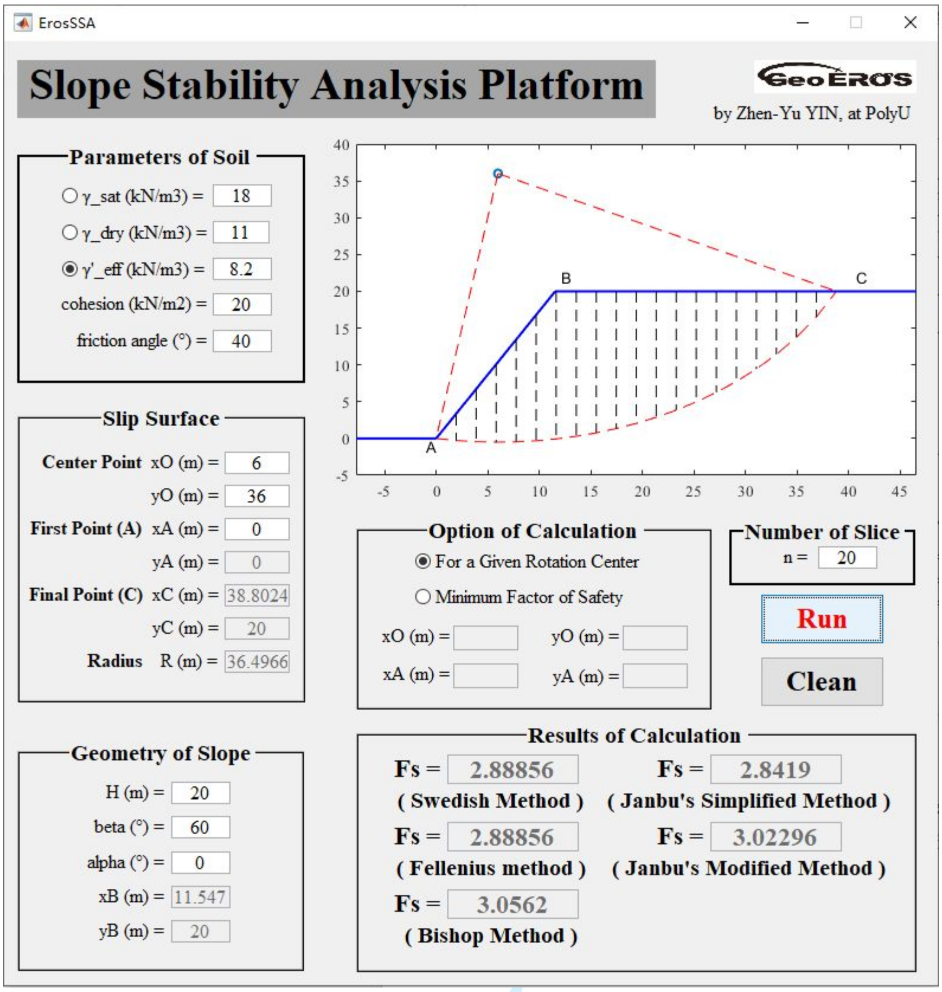


FIGURE 11 Schematic view of a reservoir full of water



(a)



(b)

FIGURE 12 Screenshot of ErosSSA showing the analysis result of Case 2: (a) Reservoir full of water; (b) Reservoir with rapid emptying

	Swedish method		Fellenius method		Bishop method		Janbu's simplified method		
	M_r/R	M_d/R	M_r/R	M_d/R	M_r/R	M_d/R	M_r/R	M_d/R	For Saturated slope (Rapid empty)
	65.87717	-9.2248	65.29433	-9.2248	73.35397894	-9.22479521	74.86635873	-9.31260221	
	116.326	-16.4394	115.7065	-16.4394	123.8834102	-16.4393695	125.0821846	-16.495191	
	165.5998	-9.00519	165.487	-9.00519	168.8832066	-9.00519336	169.2830755	-9.00857559	
	213.2522	12.42216	213.0966	12.42216	209.427677	12.42216214	209.1061552	12.42682774	
	258.8529	47.19209	257.0747	47.19209	246.3433632	47.19208861	245.8151036	47.35233385	
	296.6337	92.71418	290.7757	92.71418	275.3044076	92.71417925	275.4506118	93.59668705	
	308.2312	136.7452	296.0226	136.7452	280.6603681	136.7452265	282.5081205	139.3320283	
	299.3902	171.8198	279.4167	171.8198	268.9550765	171.8197636	273.3161764	177.2950354	
	288.4165	203.8085	258.9852	203.8085	257.06347	203.8084993	264.7122963	213.748134	
	275.369	231.9188	234.9806	231.9188	244.859534	231.9188061	256.5372601	248.1979681	
	260.3267	255.2815	207.7487	255.2815	232.2016588	255.2814948	248.6244914	280.0255353	
	243.3961	272.9227	177.7644	272.9227	218.9227256	272.9227353	240.783718	308.4250711	
	224.7213	283.7244	145.6884	283.7244	204.8160121	283.724437	232.7766734	332.3068092	
	204.5021	286.3656	112.4639	286.3656	189.613617	286.3656457	224.2767605	350.1339122	
	183.0244	279.2311	79.48609	279.2311	172.9510863	279.231132	214.7955738	359.6318746	
	160.7149	260.2594	48.92462	260.2594	154.3050413	260.2594341	203.5362879	357.2307922	
	138.2531	226.669	24.39486	226.669	132.8732757	226.6689899	189.0689622	336.8880186	
	116.8231	174.4074	12.54594	174.4074	107.3166358	174.4074049	168.5077042	287.2607476	
	98.79493	96.84943	27.58527	96.84943	75.10473431	96.84942892	134.9804727	183.5110507	
	36.83882	9.937462	28.08182	9.937462	18.96469159	9.937462118	38.91219939	21.59131648	
Sum	3955.344	3007.600	3041.524	3007.600	3655.803971	3007.599532	4072.940186	3714.137774	Janbu's modified method
		1.315		1.011		1.216		1.097	1.167
				Iteration number	Assumed Fs	Calculated Fs	Assumed Fs	Calculated Fs	
				1	1.315	1.233	1.315	1.139	
				2	1.233	1.218	1.139	1.104	
				3	1.218	1.216	1.104	1.097	

(a)

	Swedish method		Bishop method		Janbu's simplified method		
	M_r/R	M_d/R	M_r/R	M_d/R	M_r/R	M_d/R	For Saturated slope
	65.8771749	-4.20240671	68.98630279	-4.20240671	69.84981405	-4.24240767	
	116.3259518	-7.48904613	119.5534959	-7.48904613	120.1683516	-7.5144759	
	165.5997856	-4.10236586	166.9514589	-4.10236586	167.1092346	-4.10390666	
	213.2522008	5.658984975	211.7873753	5.658984975	211.7482542	5.661110416	
	258.8529261	21.49861814	254.571855	21.49861814	255.0126116	21.57161876	
	296.6336647	42.23645943	290.4965198	42.23645943	292.4589364	42.63849077	
	308.2311509	62.29504765	302.2189905	62.29504765	306.7640508	63.47347956	
	299.3901874	78.27344785	295.4470917	78.27344785	303.3756433	80.76773835	
	288.4165172	92.84609414	288.0277961	92.84609414	300.2757895	97.37414994	
	275.3689826	105.6519006	279.8525764	105.6519006	297.3825746	113.0679632	
	260.3267259	116.2949032	270.7794214	116.2949032	294.5913487	127.5671883	
	243.3960583	124.3314683	260.6195783	124.3314683	291.7576247	140.5047546	
	224.7212523	129.2522435	249.1166845	129.2522435	288.6676709	151.3842131	
	204.5021484	130.4554608	235.9125872	130.4554608	284.9848627	159.5054489	
	183.0243803	127.2052935	220.4884418	127.2052935	280.145223	163.8322984	
	160.7148571	118.5626311	202.0564031	118.5626311	273.1375334	162.738472	
	138.2530591	103.2603176	179.3428354	103.2603176	261.9920235	153.4712085	
	116.8231181	79.45226223	150.1012652	79.45226223	242.4199211	130.8632295	
	98.79492549	44.1202954	109.8172665	44.1202954	203.4066888	83.59947866	
	36.83881777	4.527066076	28.86716137	4.527066076	61.13259524	9.836044175	
sum	3955.344	1370.129	4184.995107	1370.128676	4806.380753	1691.996097	Janbu's modified method
		2.887		3.054		2.841	3.023

Iteration number	Assumed Fs	Calculated Fs	Assumed Fs	Calculated Fs
1	2.887	3.036	2.887	2.846
2	3.036	3.053	2.846	2.841
3	3.053	3.054	2.841	2.841

(b)

FIGURE 13 Screenshot of EXCELL program (LEM) showing the analysis result of Case 2: (a) Reservoir full of water; (b) Reservoir with rapid emptying

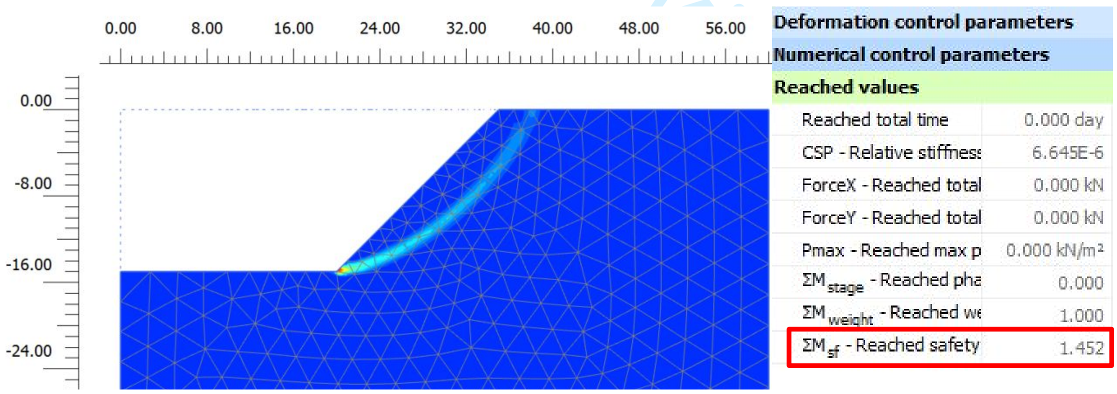


FIGURE 14 Simulation results from PLAXIS 2D

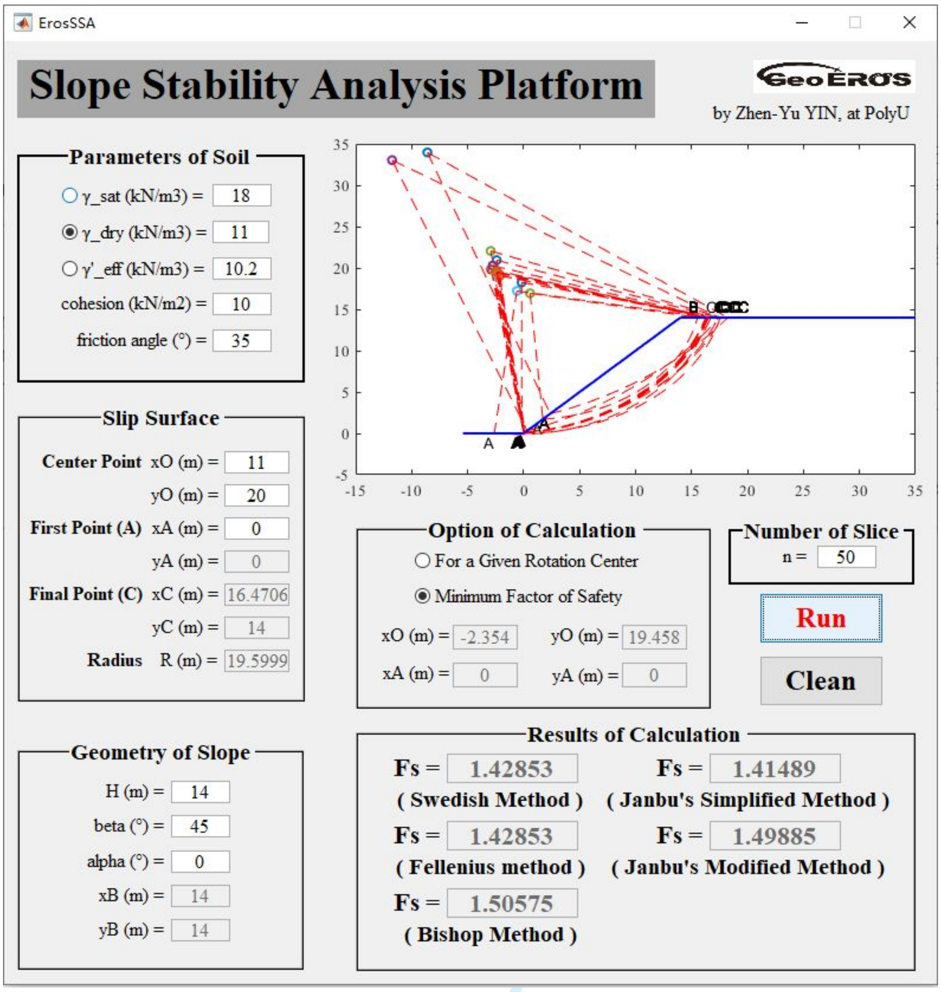


FIGURE 15 Screenshot of ErosSSA showing the analysis result of Case 3

review

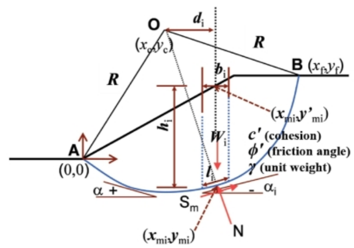


FIGURE 1 Reference diagram of parameters in the formulas for slope stability

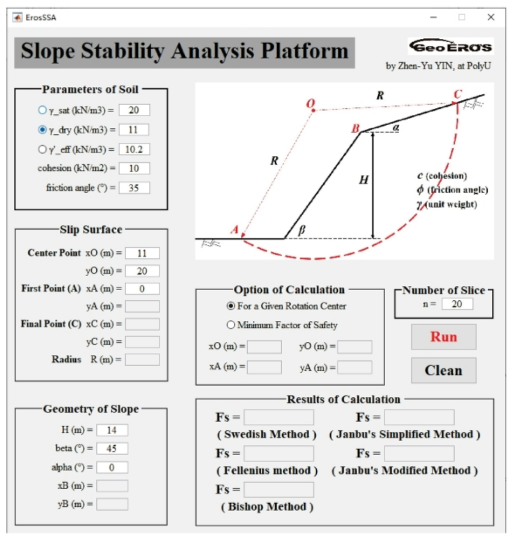


FIGURE 2 Screenshot of ErosSSA default window

1

209x296mm (300 x 300 DPI)

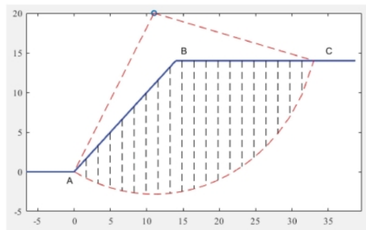
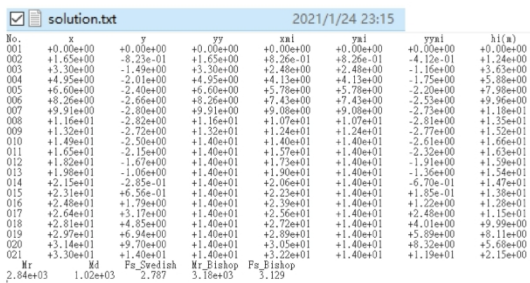


FIGURE 5 Screenshot of a typical calculation result figure



solution.txt 2021/1/24 23:15

No.	x	y	yy	xmi	ymi	yymi	hi(m)
001	+0.00e+00	+0.00e+00	+0.00e+00	+0.00e+00	+0.00e+00	+0.00e+00	+0.00e+00
002	+1.65e+00	-8.23e-01	+1.65e+00	+8.26e-01	+8.26e-01	-4.12e-01	+1.24e+00
003	+3.30e+00	-1.49e+00	+3.30e+00	+2.48e+00	+2.48e+00	-1.16e+00	+3.63e+00
004	+4.95e+00	-2.01e+00	+4.95e+00	+4.13e+00	+4.13e+00	-1.75e+00	+5.88e+00
005	+6.60e+00	-2.40e+00	+6.60e+00	+5.78e+00	+5.78e+00	-2.20e+00	+7.98e+00
006	+8.26e+00	-2.66e+00	+8.26e+00	+7.43e+00	+7.43e+00	-2.53e+00	+9.96e+00
007	+9.91e+00	-2.80e+00	+9.91e+00	+9.08e+00	+9.08e+00	-2.73e+00	+1.18e+01
008	+1.16e+01	-2.82e+00	+1.16e+01	+1.07e+01	+1.07e+01	-2.81e+00	+1.35e+01
009	+1.32e+01	-2.72e+00	+1.32e+01	+1.24e+01	+1.24e+01	-2.77e+00	+1.52e+01
010	+1.49e+01	-2.50e+00	+1.40e+01	+1.40e+01	+1.40e+01	-2.61e+00	+1.66e+01
011	+1.65e+01	-2.15e+00	+1.40e+01	+1.57e+01	+1.40e+01	-2.32e+00	+1.63e+01
012	+1.82e+01	-1.67e+00	+1.40e+01	+1.73e+01	+1.40e+01	-1.91e+00	+1.59e+01
013	+1.98e+01	-1.06e+00	+1.40e+01	+1.90e+01	+1.40e+01	-1.36e+00	+1.54e+01
014	+2.15e+01	-2.85e-01	+1.40e+01	+2.06e+01	+1.40e+01	-6.70e-01	+1.47e+01
015	+2.31e+01	+6.56e-01	+1.40e+01	+2.23e+01	+1.40e+01	+1.85e-01	+1.38e+01
016	+2.48e+01	+1.79e+00	+1.40e+01	+2.39e+01	+1.40e+01	+1.22e+00	+1.28e+01
017	+2.64e+01	+3.17e+00	+1.40e+01	+2.56e+01	+1.40e+01	+2.48e+00	+1.15e+01
018	+2.81e+01	+4.85e+00	+1.40e+01	+2.72e+01	+1.40e+01	+4.01e+00	+9.99e+00
019	+2.97e+01	+6.94e+00	+1.40e+01	+2.89e+01	+1.40e+01	+5.89e+00	+8.11e+00
020	+3.14e+01	+9.70e+00	+1.40e+01	+3.05e+01	+1.40e+01	+8.32e+00	+5.68e+00
021	+3.30e+01	+1.40e+01	+1.40e+01	+3.22e+01	+1.40e+01	+1.19e+01	+2.15e+00

Mr	Md	Fs_Swedish	Mr_Bishop	Fs_Bishop
2.84e+03	1.02e+03	2.787	3.18e+03	3.129

FIGURE 6 Screenshot of "solution" file

3

209x296mm (300 x 300 DPI)

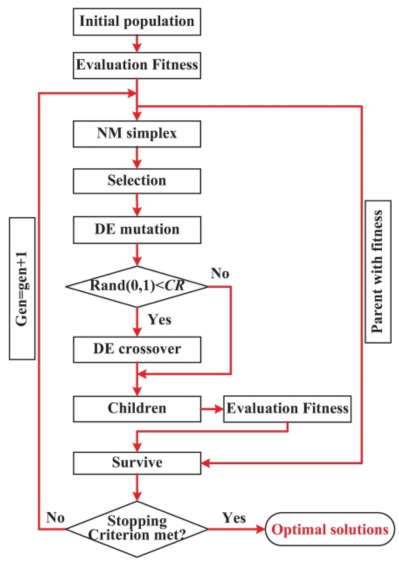


FIGURE 7 Flowchart of NMDE

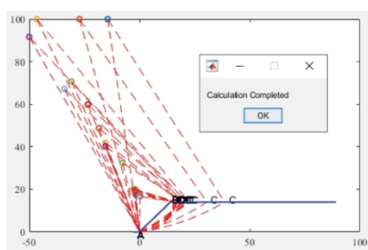


FIGURE 8 Screenshot of a typical result of the minimum factor of safety

4

209x296mm (300 x 300 DPI)

Intersection points				Middle points									For dry slope	
No_i	xi	yi	y'i											
1	0.00	0.00	0	No_mi	xmi	ymi	y'mi	Slice No.	hi (m)	bi (m)	αi (degree)	li (m)	M_r	M_d
2	2.00	-0.98	2	1	1.00	-0.49	1.00	1	1.49	2.00	-25.98	2.22	978.1876875	-327.379466
3	4.00	-1.73	4	2	3.00	-1.35	3.00	2	4.35	2.00	-20.52	2.14	1920.220425	-765.752939
4	6.00	-2.27	6	3	5.00	-2.00	5.00	3	7.00	2.00	-15.24	2.07	2847.326829	-923.776817
5	8.00	-2.63	8	4	7.00	-2.45	7.00	4	9.45	2.00	-10.09	2.03	3734.769475	-831.532876
6	10.00	-2.80	10	5	9.00	-2.72	9.00	5	11.72	2.00	-5.03	2.01	4561.768658	-515.480361
7	12.00	-2.80	12	6	11.00	-2.80	11.00	6	13.80	2.00	0.00	2.00	5310.039529	0
8	14.00	-2.63	14	7	13.00	-2.72	13.00	7	15.72	2.00	5.03	2.01	5962.822178	691.480361
9	16.00	-2.27	14	8	15.00	-2.45	14.00	8	16.45	2.00	10.09	2.03	6157.991411	1447.532876
10	18.00	-1.73	14	9	17.00	-2.00	14.00	9	16.00	2.00	15.24	2.07	5900.580174	2111.776817
11	20.00	-0.98	14	10	19.00	-1.35	14.00	10	15.35	2.00	20.52	2.14	5542.652477	2701.752939
12	22.00	0.00	14	11	21.00	-0.49	14.00	11	14.49	2.00	25.98	2.22	5087.166132	3187.379466
13	24.00	1.24	14	12	23.00	0.62	14.00	12	13.38	2.00	31.72	2.35	4538.898337	3532.539521
14	26.00	2.80	14	13	25.00	2.02	14.00	13	11.98	2.00	37.83	2.53	3905.837201	3690.81229
15	28.00	4.77	14	14	27.00	3.78	14.00	14	10.22	2.00	44.51	2.80	3202.469277	3596.770627
16	30.00	7.35	14	15	29.00	6.06	14.00	15	7.94	2.00	52.05	3.25	2459.199547	3144.370057
17	32.00	11.06	14	16	31.00	9.20	14.00	16	4.80	2.00	61.19	4.15	1760.07314	2110.544161
18	33.02	14.00	14	17	32.51	12.53	14.00	17	1.47	1.02	70.46	3.06	786.5887562	356.2569011
												sum	64656.591	23207.294
													FS	2.786

FIGURE 9 Traditional Excel method.

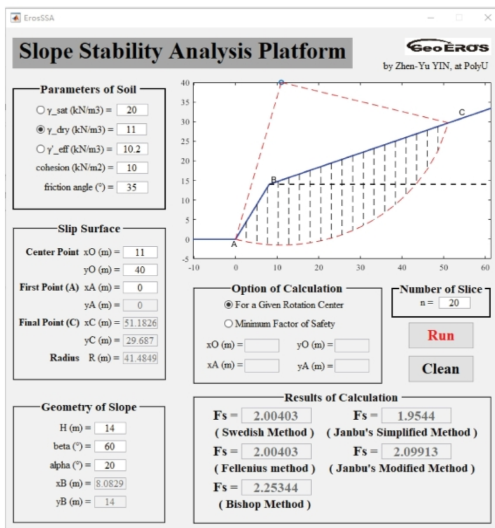


FIGURE 10 Screenshot of ErosSSA showing the analysis result of Case 1

5

209x296mm (300 x 300 DPI)

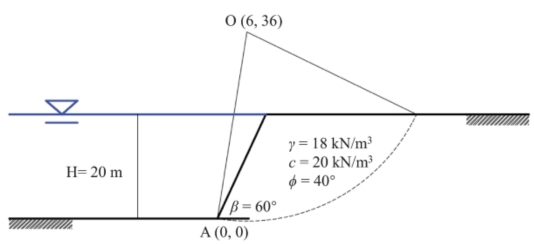
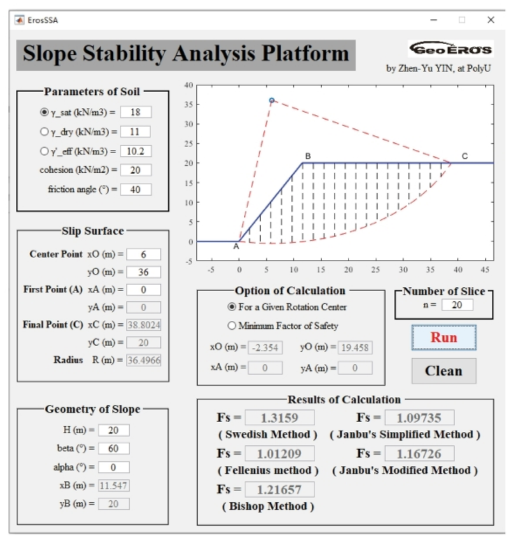


FIGURE 11 Schematic view of a reservoir full of water



(a)

6

209x296mm (300 x 300 DPI)

	Swedish method		Fellenius method		Bishop method		Janbu's simplified method		
	M_r/R	M_d/R	M_r/R	M_d/R	M_r/R	M_d/R	M_r/R	M_d/R	For Saturated slope (Rapid empty)
	65.87717	-9.2248	65.29433	-9.2248	73.35397894	-9.22479521	74.86635873	-9.31260221	
	116.326	-16.4394	115.7065	-16.4394	123.8834102	-16.4393695	125.0821846	-16.495191	
	165.5998	-9.00519	165.487	-9.00519	168.8832066	-9.00519336	169.2830755	-9.00857559	
	213.2522	12.42216	213.0966	12.42216	209.427677	12.42216214	209.1061552	12.42682774	
	258.8529	47.19209	257.0747	47.19209	246.3433632	47.19208861	245.8151036	47.35233385	
	296.6337	92.71418	290.7757	92.71418	275.3044076	92.71417925	275.4506118	93.59668705	
	308.2312	136.7452	296.0226	136.7452	280.6603681	136.7452265	282.5081205	139.3320283	
	299.3902	171.8198	279.4167	171.8198	268.9550765	171.8197636	273.3161764	177.2950354	
	288.4165	203.8085	258.9852	203.8085	257.06347	203.8084993	264.7122963	213.748134	
	275.369	231.9188	234.9806	231.9188	244.859534	231.9188061	256.5372601	248.1979681	
	260.3267	255.2815	207.7487	255.2815	232.2016588	255.2814948	248.6244914	280.0255353	
	243.3961	272.9227	177.7644	272.9227	218.9227256	272.9227353	240.783718	308.4250711	
	224.7213	283.7244	145.6884	283.7244	204.8160121	283.724437	232.7766734	332.3068092	
	204.5021	286.3656	112.4639	286.3656	189.613617	286.3656457	224.2767605	350.1339122	
	183.0244	279.2311	79.48609	279.2311	172.9510863	279.231132	214.7955738	359.6318746	
	160.7149	260.2594	48.92462	260.2594	154.3050413	260.2594341	203.5362879	357.2307922	
	138.2531	226.669	24.39486	226.669	132.8732757	226.6689899	189.0689622	336.8880186	
	116.8231	174.4074	12.54594	174.4074	107.3166358	174.4074049	168.5077042	287.2607476	
	98.79493	96.84943	27.58527	96.84943	75.10473431	96.84942892	134.9804727	183.5110507	
	36.83882	9.937462	28.08182	9.937462	18.96469159	9.937462118	38.91219939	21.59131648	
Sum	3955.344	3007.600	3041.524	3007.600	3655.803971	3007.599532	4072.940186	3714.137774	Janbu's modified method
		1.315		1.011		1.216		1.097	1.167

Iteration number	Assumed Fs	Calculated Fs	Assumed Fs	Calculated Fs
1	1.315	1.233	1.315	1.139
2	1.233	1.218	1.139	1.104
3	1.218	1.216	1.104	1.097

(a)

	Swedish method		Bishop method		Janbu's simplified method		
	M_r/R	M_d/R	M_r/R	M_d/R	M_r/R	M_d/R	For Saturated slope
	65.8771749	-4.20240671	68.98630279	-4.20240671	69.84981405	-4.24240767	
	116.3259518	-7.48904613	119.5534959	-7.48904613	120.1683516	-7.5144759	
	165.5997856	-4.10236586	166.9514589	-4.10236586	167.1092346	-4.10390666	
	213.2522008	5.658984975	211.7873753	5.658984975	211.7482542	5.661110416	
	258.8529261	21.49861814	254.571855	21.49861814	255.0126116	21.57161876	
	296.6336647	42.23645943	290.4965198	42.23645943	292.4589364	42.63849077	
	308.2311509	62.29504765	302.2189905	62.29504765	306.7640508	63.47347956	
	299.3901874	78.27344785	295.4470917	78.27344785	303.3756433	80.76773835	
	288.4165172	92.84609414	288.0277961	92.84609414	300.2757895	97.37414994	
	275.3689826	105.6519006	279.8525764	105.6519006	297.3825746	113.0679632	
	260.3267259	116.2949032	270.7794214	116.2949032	294.5913487	127.5671883	
	243.3960583	124.3314683	260.6195783	124.3314683	291.7576247	140.5047546	
	224.7212523	129.2522435	249.1166845	129.2522435	288.6676709	151.3842131	
	204.5021484	130.4554608	235.9125872	130.4554608	284.9848627	159.5054489	
	183.0243803	127.2052935	220.4884418	127.2052935	280.145223	163.8322984	
	160.7148571	118.5626311	202.0564031	118.5626311	273.1375334	162.738472	
	138.2530591	103.2603176	179.3428354	103.2603176	261.9920235	153.4712085	
	116.8231181	79.45226223	150.1012652	79.45226223	242.4199211	130.8632295	
	98.79492549	44.1202954	109.8172665	44.1202954	203.4066888	83.59947866	
	36.83881777	4.527066076	28.86716137	4.527066076	61.13259524	9.836044175	
sum	3955.344	1370.129	4184.995107	1370.128676	4806.380753	1691.996097	Janbu's modified method
		2.887		3.054		2.841	3.023

Iteration number	Assumed Fs	Calculated Fs	Assumed Fs	Calculated Fs
1	2.887	3.036	2.887	2.846
2	3.036	3.053	2.846	2.841
3	3.053	3.054	2.841	2.841

(b)

FIGURE 13 Screenshot of EXCELL program (LEM) showing the analysis result of Case 2:

(a) Reservoir full of water; (b) Reservoir with rapid emptying

8

209x296mm (300 x 300 DPI)

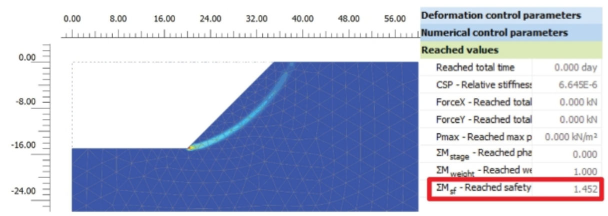


FIGURE 14 Simulation results from PLAXIS 2D

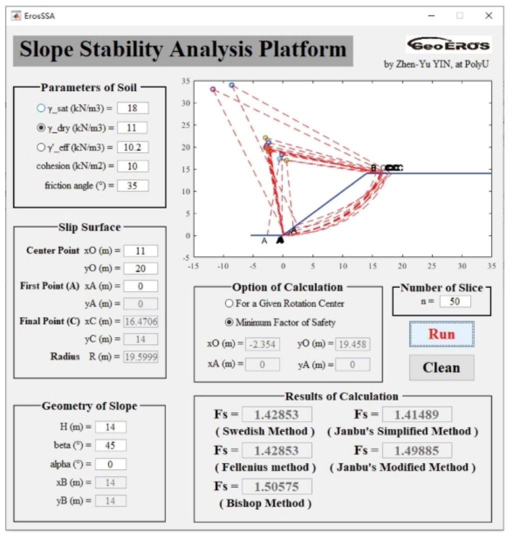


FIGURE 15 Screenshot of ErosSSA showing the analysis result of Case 3

209x296mm (300 x 300 DPI)