Comparison and Applicability Analysis of Different Slope Stability Analysis Methods Postprint

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Abstract

As highway construction progressively extends into complex terrain conditions, the importance of slope stability analysis in ensuring engineering safety has become increasingly prominent. Different analysis methods exhibit significant differences in applicability scope, computational accuracy, complexity, and engineering practicality; therefore, the rational selection of appropriate methods is of great significance for slope stability assessment. This study focuses on three typical methods most widely applied in slope stability analysis—the polygonal method based on limit equilibrium theory, the simplified Bishop method as an improved slice method, and the finite element strength reduction method based on numerical simulation—and systematically evaluates their engineering applicability through the establishment of a multi-dimensional evaluation system. Through case analysis, computation, and specific comparison, it is concluded that the polygonal method is suitable for slope analysis with straightforward computation and relatively simple geological conditions, the simplified Bishop method demonstrates enhanced computational accuracy and applicability compared to the former, while the finite element strength reduction method exhibits higher adaptability and accuracy under complex working conditions, thereby providing a scientific basis for method selection in different engineering scenarios.

Full Text

Preamble

Comparison and Applicability Analysis of Different Slope Stability Analysis Methods

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Abstract

As highway construction increasingly extends into complex terrain conditions, the importance of slope stability analysis for ensuring engineering safety has become ever more prominent. Different analytical methods exhibit significant variations in their scope of application, computational accuracy, complexity, and practical engineering utility. Selecting an appropriate method is therefore crucial for effective slope stability assessment. This study focuses on three widely-used methods in slope stability analysis: the polygonal method based on limit equilibrium theory, the simplified Bishop method as an improved slice technique, and the finite element strength reduction method based on numerical simulation. A multi-dimensional evaluation system is established to systematically assess their engineering applicability. Through case study calculations and comparative analysis, the results indicate that the polygonal method is suitable for simple geological conditions requiring straightforward calculations, the simplified Bishop method offers improved accuracy and broader applicability, while the finite element strength reduction method demonstrates superior adaptability and precision under complex working conditions. These findings provide a scientific basis for method selection across different engineering scenarios.

Keywords: Slope stability analysis; Polygonal method; Simplified Bishop method; Strength reduction method

1 Introduction

Highway construction frequently traverses mountainous, hilly, and loess plateau regions with complex topography, imposing higher demands on slope stability under natural conditions [1-3]. During construction, the original rock-soil structure may be disturbed, creating new artificial slopes. Consequently, conducting slope stability analysis and implementing appropriate reinforcement measures are essential for ensuring engineering safety and minimizing economic losses. In recent years, slope stability analysis methods have continuously evolved, including the polygonal method, simplified Bishop method, and finite element strength reduction method, which have enhanced analytical precision and efficiency while providing scientific support for slope design and management [4,5].

Slope stability is influenced by numerous factors, including natural elements such as topography, geological environment, precipitation, groundwater, and rock weathering, as well as human factors like construction activities and understanding of slope deformation and failure mechanisms. The stability state is determined by the combined effects of these factors, and comprehensive analysis facilitates accurate prediction of deformation and failure mechanisms [6,7].

The polygonal method, simplified Bishop method, and finite element strength reduction method are currently the most commonly used approaches in slope stability analysis, each with distinct characteristics and applicable scopes [8,9]. The polygonal method, based on limit equilibrium theory, is suitable for homogeneous or near-homogeneous slopes. While computationally simple, its adaptability to complex geological conditions is limited [10]. The simplified Bishop method improves upon the polygonal method by considering soil self-weight and lateral pressure effects, thereby enhancing computational accuracy, yet it still struggles to fully capture slope failure processes under complex geological conditions [11,12]. The finite element strength reduction method, based on numerical analysis techniques, can simulate the complete deformation and failure process of slopes, making it suitable for complex geological environments with high precision, though it requires greater computational resources and specialized software [13,14].

Given these differences in applicability, this study systematically compares the three methods in terms of their application scope, computational accuracy, complexity, and engineering practicality, aiming to provide a scientific basis for selecting appropriate slope stability analysis methods across different engineering scenarios.

2 Polygonal Method

2.1 Basic Principles

The polygonal method plays an important role in slope stability analysis and has garnered significant attention in practical engineering applications. This approach simplifies the slip surface by discretizing it into several polygonal segments to evaluate overall slope stability. Its implementation relies on detailed geological survey data and slope morphology analysis to accurately determine the slip surface location, thereby enhancing the scientific rigor and reliability of the analysis.

The first and most critical step in applying the polygonal method is slip surface determination, which directly affects the accuracy of subsequent normal and shear stress calculations and safety factor evaluation. Engineers must comprehensively assess slip surface location by integrating geological survey data with slope morphological characteristics to ensure computational accuracy and rationality, thereby providing reliable data for further analysis. Following slip surface determination, normal and shear stresses on the slip surface must be calculated based on mechanical principles and relevant formulas to ensure accurate stress analysis. These stress calculations not only reflect the slope stability state but also provide critical data support for safety factor assessment, offering a scientific basis for slope stability analysis and engineering decision-making.

2.2 Case Study Calculation

When the slip surface consists of multiple slope segments, it can be treated as a polygonal slip surface. This case study analyzes the K117+980 cross-section from the K117+700∼K119+700 segment of a highway using the polygonal method for slope stability evaluation.

The simplified slip surface model is shown in [Figure 1: see original paper]. The slope is divided into four slices, and the unbalanced thrust method within the polygonal method framework is employed for stability verification.

The basic formula for the unbalanced thrust method is:

$$\Psi_i = \cos(\alpha_{i-1} - \alpha_i) - \frac{\tan \varphi_i}{K} \sin(\alpha_{i-1} - \alpha_i)$$

$$E_i = W_i \sin \alpha_i - \frac{c_i l_i + W_i \cos \alpha_i \tan \varphi_i}{K} + E_{i-1} \Psi_i$$

where W_i is the weight of slice i, α_i is the angle between the slice base and horizontal direction, c and φ are the soil cohesion and internal friction angle respectively, and E is the residual sliding force.

The foundation soil unit weight is 19.5 kN/m^3, cohesion $c = 12$ kPa, and internal friction angle $\varphi = 26°$. The slip surface is divided into four soil masses numbered 1-4 from left to right for sequential unbalanced thrust analysis.

(1) Residual sliding force calculation for Soil Mass 1
From CAD, the area $S_1 = 64.3784$ m^2, and the angle between the slip surface base and horizontal direction $\alpha_1 = 32°$.
Weight $W_1 = 19.5 \times 64.3784 = 1255.38$ kN/m.
Residual sliding force:

$$E_1 = 1255.38 \times \sin 32° - \frac{12 \times 13.67 + 1255.38 \times \cos 32° \times \tan 26°}{1.35} = 159.11 \text{ kN/m}$$

(2) Residual sliding force calculation for Soil Mass 2
From CAD, the area $S_2 = 128.1401$ m^2, and $\alpha_2 = 23°$.
Weight $W_2 = 19.5 \times 128.1401 = 2498.73$ kN/m.
Transfer coefficient:

$$\Psi_1 = \cos(32° - 23°) - \frac{\tan 26°}{1.35} \sin(32° - 23°) = 0.91$$

Residual sliding force:

$$E_2 = 2498.73 \times \sin 23° - \frac{12 \times 22 + 2498.73 \times \cos 23° \times \tan 26°}{1.35} + 159.11 \times 0.91 = 302.45 \text{ kN/m}$$

(3) Residual sliding force calculation for Soil Mass 3
From CAD, the area $S_3 = 131.0297$ m^2, and $\alpha_3 = 12°$.
Weight $W_3 = 19.5 \times 131.0297 = 2555.08$ kN/m.
Transfer coefficient:

$$\Psi_2 = \cos(23° - 12°) - \frac{\tan 26°}{1.35} \sin(23° - 12°) = 0.91$$

Residual sliding force:

$$E_3 = 2555.08 \times \sin 12° - \frac{12 \times 22 + 2555.08 \times \cos 12° \times \tan 26°}{1.35} + 302.45 \times 0.91 = 193.32 \text{ kN/m}$$

(4) Residual sliding force calculation for Soil Mass 4
From CAD, the area $S_4 = 64.3264 \text{ m}^2$, and $\alpha_4 = 1°$.
Weight $W_4 = 19.5 \times 64.3264 = 1254.36$ kN/m.
Transfer coefficient:

$$\Psi_3 = \cos(12° - 1°) - \frac{\tan 26°}{1.35} \sin(12° - 1°) = 0.91$$

Residual sliding force:

$$E_4 = 1254.36 \times \sin 1° - \frac{12 \times 14.21 + 1254.36 \times \cos 1° \times \tan 26°}{1.35} + 193.32 \times 0.91 = -557.52 \text{ kN/m} < 0$$

Since $E_4 < 0$, the overall anti-sliding capacity is sufficient, indicating that the slope with this polygonal slip surface is safe and stable under the safety factor of 1.35.

2.3 Advantages and Limitations

The polygonal method offers several advantages in slope stability analysis, including simplicity, intuitive understanding, low computational demand, and ease of practical application. These characteristics make it an effective tool for rapid slope stability assessment, particularly when complex geological data are unavailable or during emergency situations requiring preliminary analysis. By assuming a polygonal slip surface shape, this method simplifies calculations while providing relatively quick stability evaluation results.

However, the polygonal method has notable limitations. First, the simplified assumption of a polygonal slip surface may not accurately reflect the actual complexity of slip surfaces in real engineering projects. When slip surfaces are influenced by multiple factors such as geological conditions, groundwater levels, and loading effects, this assumption can lead to significant analytical errors. Second, the method fails to consider internal stress distribution and deformation within the slope, which are crucial for analyzing complex slopes, especially when significant nonlinear stress-strain behavior is present. In such cases, the polygonal method cannot provide adequate analytical justification.

In summary, the polygonal method is a highly practical slope stability analysis approach that demonstrates strong advantages for preliminary assessment of simple slopes. Nevertheless, its application is limited when facing complex geological conditions or when in-depth analysis of internal stress and deformation behavior is required, as it cannot provide sufficiently accurate results for such scenarios.

3 Simplified Bishop Method

3.1 Basic Principles

The simplified Bishop method has been widely applied in slope stability analysis due to its efficiency and accuracy. Based on the classical Bishop method, this approach employs a series of simplified computational steps to determine the slope safety factor more rapidly and precisely.

To implement the simplified Bishop method, geometric parameters of the slope and mechanical properties of the soil must first be obtained. Geometric parameters include slope inclination, height, and width, while mechanical properties primarily involve cohesion, internal friction angle, and unit weight. With these parameters, the simplified Bishop method can effectively determine the slip surface location based on geometric shape and shear stress distribution. The shear stress calculation relies on soil mechanical properties and slope geometric parameters, while slip surface determination is based on force polygon closure and moment equilibrium conditions to ensure computational simplicity and result accuracy.

Once the slip surface and shear stresses are determined, the slope safety factor can be calculated. The safety factor is a critical parameter representing slope stability, where larger values indicate greater stability. By comparing the calculated safety factor with a predetermined threshold, slope stability can be evaluated and appropriate measures can be implemented to ensure safety.

3.2 Case Study Calculation

The same K117+980 cross-section from the K117+700∼K119+700 highway segment is analyzed using the simplified Bishop method for comparison with the polygonal method and the subsequent strength reduction method. The allowable safety factor $[K] = 1.35$.

The specific calculation formula is:

$$K = \frac{\sum_{i=1}^{n}(c_i l_i + W_i \tan\varphi_i)\frac{1}{m_{\alpha i}}}{\sum_{i=1}^{n} W_i \sin\alpha_i}$$

where

$$m_{\alpha i} = \cos\alpha_i + \frac{\tan\varphi_i}{K}\sin\alpha_i$$

The safety factor for each slip surface is calculated using an iterative approach:

1. Assume an initial safety factor $K_{\text{assumed}} = 1$, calculate $m_{\alpha i}$ and the resisting and driving forces for each slice.

2. Accumulate resisting and driving forces for all slices and compute the calculated safety factor $K_{\text{calculated}}$.
3. Check if $|K_{\text{assumed}} - K_{\text{calculated}}| < 0.001$. If not, set $K_{\text{assumed}} = K_{\text{calculated}}$ and repeat steps (1) and (2).

The slip circle center auxiliary line EF is determined using the 4.5H method. Since the fill slope ratio is 1:1.5, the auxiliary line angle values from the reference table give $\beta_1 = 26°$ and $\beta_2 = 35°$. After locating point F, five circle centers are established with radii: $R_1 = 30.062$ m, $R_2 = 31.842$ m, $R_3 = 34.421$ m, $R_4 = 37.636$ m, and $R_5 = 41.337$ m.

The minimum safety factor is found to be $K_{\text{min}} = 1.5238 > [K] = 1.35$, indicating that the slope stability requirements are satisfied.

Analysis of the first slip circle:
The first slip circle is divided into 16 slices. For each slice, the width b_i, center height h_i, and horizontal distance from slice center to circle center x_i are measured to calculate the inclination angle α_i, base length l_i, area A_i, and weight W_i. Through iterative calculation, the safety factor for the first slip circle is $K_1 = 1.8352$.

shows the iteration process, while summarizes the safety factors for all five slip circles. [Figure 4: see original paper] plots the relationship between slip circle radius and safety factor, from which the minimum safety factor $K_{\text{min}} = 1.5238$ is obtained.

3.3 Advantages and Limitations

The simplified Bishop method offers significant advantages in slope stability analysis, primarily through its streamlined computational process and high accuracy. Based on mechanical equilibrium principles and incorporating soil strength parameters, this method effectively solves for stability coefficients under various working conditions. Compared with traditional methods, the simplified Bishop method considers not only slope geometry and loading conditions but also fully incorporates soil mechanical properties, thereby ensuring analytical accuracy and reliability.

Despite its high precision, the simplified Bishop method has certain limitations. First, it assumes a circular slip surface shape, which may deviate from actual slip surface morphology in real slopes. In practice, slip surfaces are often influenced by geological structures, groundwater conditions, and load distribution, potentially resulting in shapes that differ significantly from circular arcs. Therefore, this assumption must be carefully evaluated during application to ensure result reliability and applicability.

In summary, the simplified Bishop method provides an efficient and accurate computational approach for slope stability analysis, applicable to various slope types including soil slopes and fractured rock slopes. Although limited by its circular slip surface assumption, with proper applicability assessment, it remains an effective tool that can provide more precise analytical results, particularly for relatively complex engineering situations.

4 Finite Element Strength Reduction Method

4.1 Basic Principles

The finite element strength reduction method has gained extensive attention and research in slope stability analysis. This approach combines elastoplastic mechanics with finite element theory to simulate slope failure processes under external loads by progressively reducing soil strength parameters [15-18]. This analytical framework fully considers the nonlinear characteristics and stress-strain relationships of geomaterials, enabling more realistic and accurate slope stability assessment.

Practical application requires establishing an accurate finite element model with detailed slope geometry, properly defined material properties, and reasonable boundary conditions. These steps are critical for subsequent analysis accuracy. Through iterative calculations, soil strength parameters are progressively reduced while recalculating the slope' s stress and displacement fields at each iteration. This process continues until the slope reaches a critical failure state, at which point the iteration terminates.

The finite element strength reduction method addresses limitations of traditional limit equilibrium theory. Unlike conventional methods, it does not require pre-assumed slip surface shapes or locations and eliminates manual slice division. Combined with finite element analysis software (e.g., Midas-GTS) [19][20], it can automatically search for slip surfaces and calculate strength reserve safety factors. In essence, this method provides a more accurate and efficient analytical approach.

4.2 Case Study Calculation

The calculation formulas are as follows:

$$c_f = \frac{c}{F_s}$$

$$\tan\varphi_f = \frac{\tan\varphi}{F_s}$$

where c_f is the reduced cohesion and φ_f is the reduced friction angle. In the strength reduction method, the reduction factor F_s can initially be set to a small value to ensure near-elastic behavior at the start. F_s is then gradually increased, causing the reduced shear strength parameters to decrease until slope instability occurs at a specific reduced strength. The stability safety factor is the ratio of actual shear strength parameters to the reduced parameters at virtual failure.

Thus, the safety factor is determined by progressively increasing the reduction factor and observing the strength parameters at failure.

The same K117+980 cross-section is analyzed using the finite element strength reduction method with Midas GTS NX software. The model is simplified and appropriately extended as shown in [Figure 5: see original paper], with the simulation profile sized according to actual dimensions. The meshed model is presented in [Figure 6: see original paper].

Material properties are assigned as follows: unit weight = 19.5 kN/m^3, cohesion $c = 12$ kPa, and internal friction angle $\varphi = 26°$. After setting material parameters, boundary constraints and self-weight loading are applied. Using the SRM slope stability analysis, the total displacement and strain contours are obtained as shown in [Figure 7: see original paper] and [Figure 8: see original paper].

The stability coefficient calculated from finite element numerical simulation under natural conditions is 1.475, indicating a stable state.

4.3 Advantages and Limitations

The finite element strength reduction method is widely applied in slope stability analysis, demonstrating unique advantages particularly for complex slope engineering. By simulating deformation and failure processes under varying strength parameters without relying on pre-defined slip surfaces, this method more realistically reflects slope stability. With advances in computational technology, significant progress has been made in computational efficiency and analytical precision, broadening its application under complex engineering conditions. For problems involving complex geological conditions, nonlinear behavior, and three-dimensional stress states, this method provides efficient and accurate solutions that offer important technical support for engineering decision-making.

However, the method has certain limitations. The computational process involves numerous iterations, demanding substantial computational resources and time. Additionally, results are sensitive to the constitutive model, strength criteria, and parameter selection, where different parameters may lead to significant variations. Engineers must possess solid professional expertise to ensure reasonable selection. Furthermore, the method involves certain assumptions and simplifications in practical application, and their validity directly affects result accuracy.

Overall, the finite element strength reduction method represents the highest precision approach among the three methods, offering high adaptability for complex working conditions. Despite its high computational complexity, its application prospects continue to expand with advancing computational technology. When using this method, engineers should comprehensively consider project conditions and resources, apply the method reasonably, and carefully handle parameter settings and assumptions to ensure reliable results.

5 Conclusions

Selecting an appropriate analysis method is crucial for ensuring engineering safety in slope stability assessment. The polygonal method, simplified Bishop method, and finite element strength reduction method each possess distinct characteristics and applicable scenarios. Method selection should be based on specific engineering conditions and requirements.

(1) Polygonal Method: Suitable for simple slopes and preliminary evaluation. This method offers straightforward calculations and is appropriate when complex geological data are unavailable or for emergency decision-making. For homogeneous or near-homogeneous slopes, it can rapidly provide approximate stability assessments, but its limitation lies in its inability to handle actual failure processes under complex geological conditions.

(2) Simplified Bishop Method: Applicable to slopes where soil shear strength and three-dimensional stress states must be considered. More accurate than the polygonal method, it is suitable for relatively complex slope analysis, particularly when detailed shear stress distribution is required. It can provide higher safety factors than the polygonal method, though it remains limited by its assumption of a circular slip surface.

(3) Finite Element Strength Reduction Method: Appropriate for complex slope stability analysis, especially when considering nonlinear behavior and three-dimensional stress states. This method can accurately simulate failure mechanisms, including slip surface location and shape, and demonstrates better adaptability to complex geological conditions. Although it offers the highest precision, it requires greater computational cost, longer time, and specialized software support, making it suitable for scenarios demanding high accuracy and involving complex geological conditions.

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