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Rigorous back analysis of shear strength parameters of landslide slip

Ke ZHANG[1], Ping CAO[1], Rui BAO[1,2]

1. School of Resources and Safety Engineering, Central South University, Changsha 410083, China;
2. Kunming Prospecting Design Institute of China Nonferrous Metals Industry, Kunming 650000, China

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Abstract: A rigorous back analysis of shear strength parameters of landslide slip was presented. Kinematical element method was adopted to determine factor of safety and critical failure surface, which overcomes the disadvantage of limit equilibrium method. The theoretical relationship between the combination of shear strength parameters and stability state was studied. The results show that the location of critical slip surface, $F/\tan\phi$ and F/c depend only on the value of $c/\tan\phi$. The failure surface moves towards the inside of slope as $c/\tan\phi$ increases. According to the information involving factor of safety and critical failure surface in a specific cross-section, strength parameters can be back calculated based on the above findings. Three examples were given for demonstrating the validity of the present method. The shear strength parameters obtained by back analysis are almost consistent with their correct solutions or test results.

Key words: slope stability; back analysis; kinematical element method; shear strength parameter; critical failure surface

1 Introduction

The determination of shear strength for landslide slip is an important research object in slope stability analysis. It is widely accepted that the shear strength parameters obtained by back analysis are more reliable than those by laboratory or in-situ test. However, back analysis is a much more difficult task. Many studies have indicated that it is insufficient to assess shear strength parameters from the information provided by a failure surface. This can be done in two ways [1−3]: one is by assuming one of these parameters; the other is by establishing a set of simultaneous equations involving the information of two cross-sections. The back analysis can also be treated as the optimization problem. NGUYEN [4] developed a simple and quick method for the back calculation of slope failures by the secant method. LI et al [5] presented hybrid genetic algorithm, and used the optimization algorithm to identify the shear strength parameters of geotechnical materials. JIANG and YAMAGAMI [6,7] illustrated the theoretical relationship between the strength parameters and the critical slip surface, and produced a new method for back analysis of strength parameters.

One of the key problems of back analysis is to calculate the factor of safety. The limit equilibrium method was adopted in the aforementioned researches, and they assumed that the slip surface is a circular one. Since this method is a statically indeterminate problem, assumptions on the inter-slice shear forces are employed to render the problem statically determinate. It is difficult to assess the accuracy of the limit equilibrium solution.

Kinematical element method (KEM) is an advanced slope limit analysis technology presented by GUSSMANN [8] with strong theoretical background. CAO and GUSSMANN [9] improved this method, and developed KEM analysis software. GUSSMANN [10] solved the limit-load problem by the KEM. LI et al [11] used KEM to analyze bottom stability of foundation pit. The main advantages of KEM are as follows: 1) it avoids assumptions of inter-slice forces in limit equilibrium method; 2) no assumption needs to be made on geometry of the slip surface; and 3) the inter-element boundaries do not have to be vertical.

The internal relationship between the combination

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Corresponding author: Ke ZHANG; Tel: +86-13467530581; E-mail: zhangke_csu@163.com
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of shear strength parameters and stability state was studied. Based on the above-mentioned relationship, a rigorous back analysis combining KEM was presented, which provided a practical and rigorous way to determine shear strength parameters of landslide slip. According to the information involving the factor of safety and the critical slip surface in a specific cross-section, strength parameters can be back calculated.

2 Theoretical background of KEM

The theory of KEM includes three parts: kinematics analysis, static analysis and optimization. First, plastic sliding zone is divided into several block elements called kinematical elements (Fig. 1). The normal force and shear force acting on the internal boundary satisfy Mohr–Coulomb failure criterion.

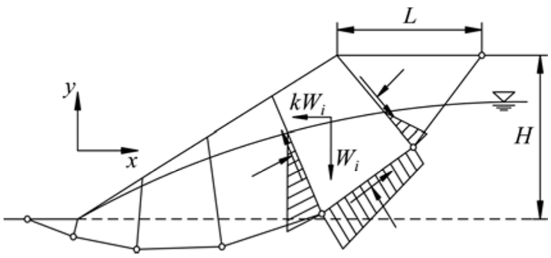

Fig. 1 Slope stability analysis model of KEM

Taking the compatibility condition of movement for elements, kinematics equation is given as

$$\boldsymbol{K}\cdot\boldsymbol{V}+\hat{\boldsymbol{V}}=0 \quad (1)$$

where $\boldsymbol{K}$ represents kinematics coefficient matrix, $\boldsymbol{V}$ represents the vector of unknown displacements of elements, and $\hat{\boldsymbol{V}}$ represents the known displacements vector on flexible boundary.

After solving the above equations, the directions of relative movement of elements are obtained. The horizontal and vertical force equilibriums for each element are converted into the matrix form, and effective normal force applied on the element is taken as unknown quantity,

$$\boldsymbol{K}_{\rm s}\cdot\boldsymbol{N}+\boldsymbol{F}=0 \quad (2)$$

where $\boldsymbol{K}_{\rm s}$ represents the static coefficient matrix, $\boldsymbol{N}$ represents the vector of unknown effective norm stress on the element, and $\boldsymbol{F}$ represents the vector of known force.

The factor of safety is obtained by employing iteration process after solving the static equations. Factor of safety is taken as an objective function, and the coordinates of the points defining the failure surface are taken as the control variables. Optimization algorithm is used to search the minimum factor of safety and critical slip surface.

3 New back analysis

3.1 Theoretical background

In slope stability analysis, the factor of safety F is usually defined as the ratio of the shear strength of the soil to the shear stress necessary to bring the slope into a state of limit equilibrium [12]. The strength of the soil is usually described by Mohr–Coulomb criterion as a function of the cohesion c and friction angle ϕ. F can be given by

$$F=\frac{c}{c^{\rm cr}}=\frac{\tan\phi}{\tan\phi^{\rm cr}} \quad (3)$$

where $c^{\rm cr}=c/F$ and $\phi^{\rm cr}=\tan^{-1}(\tan\phi/F)$ are the strength parameters necessary only to maintain the slope in limit equilibrium.

In order to demonstrate the internal relationship between the combination of strength parameters and stability state, one may consider a homogeneous slope with shear strength parameters c and ϕ. The location of critical slip surface and factor of safety F can be uniquely determined, and $c/\tan\phi=c^{\rm cr}/\tan\phi^{\rm cr}$ is obtained from Eq. (3). Let another slope be comprised of soil with shear parameters $c'=w_c c$ and $\phi'=\tan^{-1}(w_\phi\tan\phi)$, and other parameters remain constant. The location of critical slip surface and factor of safety F' can also be determined. Let $c'/\tan\phi'=c^{\rm cr}/\tan\phi^{\rm cr}$, which means that the parameters are all the same under limit equilibrium state. At the moment $c/\tan\phi=c'/\tan\phi'$ and $w_c=w_\phi=w$. Based on the definition of factor of safety, $F'=wF$ is obtained. The relationship is given by

$$\begin{cases}F'/\tan\phi'=F/\tan\phi\\ F'/c'=F/c\end{cases} \quad (4)$$

Many researchers have developed stability charts of simple homogeneous slopes by the relationship described above [6,12,13].

To demonstrate the theoretical relationship between $c/\tan\phi$ and stability state ($F/\tan\phi$, F/c and location of critical slip surface), the multi-step slope from Ref. [14] was selected as the analysis example. The soil parameter values are listed as follows: unit weight γ=18 kN/m^3, cohesion c=60 kPa, and friction angle ϕ=18°. The factor of safety and critical failure surface are obtained by KEM.

Five different combinations of strength parameters (c and ϕ) with the same value of $c/\tan\phi$ were considered. The results are shown in Table 1 and Fig. 2. The location of critical slip surface and the values of $F/\tan\phi$ and F/c remain the same for the constant value of $c/\tan\phi$.