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Influences of material dilatancy and pore water pressure on stability factor of shallow tunnels

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Abstract: Explicit finite difference code was used to calculate the stability factors of shallow tunnels without internal support in limit state. The proposed method was formulated within the nonassociative plasticity. For the shallow tunnels in soft clay, without considering the influences of pore water pressure and dilatancy, numerical results were compared with the previously published solutions. From the comparisons, it is found that the present solutions agree well with the previous solutions. The accuracy of the strength reduction technique was demonstrated through the comparisons. The influence of the pore water pressure was discussed. For the shallow tunnels in dilatant cohesive-frictional soils, the dilatant analysis was carried out.

Key words: shallow tunnel; strength reduction method; dilatancy; pore water pressure

1 Introduction

The determination of the shallow tunnel stability is a very important issue for most engineers. Many researchers have attempted to develop and elaborate the methods for tunnel stability calculation. Limit analysis, characteristics and limit equilibrium methods are the three classical methods in soil stability studies, and are widely used in geotechnical engineering such as slope, retaining walls, braced excavations and bearing capacity of foundations. With the rapid development of computer hardware and software, an alternative tool for geotechnical stability analysis is numerical simulation method based on either the finite element technique or finite difference technique, which becomes more flexible and powerful tool for stability analysis. These numerical methods often incorporate the strength reduction technique, which makes the critical failure surface to be found automatically. However, limit analysis and slices of limit equilibrium methods assume that failure occurs by sliding along a slip surface.

Strength reduction method (SRM) was proposed as early as 1955 by BISHOP. It incorporates finite element, finite difference or limit equilibrium method, and is widely used in all kinds of geotechnical stability problems. According to the SRM, DAWSON et al[1] used the explicit finite difference code to compute the stability factors of homogeneous soil slopes. Compared with CHEN's solutions, DAWSON concluded that the strength reduction results are very similar to the solutions of CHEN[2] by limit analysis. This confirms the strength reduction solution is effective. By comparing the safety factors and the locations of critical failure surfaces obtained by the limit equilibrium method and SRM for various slopes, CHENG et al[3] found that the results from these two methods are generally in good agreement under the condition of homogeneous soil slope. The SRM was also applied by researchers[4−8] to study slope stability problems. It is obvious that SRM is widely used in slope stability analysis and developed as a perfect theory. However, SRM is rarely applied in studying stability of shallow tunnels. So, how to use SRM to investigate the tunnel stability is a new challenge for tunnel engineers.

In the case of dense granular materials, a key factor in its constitutive behavior is the presence of dilatancy. Dilatancy, in the context of plasticity theory, manifests itself as nonassociativity in the flow rule. The volume of soil changes in the process of shear deformation, and volumetric change is a key factor which influences the shear strength of soil. So, dilatancy has a great effect on the stability of soils. Using the finite difference code, YIN and WANG[9] examined the ultimate bearing

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capacity of a strip footing by taking into account of the influence of dilatancy, and compared the calculated results with the classical solutions. WANG et al[10] investigated the effect of dilatancy angle on the safety factor of soil slope incorporating nonassociated flow rule in the upper bound limit analysis. YANG et al[11−12] estimated the seismic bearing capacity of a strip footing on the dilatant slopes using the upper bound method of limit analysis. The influences of different flow rules on the failure mechanism was discussed. A number of researchers used numerical simulation technology to calculate the stability problems[13−16]. However, no investigation seems to have been performed to calculate the stability factors of shallow tunnels, incorporating a nonassociated flow rule into the tunnel stability analysis.

The assessment of stability for tunnels and underground openings is based on the classification of surrounding geomaterials, which is derived from geological reconnaissance report and experience. In this work, the explicit finite difference code based on SRM is used to evaluate the stability of shallow tunnels with the nonassociated flow rule under the condition of plane strain. The shallow tunnel is subjected to pore water pressure. Numerical results are compared with the previously published solutions. The influence of pore water and nonassociative plasticity is discussed.

2 Stability factors using SRM

2.1 Finite difference based on SRM

Stability assessments of shallow tunnels require limit state calculations, which differ from those in structural engineering. This is due to the fact that soil weight not only contributes to the main load on shallow tunnels but also constitutes to the forces both resisting and driving the collapse. Similar to the common definition of the safety factor of soil slopes by BISHOP [17], the safety factor of shallow tunnels is defined as the ratio of the actual soil shear strength to the minimum shear strength required to prevent failure. Therefore, finite element or finite difference program is often employed to calculate the safety factor of shallow tunnels by reducing the soil shear strength until collapse occurs. If the shallow tunnels are unstable, the finite difference calculation will not converge in element computation. Through reducing the shear strength parameter of soil, the element computation will undergo the process from converging to non-converging when the soil reaches failure state. The reduction factor is defined as

$$c_n=c_0/F_n \tag{1}$$

$$\tan\varphi_n=(\tan\varphi_0)/F_n \tag{2}$$

where F_n is the reduction factor; c_0 and φ_0 are the actual cohesion and actual friction angle of soil, respectively; and c_n and φ_n are a series of trial cohesion and trial friction angle which have been reduced. Then, numerical simulations are run for a series of trial cohesion and trial friction angle until the shallow tunnel reaches failure state, and the corresponding maximum reduction factor is the safety factor of the shallow tunnels at the time. The detailed process is as follows: F_n is a sequence of number from F_1 to F_n, and the c_n and φ_n corresponding to F_n are also a sequence of number which is represented as $c_1=c_0/F_1$ and $\tan\varphi_1=(\tan\varphi_0)/F_1$, ···, $c_n=c_0/F_n$ and $\tan\varphi_n=(\tan\varphi_0)/F_n$. Then, c_1 and φ_1, c_2 and φ_2, ···, c_n and φ_n are used to calculate the nodal unbalanced force.

The convergence criterion for finite difference is the nodal unbalanced force, which is obtained from the sum of forces acting on a node from its neighboring elements. Theoretically, a node is in equilibrium state when the nodal unbalanced force is equal to zero. At present, the unbalanced nodal force is normalized by the gravitational body. If the maximum unbalanced force is less than 10^{-3} for the case of c_{n-1} and φ_{n-1}, while the maximum unbalanced force is larger than 10^{-3} for the case of c_n and φ_n, the node is in the equilibrium state. The corresponding c_n and φ_n are the critical values of cohesion and friction angle, respectively, which are the minimum shear strength necessary to maintain limit equilibrium of the shallow tunnels. According to the safety factor definition of shallow tunnels mentioned above, the safety factor is the ratio of the actual soil shear strength to the critical shear strength that is the minimum shear strength to prevent collapse. Therefore, the safety factor is the reduction factor corresponding to the critical shear strength.

2.2 Stability factor with nonassociative plasticity

According to a series of experiment results, BROMS and BENNERMARK[18] proposed an equation for calculation of the stability factors of shallow tunnels in cohesive soil. The equation takes the form by

$$N=\frac{\sigma_{\mathrm{s}}-\sigma_{\mathrm{t}}+\gamma(C+D/2)}{c_{\mathrm{u}}} \tag{3}$$

where C is the tunnel depth and D is the tunnel diameter. There is a uniform pressure σ_s acting on the soil surface. A uniform fluid pressure or shoring acting on the tunnel face is represented as σ_t. γ is unit weight and c_u is undrained shear strength. The simplified mechanical model of the shallow tunnel is studied. DAVIS et al[19] argued that the stability factor is an approximate function of C/D and $\gamma D/c_u$, thus the problem can be regarded as finding the value of $(\sigma_s-\sigma_t)/c_u$ in its limit once the values of the parameters C/D and $\gamma D/c_u$ are fixed. Based on the limit analysis method, DAVIS et al[19] calculated the stability factors of shallow tunnels in cohesive soil.

Many experiments showed that almost the types of soils have the nature of dilatancy[19]. The adoption of the associated flow rule results is an over prediction of soil dilatancy. The introduction of a nonassociated flow rule is necessary for a reasonable representation of the soil dilatancy characteristics. The nonassociated flow rule can be classified into two types. The first type is the coaxial nonassociated flow rule, which shows the coaxiality of the principal directions of stresses and strain rates. The second type is the nocoaxial nonassociated flow rule, which shows the noncoincidence of the principal directions of stresses and strain rates. Dilatancy angle is the main parameter which reflects the dilatation property. Dilatancy angle ψ varies from zero to the internal friction angle $\varphi(0\leq\psi\leq\varphi)$. The $\varphi=\psi$ means that the soil follows an associated flow rule. Correspondingly, dilatancy factor, m, which relates the dilatancy angle to the soil friction angle, is defined as

$$m=\psi/\varphi \tag{4}$$

However, how to judge whether the simulation reaches limit equilibrium is crucial for calculating the safety factor. At present, the limit equilibrium state is determined by the convergence of finite difference calculation. If the distinction of unbalanced force couldn't meet the required convergent condition, the soil will reach the limit equilibrium state under the given reduction factor.

3 Numerical results

An elastic-plastic model with the Mohr-Coulomb failure criterion is employed in the modeling with the explicit finite difference code based on the SRM. The elastic parameters used are the bulk modulus of 133 MPa and Poisson ratio of 0.20. In the calculation, small-strain mode is adopted. For the shallow tunnels in soft clay, the friction angle is equal to zero, and values of pore water pressure factor, n, are 0, 0.25 and 0.5. An associated flow rule is used. For the shallow tunnels in dilatant cohesive-frictional soils, the internal friction angle is varied from 0˚ to 20˚ in 5˚ increment with nonassociated flow rule. For each value of internal friction angle, the dilatancy angle is varied according to the following expression of $\psi=m\varphi$ while the factor m=0, 1/3, 2/3 and 1.

The numerical model is established as follows. The discretization soil is 50 m deep and 40 m wide, and the whole domain is divided into 2 852 grids with 46 grids in the horizontal direction and 62 grids in the vertical direction. Horizontal displacements are fixed for nodes along the left and right boundaries while both horizontal and vertical displacements are fixed along the bottom boundary. At the same time, in order to model the ground displacement, upper boundary is set free in the two directions.

3.1 Comparisons

DAVIS et al[19] evaluated the stability factor of shallow tunnel in cohesive soil with limit analysis method, and determined the least supporting pressure when the tunnel was excavated.

For the shallow tunnels in soft clay, without considering the influence of pore water pressure and dilatancy, the present solutions using the SRM are presented and compared with the published solutions of DAVIS et al[19] using limit analysis method. With the ratio of C/D varying from 1 to 4, Fig.1 shows the stability factors corresponding to $\gamma D/c_u$=2 and φ=0˚ when the shallow tunnel has a factor of safety of 1. It is found from Fig.1 that the present stability factors are generally slightly higher than those of DAVIS et al[19] by limit analysis method. However, the maximum difference does not exceed 3.7%. As a result, the stability factors calculated by SRM are effective.

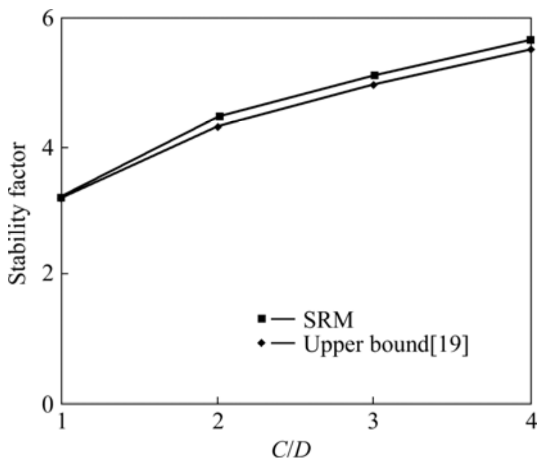

Fig.1 Comparisons of stability factors by SRM and limit analysis method

3.2 Effects of pore water pressure

Pore water is an important factor to be considered in shallow tunnel stability analysis. BISHOP put forth the concept of pore water pressure factor, and thought that pore water pressure is part of the overburden stress, varying with depth below the ground surface, which is given by

$$U=n\gamma z \tag{5}$$

where n is the pore water pressure factor, γ is the unit weight and z is the depth below the ground surface. In order to simplify the simulation, the pore water pressure is simplified as follows. What is taken into account in simplification of the influence of pore water pressure is the hydrostatic pressure effect on tunnel stability, not groundwater flow. Based on the effective stress principle, the stability factors are calculated using water-soil departure method. Pore water pressure is considered as an external force acting on the soil skeleton, similar to soil gravity.

DAVIS et al[19] only presented the numerical results for the case of n=0. In practice, due to the influence of water on natural soils, the pore water pressure factor n may be larger than 0. Fig.2 illustrates the influence of the pore water pressure factor n on the stability factors corresponding to $\gamma D/c_u$=2, φ=0° and m=0, with the C/D ratio ranging from 1 to 4, and n being equal to 0.25 and 0.5. From Fig.2, it is found that the stability factors decrease with the pore water pressure factor n increasing, and that the effect of pore water pressure is significant. The same phenomenon can also be found in Fig.3 corresponding to $\gamma D/c_u$=4, φ=0° and m=0.

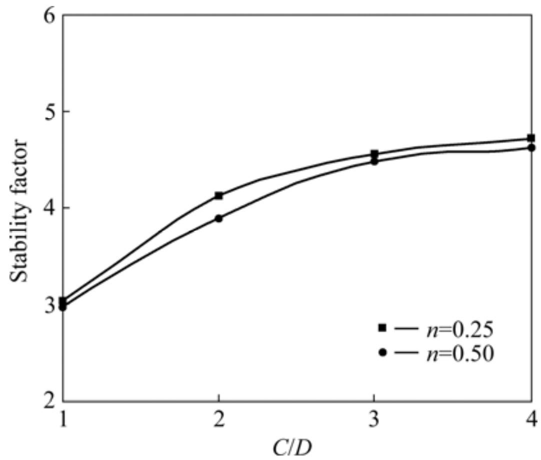

Fig.2 Influence of pore water pressure on stability factors corresponding to $\gamma D/c_u$=2, φ=0° and m=0

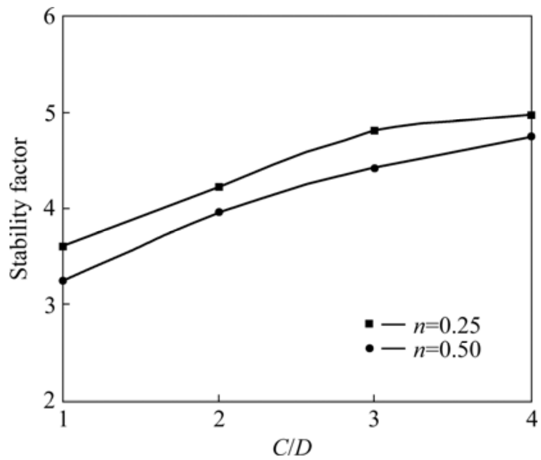

Fig.3 Influence of pore water pressure on stability factors corresponding to $\gamma D/c_u$=4, φ=0° and m=0

3.3 Effects of dilatancy

In the previously published literature, the research on dilatancy was concentrated on the bearing capacity of foundations, earth pressure of retaining walls and slope stability. However, few was focused on the stability of shallow tunnels. With dilatancy being considered, this work calculates the stability factors of shallow tunnels when dilatancy angle is equal to 0°, φ/3, 2φ/3 and φ. Fig.4 describes the stability factors at different friction angles and dilatancy angles. From Fig.4, it is found that the stability factor of shallow tunnel increases with the increase of friction and dilatancy angle.

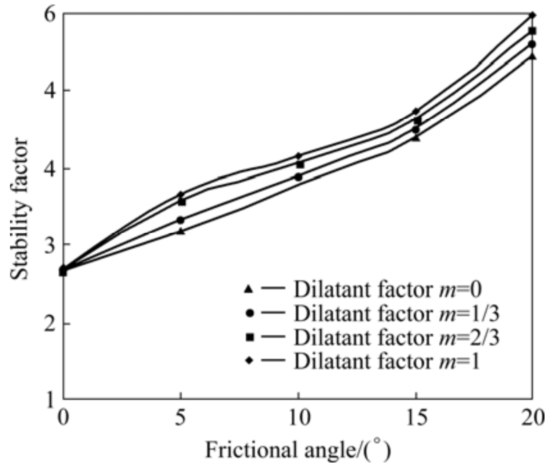

Fig.4 Stability factor of shallow tunnels under different dilatancy angles

4 Conclusions

Incorporating the effects of pore water pressure and dilatancy, the stability factors of shallow tunnels were investigated using explicit finite difference code based on SRM. The numerical results are presented and compared with the previously published solutions using limit analysis method. The comparisons show that the maximum difference between these two methods is less than 3.7%, which proves that SRM is a correct and effective numerical calculation method for calculating the stability factors of shallow tunnels. From the results of numerical calculations, it is found that the dilatancy angle and pore water pressure have significant influences on the stability factors of shallow tunnels in limit state. This work extends the calculation of the stability factors of shallow tunnels in cohesive soft soil to that in dilatant cohesive-frictional soil, where the influence of pore water pressure is considered.

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