Research on stability analysis of structural loess slopes based on combined tensile-compression-shear strength theory

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Abstract. The long-term stable existence of western high and steep loess slopes is closely related to the special structural properties of loess, and there are often tensile stress areas at the top of the slope. It is important to evaluate the stability of upright slopes by reasonably considering the tensile strength of loess. Based on the combined tensile-compressive-shear strength theory of structural loess, the structural parameter field, displacement increment contour distribution field and small principal stress distribution field law characteristics of an upright slope are analyzed and studied by using the finite method of strength discounting. The results show that when there is no load or constant load on the top of the slope, the structural parameter distribution field and displacement increment contour field of the slope show an obvious "slip zone", and the "slip zone" becomes more and more shallow with the increase of water content; when there is a uniform load on the top of the slope, the slip zone becomes more and more shallow with the increase of water content. When there is a uniform load on the top of the slope, the "shear zone" becomes more and more shallow with the increase of load intensity, and the surface uniform load intensity is bigger with the same water content, and there is a risk of local sliding; when there is no load at the top of the slope or the load remains unchanged, the small main stress field of the slope has different degrees of tension zone penetration, and the smaller the water content is, the bigger the tension zone is, and the amplitude is also bigger; when there is no load at the top of the slope or the load remains unchanged, the small main stress field of the slope has different degrees of tension zone penetration. The smaller the water content is, the larger the tensile zone is, and the amplitude is also large; when there is a uniform load on the top of the slope, the location of the tensile zone on the slope changes, shifting from the original back edge of the slope surface to a certain range on the top of the slope, and with the increase of the load strength, the tensile zone becomes smaller and smaller, and with the increase of the water content, the tensile zone also becomes smaller and smaller.

1. Introduction
Loess slopes have been eroded and cut by river valley gullies for a long time, and the prograde conditions are much more obvious than other slopes, with the characteristics of high and steep slopes. The structural properties of loess are the reason why these loess slopes can stand upright and remain stable for a long time. It is important to evaluate the stability of loess slopes by reasonably considering the structural properties of loess.

Many scholars at home and abroad have been studying the structural properties of soils from the fine mechanics, solid mechanics and geomechanics approaches. Among them, the research method of
geomechanics theory is to fully release the structural potential of in-situ soil by disturbance and saturation with water, and to construct a quantified parameter reflecting the structural properties based on this parameter, by which the relationship between structural properties and strength-deformation is analyzed, and the structural intrinsic model is established for the purpose of application\cite{1}.

In terms of the establishment of structural parameters, literature \cite{2} summarized the existing structural parameters in a more systematic comparison, and the applicability of structural parameters is characterized by different test conditions or data processing methods. Based on the reasonable structural parameters, the study of the development of strength and deformation of loess is the way to the practicality of structural properties. In the absence of a widely accepted structural intrinsic model and its maturity, the direct introduction of structural parameters as quantitative indicators into the strength theory\cite{3-5} is a way to consider the influence of structural properties at present. At present, the method of determining the loosening circle of surrounding rock based on structural parameters has been proposed\cite{6} based on the law of structural parameters change, and the instability discriminating criteria of slope\cite{7,8}.

It is worth noting that the tensile stress region often appears at the top of the slope, so the tensile strength of the soil body must be reasonably considered. In this regard, Dai Zihang\cite{9} analyzed the yielding damage behavior of geotechnical bodies in a mechanical sense, pointed out the problems of the Moore-Coulomb shear yielding criterion in slope stability analysis, used the Moore-Coulomb yielding criterion and the tensile-shear composite yielding criterion to intuitively explain the formation mechanism of the most dangerous sliding surface inside the slope, respectively, and used the strength discounting The finite element method was verified for the slope example analysis. Based on experimental studies, Rongjian Li et al\cite{10} established a bilinear strength formulation applicable to structural loess and applied it.

Based on this, this paper introduces the structural loess tensile-shear joint strength formula into the strength discounting finite element and conducts the slope stability analysis research.

2. Combined tensile-shear strength theory of structural loess

The current research on the shear strength of structural loess has yielded many results, and the introduction of structural parameters into the Mohr-Coulomb strength criterion is an effective way to introduce structural properties into engineering practice by studying the relationship between structural parameters and strength components, and many experimental results show that the cohesion in the strength components of soils varies hyperbolically with structural parameters, while the friction angle is basically constant\cite{3-5}. Since the process of establishing structural parameters already takes into account the effects of moisture, surrounding pressure, and shear deformation, this expression can reflect the strength properties of structural soils in a more reasonable way.

In addition, the large tensile strength of structural loess needs to be reasonably considered. Analysis of the test results based on tensile strength and triaxial shear tests under various stress paths shows that for soils with large tensile strength the stress point is not on the extension of the Mohr-Coulomb envelope, but in the middle of the intersection of the origin and the extension, as shown in Figure 1. In this case if the extension is used to describe the tensile properties of the soil obviously exaggerates the actual tensile strength of the soil, while it is too conservative if the tensile strength is not considered at all.

Therefore, in order to obtain a strength theory expression that can judge both tensile-shear damage and compression-shear damage, the corresponding Mohr-Coulomb strength of the main stress line of strength damage in the tensile-shear region can be changed into a smooth curve, which must pass the horizontal axis tensile strength stress point $\sigma_t$, with the Mohr-Coulomb strength line as an asymptote, derived in hyperbolic form The equation describing the joint strength is

\[ \tau_2 = (c + \sigma_t \tan \phi)^2 - (c + \sigma_1 \tan \phi)^2 \]  

(1)  

where the tensile strength $\sigma_t$, where the tensile strength, cohesion, and internal friction angle are all functions of structural parameters, is introduced.
3. Finite element implementation of combined tensile-shear strength theory

The currently established structural strength equations all consider the structural properties of loess by establishing a functional relationship between structural parameters and strength indicators, so it is very important to select reasonable structural parameters. As mentioned earlier, the stress ratio structural parameters among the currently established structural parameters have obvious advantages in describing the stress-strain development law. It is expressed in equation (2):

$$m_\eta = \frac{(q/p)_i}{(q/p)_r \cdot (q/p)_s}$$  \hspace{1cm} (2)

where \( m_\eta \) is the stress ratio structural parameter, \( (q/p)_i \) is the generalized shear stress, \( (q/p)_r \) is the spherical stress, and the subscripts \( i, r, \) and \( s \) represent the three test conditions of in-situ soil, remodeled soil, and saturated soil, respectively.

The literature [4] shows that the cohesion force shows a hyperbolic variation law with structural parameters, as shown in equation (3), while the angle of internal friction is essentially constant.

$$C(m_\eta) = \frac{m_\eta}{a + bm_\eta} - A$$  \hspace{1cm} (3)

This formula is followed in this paper to determine the relationship between cohesion and structural parameters: \( a, b, \) and \( A \) are the parameters fitted to the experimental data. \( a = 0.012, b = 0.003, \) and \( A = 81.1 \) for the tests conducted in this paper.

4. Stability analysis of upright slopes

4.1. Calculation model and parameters

In this paper, a 90° upright slope is selected for calculation and analysis. The test soil sample is loess with a depth of 3.5 to 4.5 m. The natural moisture content of the loess is 15.23%, the natural density is 1.78 g/cm³ and the dry density is 1.54 g/cm³ as determined by the conventional indoor test. The geometric parameters of the slope surface are shown in Figure 2 (unit: m).

The plane strain relationship is applied to simulate the deformation problem of the slope, and the elastic-plastic intrinsic model is used to simulate the strain relationship of the soil body. The mesh division of the computational model is shown in Fig. 3, using quadrilateral four-node cells with transverse constraints on the left and right boundaries, fixed constraints on the bottom boundary, and...
free boundaries on the upper boundary. The model is composed of 1,073 nodes and 1,000 cells. The model parameters are obtained from experiments, as shown in Table 1.

| Water content /% | Modulus of elasticity/Mpa | Density /g/cm³ | Poisson's ratio | Cohesion /kPa | Friction angle /° |
|-----------------|---------------------------|----------------|----------------|-------------|-----------------|
| 5               | 15                        | 1.49           | 0.25           | 220         | 28              |
| 10              | 12                        | 1.56           | 0.27           | 150         | 28              |
| 15              | 9                         | 1.63           | 0.29           | 90          | 28              |
| 20              | 6                         | 1.70           | 0.31           | 50          | 28              |
| 25              | 4                         | 1.80           | 0.33           | 20          | 28              |
| 30              | 2.5                       | 1.95           | 0.35           | 10          | 28              |

4.2. Calculation results and analysis

4.2.1. Structural parameter fields
Comparing the distribution field of structural parameters under each working condition, it can be found that: when there is no load or constant load on the top of the slope, the distribution field of structural parameters of the slope shows an obvious "slip zone", and with the increase of water content, the "slip zone" becomes more and more shallow; when there is a uniform load on the top of the slope, the "shear zone" becomes more and more shallow with the increase of load intensity. When there is a uniform load on the top of the slope, the "shear zone" becomes more and more shallow with the increase of load intensity, and under the same water content, the structural parameters at the top of the slope with greater uniform load intensity are smaller, and there is a risk of local sliding.

When there is no uniform load on the top of the slope, the "slip zone" in the structural parameter field is quite obvious, and the location of the potential sliding surface can be determined by the distribution field of the structural parameter, but when the load on the surface of the slope is 150kpa and the initial water content is 15, the distribution field of the slope resultant parameter is not very obvious. It is quite difficult to determine the location of potential sliding surface by the resultant parameter distribution field. Therefore, the structural parameter distribution field is conditional to determine the slope instability characteristics, and it is not applicable to all working conditions.

4.2.2. Displacement incremental contour field
Comparing the displacement incremental contour field under each working condition, it can be found that when there is no load on the top of the slope or the load remains unchanged, the displacement incremental contour field of the slope shows an obvious slip zone, and with the increase of water content, the slip zone becomes more and more shallow, and the safety factor gradually decreases until it is destroyed; when there is a uniform load on the top of the slope, the shear zone becomes more and more shallow with the increase of load intensity, and with the same water content, the surface uniform load the greater the intensity of the slip zone, the more shallow it is, and shows the characteristics of local sliding.

4.2.3. Small principal stress field
Comparing the small main stress field under each working condition, it can be found that when there is no load on the top of the slope or the load remains unchanged, the small main stress field of the slope has different degrees of tensile zone penetration, the smaller the water content is, the larger the tensile zone is, and the amplitude is also large. When there is a uniform load on the top of the slope, the tension zone of the slope will change its position, from the original back edge of the slope surface to a certain range on the top of the slope, and with the increase of load strength, the tension zone will become smaller.
and smaller, and with the increase of water content, the tension zone will also become smaller and smaller.

Figure 4 Distribution of structural parameter field of slope with 15% water content

Figure 5 Distribution of contour field of 15% slope displacement increment with water content

Figure 6 Distribution of small main stress field of slope with 15% water content

5. Conclusion
Based on the combined tensile-compressive-shear strength theory of structural loess, the structural parameter field, displacement increment contour distribution field and small principal stress distribution field law characteristics of an upright slope were analyzed and studied using the strength discounting finite method, and the following conclusions were drawn.

1) When there is no load or constant load on the top of the slope, the structural parameter distribution field and the displacement increment contour field of the slope show an obvious "slip zone", and with the increase of water content, the "slip zone" becomes more and more shallow.

2) When there is a uniform load on the top of the slope, with the increase of the load intensity, the "shear zone" becomes more and more shallow, and the surface uniform load intensity is greater under the same water content, and there is a risk of local sliding.

3) When there is no load at the top of the slope or the load remains unchanged, the small main stress field of the slope has different degrees of tension zone penetration, and the smaller the water content is, the larger the tension zone is, and the amplitude is also large.

4) When there is a uniform load at the top of the slope, the location of the tensile zone of the slope changes, shifting from the original back edge of the slope surface to a certain range at the top of the
slope, and with the increase of the load intensity, the tensile zone becomes smaller and smaller, and with the increase of water content, the tensile zone also becomes smaller and smaller.

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