Research on The Interaction Mechanism and Stability Analysis of Unsaturated Soil Slope and Support Structure

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Abstract

Unsaturated soil, as a widely existing soil in nature, has significant differences in mechanical properties compared to saturated soil. Especially when considering water migration and changes, its stability issues become more complex. Therefore, in-depth research on the interaction mechanism and stability of unsaturated soil slopes and support structures is significant. This study first analyzes the mechanical properties of unsaturated soil and the influence of water migration on soil strength based on the principles of unsaturated soil mechanics. It establishes a mechanical model for unsaturated soil slopes. Subsequently, the pseudo-dynamic method was used to simulate the response of slopes under dynamic loads such as earthquakes and rainfall, and the deformation and failure modes of unsaturated soil slopes were explored. Regarding

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support structures, this article studies the interaction mechanism between retaining walls, anchor rods, and unsaturated soil slopes. A mechanical model of the interaction between the support structure and unsaturated soil slopes was established by analyzing the influence of the support structure on the distribution of soil pressure on the slope, as well as the stability and bearing capacity of the support structure itself. In terms of stability analysis, this article uses numerical analysis methods such as the limit equilibrium and finite element methods to evaluate the overall stability of unsaturated soil slopes and support structures. Suggestions for optimizing the design of support structures were proposed by comparing the stability performance of slopes under different support schemes. The experiment shows that increasing soil cohesion by 1kPa per unit area can increase the stability coefficient by about 5%. The interface friction angle between the fill and the wall back increases by 1 degree, resulting in an increase of approximately 7% in the overturning stability coefficient.

Keywords: Retaining walls, pseudo dynamic method, unsaturated soil mechanics, overturning stability.

1 Introduction

In recent years, with the in-depth understanding of unsaturated soil mechanical behavior and pseudo-dynamic method, the research on earth pressure and overturning stability of retaining wall has gradually become one of the focuses of attention. Pseudo-dynamic method, as a method of simulating soil movement and the introduction of unsaturated soil mechanics principle, provides a more comprehensive and accurate analysis method for retaining wall design [1, 2]. Retaining wall is a kind of structure in civil architectural engineering. Its main function is to prevent soil from collapsing or cut off the extension of soil slope. It is widely used in various projects such as housing construction, railway and highway [3]. However, with the continuous development of contemporary infrastructure projects, the development and utilization of various spaces have led to the emergence of sloping soil with limited width behind high embankment retaining walls and retaining structures near excavation in cities. At this time, it will be inappropriate to continue to solve the earth pressure according to the assumption of semi-infinite soil, and it will also cause unnecessary economic waste when designing retaining walls. The existing analysis of retaining wall stability is generally divided into two categories, namely, checking calculation of anti-slip stability and checking calculation of anti-overturning stability [4, 5]. When conducting strength reduction analysis on unsaturated soil slopes, only the traditional soil mechanics constitutive model is used to reduce the shear strength of the slope soil, without fully considering the changes in soil suction, both the shear strength and compressive strength of the soil are reduced simultaneously. In addition, the strength reduction method for stability analysis of unsaturated soil slopes is developed and applied on the basis of traditional continuum mechanics, lacking consideration of the microscale effects of unsaturated soil, and lacking the introduction of regularization mechanism in the finite element simulation analysis of strength reduction for plastic sliding of slopes. Therefore, the current reduction for analyzing stability of unsaturated soil has obvious shortcomings and cannot accurately analyze the stability of unsaturated soil slopes.

Compared with semi-infinite soil, with the continuous exploration and utilization of urban space, more and more finite soil appears in life. Finite soil refers to the range of damaged soil: one is the finite soil between two walls, and the other is the finite soil with a slope on one side [6]. The checking calculation of anti-sliding stability needs to determine the ratio between the force resisting sliding and the force causing sliding; the higher the ratio, the safer it is, and vice versa. The stability calculation takes the toe of the wall as the moment center, and it is necessary to determine the ratio of the stable moment to the overturning moment [7]. Like the sliding calculation, the higher the ratio, the safer it is; the opposite is true [8, 9]. Using saturated soil theory to solve unsaturated soil engineering problems will affect engineering quality [10]. The most significant difference between the shear strength of unsaturated and saturated soil lies in the adsorption cohesion caused by matrix suction, which is significant but unstable and changes with the change of soil water content [11, 12]. Accidents may occur if the unstable adsorption cohesion is regarded as the stable, effective cohesion in saturated soil in engineering practice.

This study combines the pseudo-dynamic method and the principle of unsaturated soil mechanics to study the deep overturning stability of walls under unsaturated conditions. Through this study, we will be able to understand soil behavior in an unsaturated state better and then improve the design accuracy and stability of the retaining wall structure. Against this background, this paper will systematically introduce the basic principles of the pseudo-dynamic method and unsaturated soil mechanics and emphatically discuss their applications in the study of overturning stability. Through an in-depth analysis of interaction mechanisms, we aim to provide more reliable design guidance for engineering practice to meet the actual needs of different engineering environments. Through the contribution of this study, we hope to provide a new perspective and method for retaining wall design and soil mechanics research in civil engineering.

2 Pseudo Dynamic Method

2.1 Mechanical Properties of Unsaturated Soil Slopes

The main task of unsaturated soil mechanics research is to abstract properties and relations based on this perceptual knowledge, to establish the essential thinking of unsaturated soil research, to explore the constitutive relations and qualitative and quantitative analysis methods considering these properties in engineering, to put forward reasonable calculation formulas, to select appropriate test methods of characteristic parameters, to determine the range of value of each characteristic parameter, and to verify and revise the analysis results in practice [13, 14]. The saturation of saturated soil is 1, and the saturation of unsaturated soil is less than 1, so the two can be converted to each other, expelling all the gas in the unsaturated soil, making the saturation become 1, which is called saturated soil. Moreover, by draining a portion of the water from saturated soil and allowing air to enter, it becomes unsaturated soil [15]. Most soils in nature are unsaturated, with only a few being saturated. For the convenience of engineering research, ideal soils, namely saturated soils, are generally considered. The research and development of unsaturated soil is slower and slower than that of saturated soil, mainly because unsaturated soil has more gas phase and shrinkage film than saturated soil. Saturated soil mechanics mainly studies three problems: deformation of soil, strength of soil, and seepage of soil. The most famous three laws are mainly proposed based on saturated soil as the research object: the effective stress principle of Terzaghi, Darcy's seepage law, and the limit equilibrium principle [16]. Unsaturated soil, as a commonly existing soil in nature, must also consider these aspects in its research, namely deformation, strength, and seepage. However, due to the presence of suction, it is more complex.

2.2 Analysis of Soil Pressure and Anti Overturning Stability of Retaining Walls under Soil Arch Effect

Retaining walls and anchor rods are commonly used engineering measures to maintain slope stability, and soil pressure is a key factor determining the stability of retaining walls and anchor rods. Usually, designers use Coulomb theory or Rankine theory to calculate static soil pressure, and use physical theory to calculate seismic soil pressure. Although these theories provide relatively accurate values of soil pressure, the points and distribution of soil pressure they provide differ significantly from the measured results. Practice has proven that the stability of retaining walls and anchor rods depends not only on the magnitude of soil pressure, but also on the point and distribution of soil pressure [17, 18]. Therefore, it is necessary to make certain improvements to the classical soil pressure theory, provide a reasonable distribution of soil pressure and a simple and practical method for determining the point of resultant force, and study its impact on the stability of retaining walls and anchor rods.

Thin-walled retaining walls are usually made of reinforced concrete slabs. Although the dead weight Q of the walls is not large, it is enough to resist the earth pressure E because of the help of the soil weight G on the horizontal slabs. The sheet pile retaining wall has a considerable cross-section height and a small thickness. It is built by wooden piles, reinforced concrete piles, or steel sheet piles, and its balance is maintained by the depth driven into the soil [19, 20]. Research on stability, including checking the calculation of safety factors and reliability analysis. The ratio shall meet the requirements of Equation (1):

$$K_t = \frac{Gx_0 + P_{\alpha z}x_f}{P_{\alpha x}z_f} \geq 1.6 \tag{1}$$

Ratio of anti-sliding force shall meet the requirements of Equation (2):

$$K_s = \frac{G_n + P_{\alpha n}f}{P_{\alpha t} - G_t} \geq 1.3 \tag{2}$$

If the basic random variable X = (X1, X2, …, Xn) of the structure is expressed by random vector, which is called the structural function, then the working structure can be expressed by formula (3):

$$Z = g(X)\begin{cases} < 0(1) \\ = 0(2) \\ > 0(3) \end{cases} \tag{3}$$

If R is used to denote the resistance of the structure, S is used to denote the action (load) effect on the structure. The function structure can be expressed by Equation (4):

$$Z = g(R, S) = R - S \tag{4}$$

In the calculation and analysis, the structural function is a nonlinear function, which is expanded into Taylor series at the average value of random variables, as shown in Equation (5):

$$Z = g(\mu_{X_1}, \mu_{X_2}, \ldots, \mu_{X_n}) + \sum_{i=1}^{n} \left(\frac{\partial g}{\partial X_i} \right)_{\mu} \tag{5}$$

Mean and variance can be expressed by Equations (6) and (7):

$$\mu_Z = E(Z) = g(\mu_{X_1}, \mu_{X_2}, \ldots, \mu_{X_n}) \tag{6}$$

$$\partial_Z^2 = E[Z - E(Z)]^2 = \sum_{i=1}^{n} \left(\frac{\partial g}{\partial X_i} \right)_{\mu}^2 \sigma_{X_i}^2 \tag{7}$$

Therefore, the reliability index can be expressed by Equation (8):

$$\beta = \frac{\mu_Z}{\sigma_Z} = \frac{g(\mu_{X_1}, \mu_{X_2}, \ldots, \mu_{X_n})}{\sqrt{\sum_{i=1}^{n} (\frac{\partial g}{\partial X_i})_{\mu}^2 \sigma_{X_i}^2}} \tag{8}$$

Failure probability is expressed by Equation (9):

$$P_f = P(Z < 0) = \int_F f(Z)dz = \Phi(-\beta) \tag{9}$$

Because the instability of retaining wall has both fuzziness and randomness, it is a fuzzy random event. According to the theory of fuzzy mathematics, the probability of its occurrence is expressed by formula (10):

$$P_f = \int_{-\infty}^{+\infty} f(z)\mu_A(z)dz \tag{10}$$

When μ_A represents the degree of failure, when μ_A is close to 0, the possibility of failure is small; When $\mu_A = 0.5$, it is in the fuzziest state, which can be used as the limit equilibrium state in traditional analysis; When $\mu_A = 1$, the possibility of failure is high. When $\mu_A(z)$ adopts a reduced half trapezoidal distribution, the Equation (11) is obtained:

$$\mu_A(z) = \begin{cases} 0 & Z \geq b \\ \dfrac{b - Z}{b - a} & a < z < b \\ 1 & Z \leq a \end{cases} \tag{11}$$

Because the function of the structure is random, it can be simulated by its mean value. The fuzzy reliability of retaining wall instability is shown in Equation (12).

$$\beta = \Phi^{-1}(1 - P_f) \tag{12}$$

2.3 Stability Analysis of Soil Retaining Walls in Multiple Aspects

In order to calculate the stability of a retaining wall with finite soil, it is necessary to construct a wall-soil system. In order to calculate the energy dissipation, it is necessary first to determine the contact area between the wall and the soil. Hence, this paper needs to calculate the critical depth of the soil first [21]. Due to the action of cohesive force and the inability of the soil to bear tensile stress, cracks will appear within a certain depth below the surface of the fill, and a wall-soil separation phenomenon will occur. This crack depth is defined as critical depth. In this paper, the soil within the critical depth range is regarded as an elastic overburden; it acts on the finite soil behind the wall as an external load. Figure 1 is the analysis result. According to the wedge stress analysis of the seismic active pressure of the retaining wall at the water level, the sliding soil is unsaturated above the water

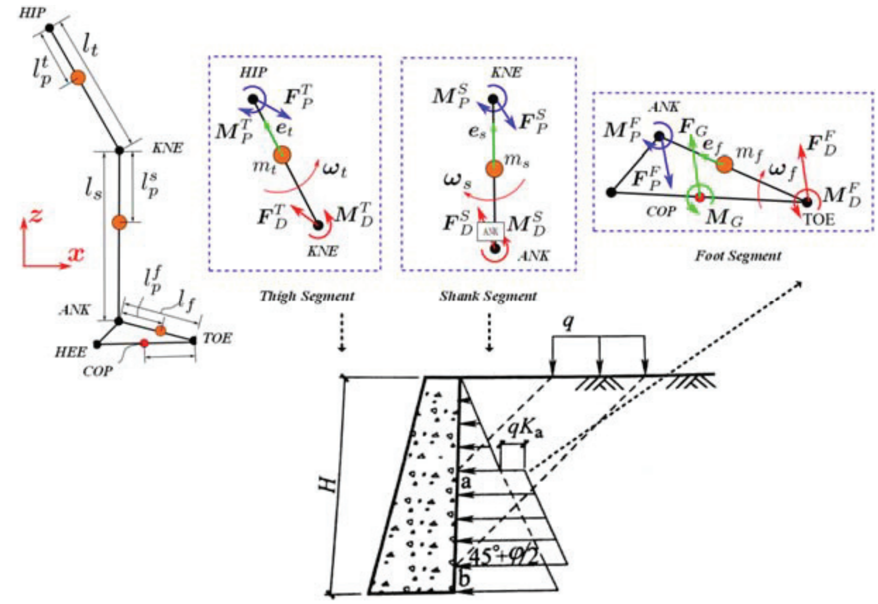

Figure 1 Stability analysis of soil retaining wall.

level and saturated below, forming double-layer soil with different cohesion and the same effective internal friction angle.

3 Analysis of Unsaturated Soil Slope and Retaining Wall Overturning Stability

3.1 Analysis of Soil Pressure Considering Water Level

The influence of water level change is global. When the seam depth ho = 0 m, with the increase of water level from 0 m to 12 m, the retaining wall experiences middle water level and low water level in turn, and the seismic active earth pressure coefficient Kac decreases nearly linearly under the two suction distributions, and the difference increases gradually; Earthquake active earth pressure coefficient Ka under uniform suction is smaller than that under linear suction, but it is more affected by water level; Under the same suction distribution [22, 23].

Figure 2 shows the structure of the water level analyzer. When the water level is at the surface, that is, Dw=0m (high water level), the sliding soil and cracked soil behind the wall are saturated soil; When the water level is at the wall heel, i.e., Dw = 10 m (low water level), the sliding soil and cracked soil

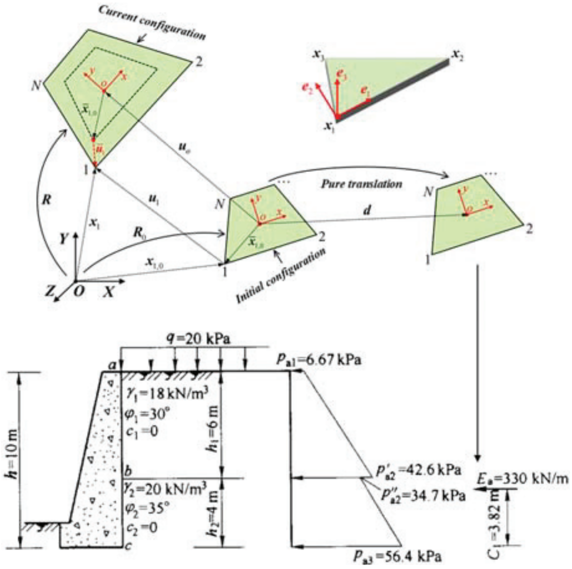

Figure 2 Water level analyzer architecture.

behind the wall are both unsaturated soil, and there is a big difference under the two suction distributions; When the water level is at half of the wall height (Dw = 5 m), the sliding soil and cracking soil behind the wall are unsaturated. The sliding saturated soil is below the water level. At this time, the increase rate of seismic active earth pressure coefficient Ka decreases compared with Dw = 10 m, and the difference between the two suction distributions is also obviously reduced. When Dw = 10 m, the sliding and cracked soil behind the wall are both unsaturated, and the difference increases under the two suction distributions. When Dw = 5 m, the sliding soil and cracked soil behind the wall are unsaturated, and the decrease rate of seismic active earth pressure coefficient Kac is lower than that when Dw = 10 m, especially for uniform suction distribution, and the difference of seismic active earth pressure coefficient Kac is also significantly reduced under two suction distributions [24].

3.2 Analysis of Soil Pressure on Retaining Walls at Medium Water Level

The wedge-shaped force analysis of seismic active earth pressure of the retaining wall at the middle water level shows that the sliding soil is unsaturated soil above water level and saturated soil below water level, forming double-layer soil with different cohesion and the same effective internal friction angle. The unsaturated soil is in the limit equilibrium state at the slip surface and reaches the shear strength. The frictional shear force generated by the everyday net stress and upward along the slip surface has been included in the non-sliding soil reaction force R (the angle between the direction and the normal of the slip surface is φ), leaving only the internal cohesion force C generated by the total cohesion force and upward along the slip surface [25, 26]. For the total cohesive force c, c' for saturated soil below water level and c' + cs for unsaturated soil above water level, and the adsorption cohesive force cs is related to suction distribution.

The pressure of unsaturated soil based on limit equilibrium method can reasonably reflect the comprehensive influence of water Dw, joint depth ho and unsaturated soil characteristics (matrix suction and its distribution, suction angle φ), and can naturally degenerate into Coulomb active earth pressure (kh = kv = 0) or Rankine active earth pressure (h = k = 0, a = δ = 0) of unsaturated soil, and seismic active earth pressure of saturated soil (ua-uw) = (ua-uw) o = 0). When the water level changes, according to the relative position of the water level at the bottom of the joint and the heel

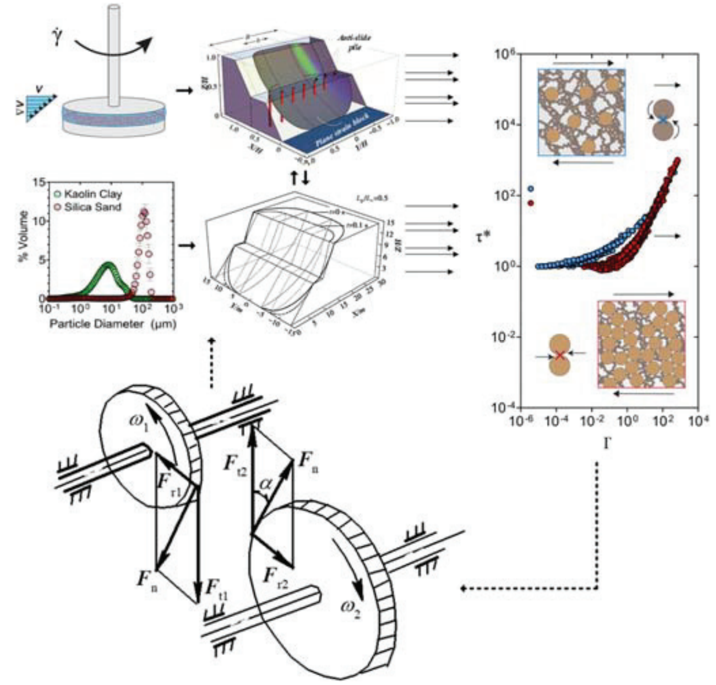

Figure 3 Calculation model of anti-overturning stability of retaining wall.

of the wall, the seismic active earth pressure change law of the retaining wall in the whole process from high water level to low water level can be realized [27, 28].

3.3 Construction of Stability Model for Retaining Walls Against Overturning Under The Action of Soil Filling in Front of The Wall

The fill before and after the wall is homogeneous fill, and the fill behind wall is same height as the retaining wall and has a horizontal surface. Rupture surface in front of wall and filling behind the wall are all straight lines. Both retaining wall and soil are regarded as ideal rigid members.

Figure 3 shows the calculation system; the surface is horizontal and equal to the height of the retaining wall, the cohesion is c, which is also cohesive soil, the cohesion is c, the gravity is y, and the fill surface is horizontal. The rupture angle in the active zone is α, the rupture angle in the passive zone is a, the slope bottom angle is y, and the wall toe angle is β. The plastic zone of backfill is divided into innumerable rigid soil strips, and energy dissipation exists among the soil strips. Similarly, the plastic zone of backfill is divided into innumerable rigid soil strips, and energy dissipation also exists among the soil strips; that is, the plastic zone of backfill before and after the wall is essentially two rigid bodies, but there is energy dissipation inside it, and it forms a wall-soil system with a rigid retaining wall. Internal energy dissipation includes energy dissipation at the interface, energy dissipation at the interface, energy dissipation in the plastic zone of fill behind the wall, and energy dissipation in the plastic zone of fill in front of the wall [29]. Among them, the more complicated calculation is the dead weight and internal energy dissipation of the plastic zone of the fill before and after the wall. For the calculation of the back part of the wall, the new part of the fill in front of the wall is emphatically solved here.

4 Experimental Results and Analysis

In seismic design, studying the soil pressure on retaining walls under earthquake action is an essential link in the seismic safety design of retaining walls. The methods for obtaining the soil pressure on retaining walls under earthquake action mainly include theoretical calculation, numerical analysis, and model testing. The commonly used methods for the theoretical calculation of pressure include a quasi-static method, pseudo-dynamic method, and elastic wave method. This article is based on the basic principle of the pseudo-dynamic method, assuming that the critical failure surface of the backfill behind the wall is a composite surface of a logarithmic spiral and a straight line. Subsequently, the focus was on analyzing and discussing the effects of soil vibration amplification coefficient, internal friction angle of fill, phase, and horizontal seismic coefficient.

Because there are many factors in the stability calculation formula, and many parameters are used in this paper, so Matlab software is used to analyze and check the formula. Considering the complexity of the formula, this paper calculates the numerical solution here. The program idea is as follows: first, input all the parameters, establish an empty matrix to improve the operation speed, use the input parameters to form all the external force calculation power and internal energy dissipation calculation formulas solved in this paper and calculate the derivative formula of each formula at the same time, start to cycle the fracture angle, and get the angle corresponding to the minimum value and then substitute it into the stability coefficient calculation formula [30].

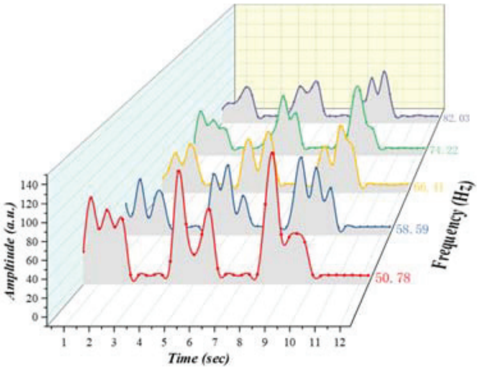

Figure 4 Variable analysis of soil width.

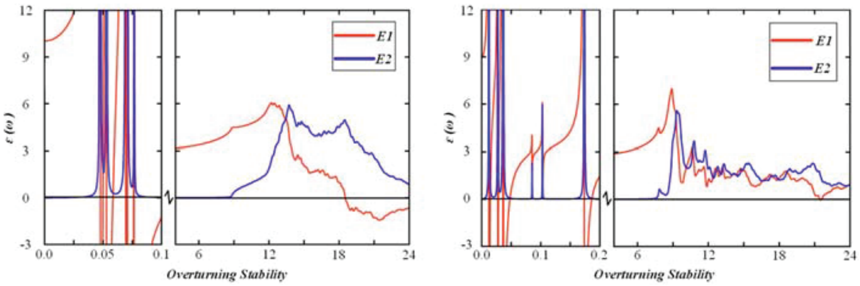

Figure 5 Analysis of internal relationships in soil.

Figure 4 shows the variable analysis of soil width. In the finite soil width, when the top width of the fill is constant, the fracture angle α increases with the increase of slope bottom angle φ. When the top width of the fill is constant, the stability coefficient F increases with the increase of slope bottom angle φ; When I increase, the stability coefficient tends to be smaller with the increase of φ. The stability coefficient F decreases with the increase of l and gradually becomes stable. The stability coefficient F, considering the action of filling in front of the wall, is more significant than that without consideration. When I approach semi-infinite soil, it is equal to the unconsidered algorithm value when H equals 1 m, and the difference is 18.25% when H equals 3 m.

Figure 5 shows the analysis of internal relationships in soil. Present methods do not consider the stress-strain relationship inside the soil. They are various stability analysis methods based on limit equilibrium theory and cannot analyze the occurrence and development process of slope failure. Subsequently, the finite difference method for slope stability analysis emerged,

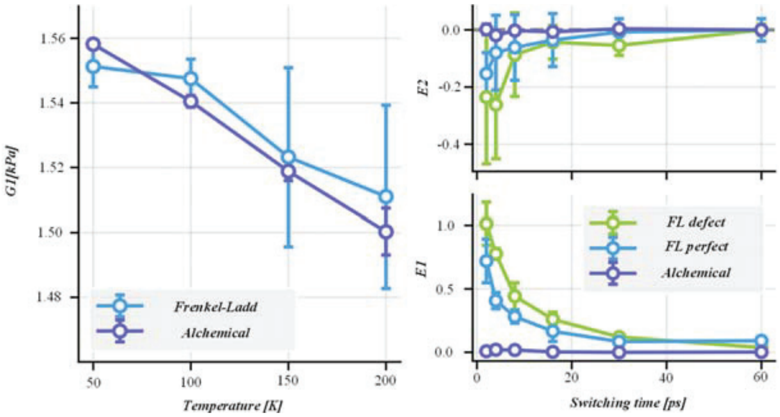

Figure 6 Analysis of influencing factors of wall soil system.

which divides the solution domain into differential grids and replaces the continuous solution domain with a finite number of grid nodes.

Figure 6 shows the analysis of influencing factors of wall soil System. The strength reduction finite element method developed on this basis inherits the advantages of finite element calculation, which can reasonably and comprehensively consider the constitutive relationship of the soil, without assuming the shape of the sliding surface, and can obtain the most easily sliding surface through calculation. It can reflect the non-uniformity of slope soil and the nonlinearity of deformation and slip. It can calculate a potential sliding surface, corresponding safety factor, and simulate mechanical responses such as stress and strain inside the slope.

Figure 7 shows the analysis of rupture in translation mode. In translation mode, the fracture angle α varies with slope bottom angle φ, fill friction angle φ. In limited soil range, the anti-slip stability of retaining wall decreases with the increase of fill top width 1, and the stability value tends to be stable gradually.

Using the sliding wedge limit equilibrium theory and considering the amplification effect of acceleration, the pseudo-dynamic analysis of the passive earth pressure of the retaining wall is carried out, and the calculation formula of the passive earth pressure is obtained. The influence of the filling surface's slope foot, the soil's internal friction Angle, and the interface friction Angle between the retaining wall and the filling on the earth pressure coefficient and the rupture Angle is analyzed. The results show that the coefficient of earth pressure and the magnitude of rupture Angle is nonlinear

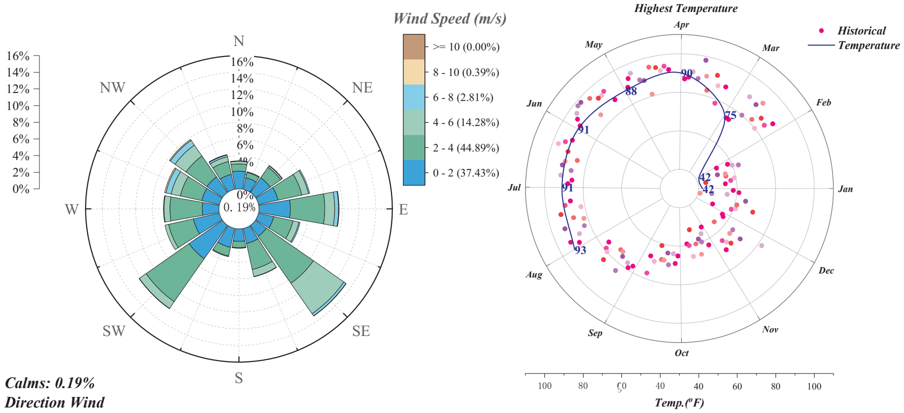

Figure 7 Analysis of rupture angle in translation mode.

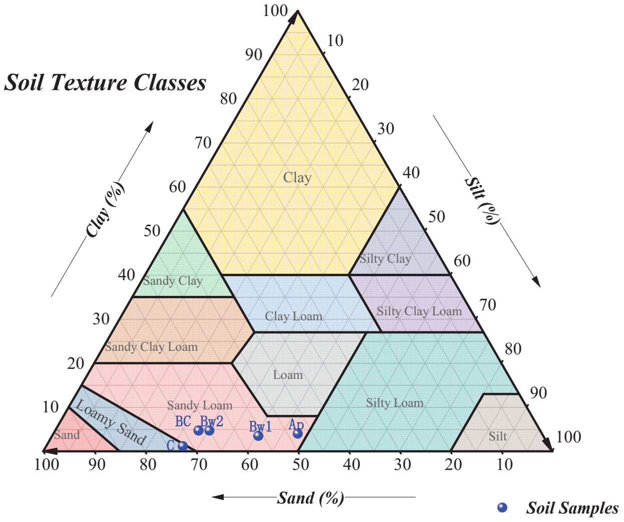

Figure 8 Soil classification results.

with the changes of the surface slope foot, the friction Angle inside the fill, and the friction Angle between the retaining wall and the fill. Figure 8 shows the classification results of soil quality, and the comparison shows that the calculation method in this paper is in good agreement with the code method. Figure 9 shows the results of the wall soil system model for filling soil in front of the wall. In rotation mode, without the influence of wall-bottom

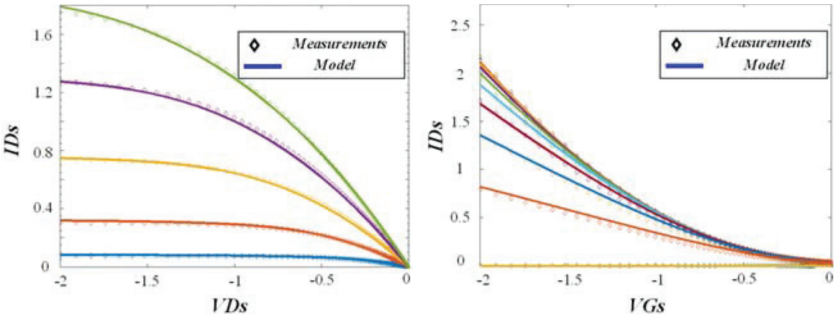

Figure 9 Results of wall soil system model for filling soil in front of wall.

interface friction angle and wall-bottom interface cohesion, the fracture angle α increases with the increase of fill internal friction angle φ and slope bottom angle φ, and decreases with the increase of soil cohesion c, wall-soil interface friction angle δ, and wall-soil interface cohesion c; The change of anti-overturning stability is consistent with that in translation mode. Compared with the standard algorithm, the calculated results in this paper are slightly larger than the stability coefficient calculated by the standard.

5 Conclusion

This study analyzes the interaction mechanism and stability of unsaturated soil slopes and support structures. A model is constructed by integrating the principles of unsaturated soil mechanics and the pseudo-dynamic method, and stability analysis is conducted based on this model. Various factors influence unsaturated soil slope stability, including moisture content, matrix suction, soil structure, etc. The changes in these factors will directly affect the mechanical properties of the soil and impact the slope's stability. The design and construction of support structures must fully consider the interaction with unsaturated soil.

Regarding interaction mechanisms, unsaturated soil slopes and support structures have a complex mechanical relationship. On the one hand, the support structure enhances the stability of the slope by providing additional support force. On the other hand, the characteristics of unsaturated soil can also affect the stress and stability of support structures. In terms of stability analysis, this article adopts various numerical analysis methods, such as the limit equilibrium and finite element methods, to accurately simulate the response of slopes under various conditions and predict their possible failure modes. By comparing the stability performance of slopes under different support schemes, recommendations for optimizing support structure design are derived. The experiment found that when the slope bottom angle increases by 5 degrees, the stability coefficient increases by about 15%; Increasing the friction angle by 1 degree can increase the stability coefficient by about 8%. By increasing the interface friction angle between the wall and bottom by 2 degrees, the stability coefficient can be increased by 10%.

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