Analysis of Loess Wet Deformation and Slope Stability under Rainfall Conditions

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Abstract. Loess is a typical unsaturated soil, and the unsaturated strength is the basis for the analysis and evaluation of engineering stability in the loess area. Based on the analysis of the wet load deformation strength, rainwater infiltration and slope stability of unsaturated loess, this paper obtains the yield stress under different suction caused by soil humidification at different depths, the water retention characteristic curve and the different loess with different dry-wet cycle history. The research conclusions can provide reference for the construction of loess collapsibility model and the numerical calculation of the collapsibility deformation of the loess site under the infiltration of rainwater.

1. Introduction
The collapsible loess is immersed in water, its original structure is destroyed, resulting in reduced shear strength and collapsibility. The primary condition for infrastructure construction in the loess area is to evaluate the collapsibility of the loess on the site[1]. The compression and consolidation characteristics of unsaturated soil reflect the deformation of soil under different load and water content conditions, and it is an important parameter in the design of foundation settlement control for infrastructure[2]. The water-holding characteristics curve of unsaturated soil under different stress states can be used to analyse the permeability characteristics. Under rainfall conditions, the change of matrix suction will reduce the mechanical parameters of the soil, which may lead to the instability of the slope[3]. Therefore, the water-holding characteristics of unsaturated soils are necessary for calculating the temporal and spatial distribution of moisture in foundations under rainfall conditions, and provide a basis for subsequent analysis of the deformation and stability of unsaturated soil foundations. The moisture deformation test of unsaturated soil under different stress states reflects the collapsibility or expansion deformation characteristics of the soil.

This paper obtains the humidification deformation characteristics of unsaturated loess, and applies it to the analysis of rainwater infiltration of loess slopes. It has fundamental significance for studying the influence of collapsible loess deformation characteristics on engineering construction.
2. Introduction to Unsaturated Soil Theory

2.1 Unsaturated soil seepage theory

Assuming that the soil skeleton is not deformed, the water in the soil unit body is an incompressible fluid. As shown in Figure 1, it is a unit thickness of a soil unit body with water flowing in the x and y directions[4].

![Two-dimensional seepage model of soil element.](image)

From the continuity condition:

\[
v_x dy + v_y dx + Q dx dy - \left( v_x + \frac{\partial v_x}{\partial x} dx \right) - \left( v_y + \frac{\partial v_y}{\partial y} dy \right) = \frac{\partial \theta}{\partial t} dx dy
\]

(1)

In the formula, Q represents the change in water content caused by evaporation or rainfall; \( \theta \) is the water content of the soil unit body; \( t \) is the time.

The general expression of the two-dimensional seepage differential equation:

\[
\frac{\partial}{\partial x} \left( k_x \frac{\partial \theta}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial \theta}{\partial y} \right) + Q = \frac{\partial \theta}{\partial t}
\]

(2)

The equation of water content per unit volume changing with pore water pressure:

\[
\frac{\partial \theta}{\partial t} = m_w \frac{\varphi}{\partial u_w}
\]

(3)

In the formula, \( m_w \) is the slope of the water storage curve, and \( u_w \) is the pore water pressure.

Get the following expression:

\[
\frac{\partial}{\partial x} \left( k_x \frac{\partial \varphi}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial \varphi}{\partial y} \right) + Q = m_w \varphi \frac{\varphi}{\partial \varphi}
\]

(4)

In the formula, the elevation \( y \) is constant and the derivative with respect to time is zero.

2.2 Characteristic curve model of water holding capacity of unsaturated soil

Scholars from various countries have proposed many soil-water characteristic curve models, such as Gardner model (1958), Brooks and Corey model (1964), van Genuchten model (1980), Fredlund and Xing model (1994) and so on[5]. Three typical model formulas are shown in Table 1.

| Permeability model | Soil-water characteristic curve equation | Symbol meaning |
|--------------------|------------------------------------------|----------------|
| Gardner            | \( \theta_w = \theta_r + \frac{\theta_s - \theta_r}{1 + (\frac{\varphi}{a})^n} \) | \( \theta_w \) — Volumetric water content; \( \theta_r \) — Residual volume water content; \( \theta_s \) — Saturated volume water content; \( a \) — Matrix suction; |
| Van Genuchten      | \( \theta_w = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\frac{\varphi}{a})^n \right]^m} \) | \( \theta_w \) — Volumetric water content; \( \theta_r \) — Residual volume water content; \( \theta_s \) — Saturated volume water content; \( a \) — Matrix suction; \( n \) — Parameter of characteristic curve; |

Table 1. Typical soil-water characteristic curve model.
3. Research on deformation under stress and moisture of collapsible loess

The collapsibility curve of the sample at 1.0 m is shown in Figure 1(a). In the process of compressing the sample by the control suction, the void ratio and weight water content of the D1S200V200 and D1S200V800 samples are similar to those of the D1S200 sample. When the moisture absorption range is 200 ~ 0 kPa (Figure 1(b) and Figure 1(c)), the void ratio and weight water content of samples D1S200V200 and D1S200V800 under corresponding vertical stress are close to the results of sample D1S0. In the subsequent compression process, the soil porosity and weight water content of D1S200V200 and D1S200V800 samples are consistent with the compression results of D1S0 samples.

\[
\theta_v = \theta_r + \frac{\theta_s - \theta_r}{\ln \left( e + \left( \frac{\theta_s}{\theta_r} \right)^{m} \right)} \quad a, n, m - \text{Test parameters.}
\]

Fredlund & Xing

Figure 2. Unsaturated loess wet load deformation curve.
calculated collapsibility potential curve, and they are all parabolic. The initial void ratio of the sample at 5.0 m is basically the same as that at 1 m and 3 m, but on the whole it exhibits a greater collapsibility potential than that at 1.0 and 3.0 m. The maximum collapsibility potential of the specimen at 5.0 m is 38% and 54% larger than that of specimens at 1.0 and 3.0 m, respectively.

4. Research on Rainwater Infiltration of Unsaturated Loess Slope

In order to study the impact of rainfall infiltration on unsaturated loess slopes, the slope is set as a homogeneous slope before rainfall, and the groundwater level is at the bottom of the slope. Regardless of natural conditions such as fissures, the pore water pressure is linearly distributed. The original drainage path water retention characteristic curve is simulated and analyzed. Calculate the slope pore pressure change and stability change when the rainfall intensity is 50mm/d, 100mm/d, 250mm/d. Figure 3 is a 250mm/d water retention characteristic curve showing the distribution of pore pressure of the slope under the drainage path. It can be seen from the figure that the affected area of the slope top pore pressure gradually increases to 2.6 meters with the increase of rainfall intensity, and the flooding surface Gradually connect.

Figure 4 shows the pore pressure diagram of the compacted drainage path and the pore pressure diagram of the compacted water absorption path. The pore pressure is found to adopt the compacted water retention characteristic curve drainage path or the water absorption path. The slope pore pressure is not affected by rainwater infiltration. The influence range of the roof is about 1 meter. Figure 5 shows the water retention characteristic curves of the undisturbed loess drainage path and water absorption path. The rainfall intensity is 50mm/d, 100mm/d, and 250mm/d respectively, and the slope safety factor is reduced from 2.08 to 1.4, 0.87 and 0.82, respectively. The slope safety factor is uniformly reduced to varying degrees. The rain intensity is 100mm/d and 250mm/d. In the middle of the rain, the safety factor shows a sharp drop.
Figure 4. Pore pressure distribution of compacted drainage path.

Figure 5. Safety factor changes with time of drainage path.

Figure 6. Safety factor changes with time of suction and drainage path.

Figure 6 shows the water retention characteristic curve of the undisturbed loess drainage path and the water absorption path at a rainfall intensity of 100mm/d and a 7-day slope safety factor. It can be seen from the figure that the safety factor of the water absorption path has dropped from 2.09 to 2.0, which is only reduced The safety factor obtained by the drainage path has dropped more significantly. This is because the permeability coefficient function fitted by the water retention characteristic curve of the drainage path is larger. Under the same suction force, the permeability coefficient is large and the water seepage is relatively high. The safety factor obtained by the suction path decreases relatively slowly with the rainfall duration. This is because the permeability coefficient is relatively small. In addition, the simulation mainly compares the influence of the suction and drainage path on the slope stability without considering the effect of cracks. There will be many cracks in loess slope, so the safety factor of the actual result should be lower.

5. Conclusion
Through the unsaturated consolidation test of specimens at different depths, the yield stress under different suction caused by soil humidification at different depths is obtained, and the collapsibility potential increases gradually with the increases of the sampling depth. For the same unsaturated loess slope, the water retention characteristic curve adopting the drainage path or the water absorption path will have a very large impact on the pore pressure distribution of the slope. The water retention characteristic curve of the undisturbed loess drainage path and the water absorption path changes on the
slope safety factor under the same rainfall intensity, and the safety factor obtained from the drainage path decreases more significantly. Therefore, it is necessary to consider the influence of different depths of loess on rainwater infiltration due to different water-holding characteristics and permeability caused by different dry-wet cycle history in the design and calculation.

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