Stability analysis of unsaturated soil slope under rainfall and seepage conditions

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Abstract. Rainfall infiltration and canal seepage are the main causes of slope instability, the paper considered the factors such as soil type, soil-water characteristic curve and rainfall duration, and analysed the stability of unsaturated soil slope. The calculation results show that rainfall has a significant impact on the stability of the slope, as the matric suction in the unsaturated soil makes the slope safer. However, it reduced during rainfall, so the safety factor is greatly reduced when the continuous rainfall occurred. Moreover, when rainfall infiltration and canal seepage coupled, it is worse than just taking one factor into account, and the slope safety factor decreases from stable to unstable.

1.Introduction
Rainfall infiltration and canal seepage are the main causes of slope instability, the infiltration and seepage leads to changes the soil strength characteristics and the adjustment of the stress state. Therefore, the analysis of unsaturated soil slope stability under rainfall infiltration and canal seepage conditions is significance.

Slope stability is generally calculated by the classical Mohr-Coulomb theory, without considering the unsaturated character of the soil. A large number of studies [1-5] have shown that the matric suction in the unsaturated soil makes the slope safer in the absence of rainfall. However, under rainfall conditions, the suction is reduced, and the strength of the soil is weakened, so that the stability of the slope is reduced, which may lead to the instability of the slope [6-7].

In this paper, the factors such as soil type, soil-water characteristic curve and rainfall duration are considered, and the stability analysis of unsaturated soil slope can be used to provide reference for similar slope calculations.

2.Saturated-unsaturated infiltration theory and parameters
The loess in the study area is basically unsaturated soil, which is generally composed of three phases, namely solid, liquid and gas. In the unsaturated soil, due to the existence of three phases of solid-liquid-gas, the physical and mechanical properties of the unsaturated soil are more complicated, and the change of soil water content is the direct cause of the change of mechanical properties of unsaturated soil.
2.1 Soil-water characteristic curve of unsaturated loess

The soil-water characteristic curve of different formation soils was determined by using the Whatman filter paper for the humidification test. Through the data obtained by the experiment, the relationship between the matric suction and the volumetric water content is fitted by the Van Genuchten equation (1-1) of the SWCC theoretical model, and the soil-water characteristic curves and fitting parameters of each soil layer are obtained (Table 1).

\[
\theta = \theta_s - \frac{\theta_r - \theta_s}{1 + (\frac{\phi}{\alpha})^n}^\frac{1}{\theta_r} 
\]

where “\(\phi\)” is the matric suction; “\(\theta\)” is the volumetric water content; “\(\theta_r\)” is the residual humidity; “\(\theta_s\)” is the saturated volumetric moisture content; “\(\alpha\)” and “\(n\)” are fitting parameters.

| Soil Layer | \(\theta_s\) | \(\theta_r\) | \(\alpha\) | \(n\) |
|------------|--------------|--------------|------------|-------|
| Q1          | 0.3229       | 0.0451       | 0.0041     | 1.2881|
| Q2          | 0.4032       | 0.0687       | 0.0590     | 1.2971|
| Q4         | 0.4044       | 0.0686       | 0.0587     | 1.2662|

2.2 Unsaturated loess permeability coefficient curve

Combined with the test results of soil-water characteristic curve, using the statistical conduction model (1-2) proposed by Van Genuchten (1980), the infiltration coefficient of unsaturated soil is derived based on the soil-water characteristic curve. The permeability coefficient curve is shown in the figure below (Figure 1).

\[
k_w = k_s \left[ \frac{1-(\alpha \phi)^n-1[1+(\alpha \phi)^n]^{-\frac{n-1}{n}}}{[1+(\alpha \phi)^n]^{-\frac{n-1}{2n}}} \right]^{-2}
\]

where “\(k_s\)” is saturation permeability coefficient; “\(\phi\)” is matric suction; “\(\alpha\)” and “\(n\)” are fitting parameters.

2.3 Unsaturated soil shear strength

According to the Mohr-Coulomb criterion and the effective stress concept of Terzaghi, the shear strength of saturated soil can be expressed as:

\[
\tau_f = c' + (\sigma_n - \mu_w \tan \phi^b)
\]

where “\(\tau_f\)” is shear stress; “\(c'\)” is effective cohesion; “\(\sigma_n\)” is total normal stress; “\(\mu_w\)” is pore water pressure; “\(\phi^b\)” is effective angle of internal friction. The expression of the shear strength of unsaturated soils is:

\[
\tau_f = c' + \sigma_n \tan \phi^b - \mu_w \tan \phi^b
\]

where “\(\mu_w\)” is matric suction; “\(\phi^b\)” is angle of internal friction varies with the matric suction. “\(c' - \mu_w \tan \phi^b\)” is total cohesion of unsaturated soils, and “\(-\mu_w \tan \phi^b\)” is the intensity generated
by suction from an unsaturated matrix.

3. Influence factor analysis

3.1 General geology
The height of the high slope is 25m to the bank of the canal, and the average slope of the slope is 69°. And the vertical distance from the bank to the foot of the slope is 23m, and the average slope of the slope is 30°. The study area is a residual third-order terrace, and the terrace is located on the Q1 loess. The bottom of the terrace is the gravel layer of the river alluvial, the thickness is 1-2m, and the elevation of the bottom of the alluvial is about 590m. The loess and the layer of paleosol are stacked on the top of the terrace, and the thickness of the two is about 11m. The loess has self-weight collapsibility and is high compressive soil. The artificial accumulation thickness of the right bank is 4-6m, which is filled with soil. The upper part of the left bank is paleosol, and the lower part loess (Q1eol+pl) and paleosol have uniform texture, mostly below the groundwater level, which is low compressive soil.

3.2 Calculation model and parameters
The calculation model, which is shown in figure 2, and the boundary is hinged (Figure 3). Q21eol+pl, Q12eol+pl, Q1al, Q11al+pl are developed successively from the earth's surface. The parameters were selected in combination with laboratory tests and in-situ test results. The calculation parameters are shown in Table 2.

| soil layer | cohesion (kPa) | friction angle (°) | natural bulk density (kN/m³) | saturated bulk density (kN/m³) | permeability coefficient (10⁻⁵cm/s) | shear modulus (MPa) | damping ratio |
|------------|----------------|--------------------|------------------------------|-------------------------------|-----------------------------------|---------------------|--------------|
| Q21eol+pl  | 25             | 35                 | 18.5                         | 21.5                          | 17.10                             | 20.44               | 0.25         | 0.36         | 16.08         | 0.2           |
| Q12eol+pl  | 35             | 55                 | 24.5                         | 26.5                          | 18.30                             | 19.72               | 2.20         | 0.93         | 53.79         | 0.14          |
| Q1al       | 45             | 65                 | 24.0                         | 27.0                          | 18.70                             | 19.87               | 0.59         | 0.72         | 40.77         | 0.12          |
| Q11al+pl   | 50             | 64                 | 23.0                         | 26.0                          | 15.64                             | 16.73               | 0.57         | 0.86         | 48.96         | 0.12          |

Note: total- total stress index; effective- effective stress index.

3.3 Calculation results analysis
The calculation is divided into normal condition, rainfall infiltration condition and rainfall-canal seepage condition. The rainfall lasts for 30 days, and the leakage is 0.107m³/d. Under normal conditions, the safety factor of the slope calculated by the total stress index and effective stress index are 1.199 and 1.598 respectively.
Calculation results variation with time in the case of rainfall infiltration and rainfall-canal seepage are shown in figure 4 and figure 5 respectively, and the slope safety factor versus time curves of rainfall infiltration and rainfall-canal seepage are shown in figure 6 and figure 7 respectively. The safety factor of rainfall infiltration and rainfall-canal seepage after 30 days are 1.004 and 0.950 respectively.

![Groundwater flow field during rainfall infiltration condition](image)

Figure 4. Groundwater flow field during rainfall infiltration condition

![Groundwater flow field during rainfall-canal seepage condition](image)

Figure 5. Groundwater flow field during rainfall-canal seepage condition

![Slope safety factor versus time curve during rainfall](image)

Figure 6. Slope safety factor versus time curve during rainfall

![Slope safety factor versus time curve during continuous rainfall and canal seepage](image)

Figure 7. Slope safety factor versus time curve during continuous rainfall and canal seepage

4. Conclusions

(1) The safety factor of the slope is 1.199 under normal condition, the safety factor of rainfall infiltration and rainfall-canal seepage after 30 days are 1.004 and 0.950 respectively.

(2) Rainfall infiltration has a significant impact on the stability of the slope. Although landslide did not occurred during the rainfall period and after the rain, the safety factor reduced greatly, and the slope was already on the critically state. Special attention should be paid to the safety and stability during the rainfall period.

(3) When rainfall infiltration and canal seepage occurs, the degree of danger is increased. In addition, the slope is unstable when the two factors coupled, which explains that the rainfall and infiltration have a joint effect on the safety and stability of the slope.
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