Finite Element Analysis of Failure Characteristics of Structural Soil Slope under Different Rainfall Patterns

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Keywords: Structural-soil slope, Monitoring point, Pore water pressure, Displacement, Rainfall patterns.

Abstract. The slope model is established by Geo-Studio, and the deformation characteristics and stability of structural-soil slope in Zhanjiang area under different rainfall patterns are analyzed. The MK model was used basing on Morgenstern-price method. By setting monitoring points at the top, toe and slope surface of the slope, the variation rule of pore water pressure and displacement at the monitoring points under the four types of rainfall are gotten, and the shapes of different types of sliding surfaces are obtained. By the analysis of the most dangerous sliding surfaces, some suggestions are put forward. Those have important reference value for prevention or controlling the geological disasters such as landslides in Zhanjiang area.

Introduction

China is a country with frequent natural disasters. In 2013, there were 15403 geological disasters in China, including 14703 landslides, collapses and mudslides, accounting for 95.4% of the total number of geological disasters. 669 people were killed or missing, with a direct economic loss of 10.2 billion[1]. However, the landslide caused by rainfall accounts for 51% of the total landslide disasters[2]. Especially under the condition of heavy rainfall.

Before and after rainwater infiltration, the mechanical properties and deformation characteristics of structural soil vary greatly, which results in obvious suddenness and unpredictability when the soil slope is damaged. Therefore, we need to study the structural soil slope under the condition of rainfall, so as to monitor the areas prone to landslides in real time, so as to reduce casualties and economic losses, which is helpful for prevention and control Geological disasters such as landslides have important practical significance.

Research Model and Theory

In order to study the deformation characteristics of the structural soil slope in Zhanjiang area under the rainfall condition, this paper selects a certain slope section of Shenhai Expressway in Zhanjiang area, Guangdong Province, uses the Geo Studio software to analyze its failure characteristics and stability. According to the test results, soil water characteristic curve models were often used include in Gardner model[3], Brooks and Corey model[4], Van Genuchten model[5], Fredland & Xing model[6], Modified kovács model (namely MK model)[7]. Here MK model is selected to analyze the structural clay slope in Zhanjiang area based on Morgenstern price method, the failure characteristics were analyzed under the action of four rainfall patterns.

MK model (data point function):

\[ S_r = \frac{\theta}{n} = S_C + S_a^* (1 - S_C) \]  

(1)

where, \( S_r \) is the degree of saturation; \( \theta \) is the volume water content; \( n \) is the porosity, \( S_C \) is the degree of saturation under the capillary action; \( S_a \) is the degree of saturation under the adsorption action, when the adsorption sub item \( S_a > 1 \), then \( S_a^* = 1 \); when \( S_a \leq 1 \), then \( S_a^* = S_a \).
In the process of rainfall, since the soil mass of slope is varied from unsaturated to saturated state, the shear strength formula of unsaturated soil is adopted\(^8\) the Eq. 2 which proposed by Fredlund:

\[
\tau_f = c' + (\sigma - u_a)\tan\phi' + (u_a - u_w)\tan\phi_b
\]  

(2)

Figure 1. Time varying curve of average annual rainfall in recent 55 years in Zhanjiang area.

Used the above model and theory, the failure characteristics and stability of slope are analyzed.

**Research Plan**

Based on the meteorological data of Zhanjiang area, the appropriate rainfall is selected to design four types of rainfall: front type, center front type, back front type and average type, and the appropriate slope model is established. Monitoring points are set at the foot, slope surface and 2m below the top of the slope respectively, and the failure characteristics and stability of the slope are analyzed by using Geo-Studio.

**Rainfall Selection**

Based on the analysis of the annual rainfall trend in Zhanjiang in recent 55 years\(^9\), as shown in the following Fig.1:

According to the analysis, four types of rainfall are adopted: front peak type, center peak type, back front type and average type, with a total rainfall of 300 mm and a rainfall duration of 30 days. Meanwhile, the duration of rain stopping is considered to be 20 days, as shown in the Fig. 2:

![Front peak rainfall type](image)

(a) Front peak rainfall type

![Center peak rainfall type](image)

(b) Center peak rainfall type

![Back peak rainfall type](image)

(b) Back peak rainfall type

![Average rainfall type](image)

(d) Average rainfall type

Figure 2. Rainfall scheme design.
Calculation Model and Grid

The soil layer is clay. The calculation model is shown in Fig. 3: The three monitoring points are located at 2m away from the top, slope and foot of the slope vertically downward from f, e and d. The pore water pressure and displacement changes of the top, foot and slope are detected under four rainfall conditions. Among them, bc, ig and aj are impermeable boundaries; ab and ij are left and right constant head boundaries, respectively, 10m and 28m; cdfg is rainfall infiltration boundary, and the model grid is divided into 312 nodes and 272 units, with calculation step of 1d.

Model Parameter Selection

Through reference[8], the parameters required for MK model are determined as follows: volume compression coefficient \( m_v = 0.000125/\text{kPa} \), saturated volume water content \( \theta_s = 0.48 \); the basic physical and mechanical parameters[10-11] of Zhanjiang structural soil are shown in Table 1:

Based on the above model parameters, we will import them into the Geo-Studio, and analyze the changes of pore water pressure, displacement and sliding surface of the slope through the monitoring points of the slope under the conditions of four rainfall patterns.

Result Analysis

Analysis of Pore Water Pressure Change with Time

Through simulation, the variation curves of pore water pressure with time are shown in the Fig. 4. According to the four charts, the initial pore water pressure of the monitoring points at the top, foot and 2m below the slope before the rainfall is about -253.7kpa. Because of the different rain patterns, their changing trends are also different. Under the condition of front rainfall type, the pore water pressure of the three monitoring points increases rapidly in the early stage of rainfall, especially in the early stage of rainfall infiltration and infiltration speed. After the rainfall stops, the pore water pressure begins to dissipate slowly; under the condition of center rainfall type, the pore water pressure of the three monitoring points increases rapidly in the middle stage of rainfall, especially in the early stage of rainfall infiltration amount and infiltration speed is particularly obvious in the middle stage; under the condition of back front type rainfall, the pore water pressure of three monitoring points increases rapidly in the later stage of rainfall, especially in the middle stage; under the condition of average type rainfall, the increase of pore water pressure of three monitoring points is basically the same in the whole rainfall process, and the rainfall infiltration

| Natural density \( \rho_d [\text{kg/m}^3] \) | Dry density \( \rho_d [\text{kg/m}^3] \) | Liquid limit \( \omega_L [\%] \) | Initial void ratio \( \varepsilon_0 \) | Water content \( \omega_0 [\%] \) | Specific gravity \( d_s \) | Effective cohesion \( c' [\text{kPa}] \) | Internal friction angle increment \( \varphi_b \) [\(^\circ\)] |
|---|---|---|---|---|---|---|---|
| 1575 | 1125 | 50 | 1.4 | 40 | 2.7 | 21 |

| Matric suction \( (u_a - u_w) [\text{kPa}] \) | Controlling particle size \( d_{60} [\text{mm}] \) | Effective particle size \( d_{10} [\text{mm}] \) | Permeability coefficient \( k [\text{cm/s}] \) | Compression coefficient \( a_1-2 [\text{MPa}^{-1}] \) | Effective internal friction angle \( \varphi' [\text{°}] \) |
|---|---|---|---|---|---|
| 6 | 17 | 0.33 | 0.005 | 1.35x10^{-8} | 0.3 | 10 |
increase of infiltration amount and infiltration speed is almost the same in the whole process; however, after rainfall, the pore water pressure starts to dissipate gradually, and gradually recovers to the initial state; in the whole process, the dissipation speed of monitoring point at the foot of slope is the slowest, and that at the top of slope is the fastest, which is related to the height of the feature point. Due to the effect of gravity, rainwater accumulates at the lowest height. Because of the residual water in the lower position, the dissipation rate of pore water pressure is slower than that of the slope surface and the top of the slope.

![Image](figure4.png)

Figure 4. Varying curve of pore water pressure with time under four rainfall patterns.

It can be known from the four rainfall schemes that the larger the rainfall at a certain time, the greater the change of pore water pressure. This is because the larger the rainfall, the greater the short-term water supplement amount of the soil, resulting in the rapid increase of the infiltration amount and infiltration rate in this short time.

![Image](figure5.png)

Figure 5. Displacement time curve of monitoring points under four rainfall patterns.
Analysis of the Change of Slope Displacement with Time

Through simulation, the change curve of displacement with time of three monitoring points at 2m under four kinds of rainfall slope is obtained, as shown in the Fig. 5:

When there is no rainfall, the initial displacement of the monitoring points is 0. With the development of the rainfall process, the displacement of the monitoring points shows different trends with the different types of rainfall. When the rainfall type is front type, the curve slope changes greatly in the early stage of rainfall; when the rainfall type is center type, the curve slope is the largest in the middle stage of rainfall; when the rainfall type is back front type, the curve slope is the largest in the late stage of rainfall; when the rainfall type is average type, the curve slope is almost the same in the whole rainfall period. It shows that the displacement change of monitoring point is affected by the change of rainfall type. The larger the rainfall increases, the larger the displacement increases.

In addition, the displacement of the three monitoring points of slope toe, slope surface and slope top is also different. Before the rainfall, the initial displacement of the three monitoring points are all 0. With the progress of the rainfall process, the displacement shows the trend: toe of slope > surface of slope > top of slope, and this trend will continue with the end of the rainfall process. The maximum displacement of the foot of the slope under four kinds of rainfall is 0.0527m. It shows that the damage of rainfall to the slope toe is the biggest. No matter what type of rainfall, the deformation of the slope toe is the largest finally, because rainfall causes the weight of the soil mass of the slope to increase, and the stress concentrates to the slope toe, leading to the slope instability. Therefore, in engineering design, attention should be paid to the protection and reinforcement the toe of slope.

Analysis of the Shape Change of Sliding Surface

There are four types of common sliding surface shapes: circular arc type, straight line type, step type and combination type. Because the shape of the slope sliding surface is almost the same under various rainfall conditions, the rainfall type is selected here as the front type for analysis. The following Fig. 6(a) shows various situations of the slope sliding surface searched by the finite element software with the rainfall type as the front type. The basic shape is circular arc type, and only one is straight line type.

It can be seen that in the case of frontal rainfall, there are multiple sliding surfaces on the slope, most of which are within the safety range, but there are still two sliding surfaces in the danger range, as shown in the following Fig. 6(b) and 6(c):

Their safety coefficients are 1.202 and 1.211 respectively, which belong to dangerous sliding surface. Among them, the sliding surface with a safety factor of 1.202 is circular arc type, and the sliding surface with a safety factor of 1.211 is straight line type, which indicates that the shape of dangerous sliding surface of structural soil slope in Zhanjiang area has different shapes under the condition of heavy rainfall, not a single shape. These shapes have an impact on the stability of the slope. When the sliding surface is linear, the slope is the most unstable. For this purpose, it is necessary to prevent the appearance of sliding surfaces similar to straight lines. Therefore, it is necessary to strengthen the real-time monitoring of the structural soil slope in Zhanjiang area, make a landslide warning before the extreme weather.

![Figure 6. Shape of sliding surfaces under the front rainfall type.](image-url)
Summary

Through the above numerical simulation analysis, the conclusions are listed as follows:

(1) Under the condition of four types of rainfall, the varying amplitude of pore water pressure at three monitoring points of the slope shows: toe of slope > surface of slope > top of slope, which caused by the accumulation of rainfall at the slope; in addition, the change trends of four types of rainfall are also different: for front peak type, center peak type, back peak type, the peak value of pore water pressure growth appears in the early, middle and late stages of rainfall respectively. That is to say, the peak value of pore water pressure growth appears in the corresponding rainfall peak stage, for the average rainfall the pore water pressure growth is faster in the whole rainfall process.

(2) Under four kinds of rainfall patterns, the displacement varying amplitude of three monitoring points on the slope shows: toe of slope > surface of slope > top of slope. Because the rainfall increases the weight of the soil mass on the slope, so the sliding force increases. The sliding force is transmitted to the soil mass of the slope and compresses the soil mass at the slope foot, so the displacement at the slope foot increases. In addition, the change trends of the four rainfall patterns is different each other, is same with the trend of water pressure growth: that is to say, the peak value of displacement growth occurs at the corresponding peak stage of rainfall, for average rainfall the displacement growth is faster in the whole rainfall process; because the larger the rainfall, the more the weight of soil mass, the more the slope sliding force increases, those caused rebound deformation towards the free surface, so the slope failure occur more easily.

(3) The shape of the sliding surface of the slope in Zhanjiang area include in circular arc type and linear type. The linear sliding surface has the greatest influence on the stability of the slope, so it is necessary to prevent the appearance of the linear sliding surface. Therefore, it is necessary to monitor the areas prone to landslides in this area, and give early warning in time, those maybe can reduce casualties and economic losses under extreme rainfall.

Acknowledgement

This research was financially supported by the National Science Foundation (Grant No: 51778508) and the Scientific Plan Guidance Project come from Hubei Education Department (Grant No: B2019010).

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