Analysis of stability factors and interaction rules of soil slope under heavy rainfall

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Abstract. Short-term heavy rainfall is an important inducement factor of soil landslide disaster in southern China. In order to study the influence degree of different factors on slope stability under heavy rainfall conditions, combining numerical simulation and mathematical statistics method, taking a certain slope in Guangzhou as the engineering background, the slope stability coefficient was calculated based on the coupling of Seep/W and Slope/W modules in Geo-studio software. Then the orthogonal experiment designed by Minitab was used to select rainfall intensity, rainfall time, cohesion, internal friction angle and severity for univariate range and variance analysis. On this basis, the rainfall intensity, rainfall time and internal friction angle were selected for the multi-factor interactive analysis. The results show that the five factors have significant influence on the slope stability. The order of sensitivity is: angle of internal friction of residual soil > rainfall intensity > rainfall time > cohesion > heavy. The interaction between the Angle of internal friction and rainfall has a high influence on the slope stability. The effect of interaction on slope stability should be emphasized in slope warning.

1. Introduction
Guangzhou area belongs to the subtropical monsoon climate, and the residual soil layer of granite is widely distributed. In the heavy rainfall weather, it is easy to soften and disintegrate and the shear strength is reduced, and the shallow landslide disaster is very easy to occur[1-2]. Slope stability is affected by many factors, which can be divided into two categories: external factors such as rainfall intensity, rainfall time and internal factors such as internal friction angle and cohesion [3-5]. It is essential to scientific guidance of design and construction, effective disaster prevention and mitigation, if we can make clear the primary and secondary relationship between these factors and slope stability. Based on the typical residual soil slope in Fuzhou area, Que Yun[6] et al analyzed the sensitivity of 11 factors, such as rainfall conditions and internal friction angle, to the slope stability by using grey correlation method. Shi Chenghe [7] et al analyzed the primary and secondary relationship between the rainfall intensity, rainfall time and other five factors on the slope seepage field and stability sensitivity in the rainfall process. However, the heavy rainfall condition is not considered in the design parameters. Because the slope is in complex geological conditions, the influence of various factors on the stability of the slope is often not a single action, but mutual influence and common action [8]. The above study does not consider the interaction between factors. Hence, this paper used the slope / W module coupled with seep / W of Geo-Studio software to calculate the slope stability coefficient under the condition of heavy rainfall, and
selects five factors of rainfall intensity, rainfall time, internal friction angle, cohesion and gravity and their interaction factors to design orthogonal experiment to conduct sensitivity analysis, discusses the primary and secondary sensitivity of each factor to the slope stability, which can provide a reference for the analysis of slope stability and slope engineering treatment under heavy rain conditions in Guangzhou.

2. Project Profile
The ydk24 + 320.000~ydk24+480.000 slope of Guangzhou rail transit line 21 is located in the valley landform between low mountains and hills. The elevation of the slope is 50.32 m~81.8 m, with a relative height difference of 32 M. The slope is undulating, steep at the bottom and gentle at the top. The natural slope angle is about 20 ~ 40°. There are many fruit trees and shrubs on the slope. The upper overburden layer is mainly deluvial silty clay and sandy cohesive soil, brownish yellow, plastic, slightly compacted, with a general thickness of 8-15 m, and the lower bedrock is Silurian completely or moderately weathered granite. The groundwater is mainly Quaternary loose rock pore water and massive bedrock fissure water.

2.1. Calculation model
According to the typical geological profile of slope, a two-dimensional model is established based on Geo-Studio software, and the calculation diagram is shown in Figure 1. The slope geological model is composed of deluvial soil layer and completely to moderately weathered granite bedrock layer. Coupled with seep / W and slope / W modules, the slope stability under the condition of short-term heavy rainfall is analyzed according to Mohr Coulomb criterion. The grid division is composed of quadrilateral and triangular elements. Combined with the indoor unsaturated characteristic test results of undisturbed soil samples on site, the previous investigation data and practical experience values. The density of deluvial soil is 17.0KN/m3, cohesion is 26.3KPa, internal friction angle is 19.0°, the density of all moderately weathered granite bedrock is 22.0KN/m3, cohesion is 26.5KPa, internal friction angle is 22.1°.

![Fig.1 The diagram calculation](image)

2.2. Calculation parameter selection
Based on the indoor pressure plate test and permeability test data of the original slope soil in the field, FX model and VG model are used for fitting respectively to determine the soil water characteristic curve data and permeability coefficient curve of the slope soil. The soil water characteristic curve and permeability coefficient curve of all medium weathered granite are determined according to the data of slope geotechnical investigation and relevant empirical values, as shown in Figure 2 below.
3. Sensitivity analysis of influencing factors

3.1. Single factor sensitivity analysis

3.1.1. Orthogonal experiment design

This study selects five influencing factors on slope stability, such as rainfall intensity (A), rainfall time (B), slope soil cohesion (C), slope soil internal friction angle (D), slope soil density (E). For each factor, five levels are selected. The range and level of each influencing factor are selected as shown in Table 1. Minitab software was used to design the L25 ($5^4$) orthogonal table, and the calculation results are shown in Table 2.

| Level | A/（mm/d） | B/d | C/KPa | D/° | E/（kN·m⁻³） | Empty column |
|-------|-----------|-----|-------|-----|-----------|-------------|
| 1     | 40        | 10  | 23.9  | 17  | 14.8      |             |
| 2     | 60        | 20  | 25.1  | 18  | 16.3      |             |
| 3     | 80        | 30  | 26.3  | 19  | 17.8      |             |
| 4     | 100       | 40  | 27.5  | 20  | 19.3      |             |
| 5     | 120       | 50  | 28.7  | 21  | 20.8      |             |

3.1.2. Range analysis

Range analysis is based on the size of the range $R_i$ to determine the degree of sensitivity of each factor. $R_i$ reflects the variation range of the test index when the level of the factor changes. The greater the range, the greater the impact of the level of the factor on the response factor [9]. $R_i$ is calculated from the index parameter $K_{ij}$ at different levels of the factors in Table 2:[10].

$$K_{ij} = \frac{1}{P_{ij}} \sum_{k=1}^{P_{ij}} Y_k - \bar{Y}$$

$$R_i = \max(K_{i1}, K_{i2}, ..., K_{im})$$

$$- \min(K_{i1}, K_{i2}, ..., K_{im})$$

In the formula:

- $K_{ij}$ is the average value of the orthogonal experiment results of the factor j at the i level;
- $P_{ij}$ is the number of experiments of the factor j at the i level;
- $Y_k$ is the $k$th experimental index value;
\( \bar{Y} \) is the average value of all the experimental results.

| Program | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---------|---|---|---|---|---|---|---|---|---|----|----|----|----|
| A       | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 | 2 | 2  | 3  | 3  | 3  |
| B       | 1 | 2 | 3 | 4 | 5 | 1 | 2 | 3 | 4 | 5  | 1  | 2  | 3  |
| C       | 1 | 2 | 3 | 4 | 5 | 2 | 3 | 4 | 5 | 1  | 3  | 4  | 5  |
| D       | 1 | 2 | 3 | 4 | 5 | 3 | 4 | 5 | 1 | 2  | 5  | 1  | 2  |
| E       | 1 | 2 | 3 | 4 | 5 | 4 | 5 | 1 | 2 | 3  | 2  | 3  | 4  |
| Empty column | 1 | 2 | 3 | 4 | 5 | 5 | 1 | 2 | 3 | 4  | 4  | 5  | 1  |

| Stability factor (Fs) | 1.185 | 1.216 | 1.249 | 1.275 | 1.31 | 1.22 | 1.258 | 1.296 | 1.159 | 1.113 | 1.301 | 1.138 | 1.157 |

Table 2 Schedule

| Program | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
|---------|----|----|----|----|----|----|----|----|----|----|----|----|
| A       | 3  | 3  | 4  | 4  | 4  | 4  | 4  | 4  | 5  | 5  | 5  | 5  |
| B       | 4  | 5  | 1  | 2  | 3  | 4  | 5  | 1  | 2  | 3  | 4  | 5  |
| C       | 1  | 2  | 4  | 5  | 1  | 2  | 3  | 5  | 1  | 2  | 3  | 4  |
| D       | 3  | 4  | 2  | 3  | 4  | 5  | 1  | 4  | 5  | 1  | 2  | 3  |
| E       | 5  | 1  | 5  | 1  | 2  | 3  | 4  | 3  | 4  | 5  | 1  | 2  |
| Empty column | 2 | 3 | 3 | 4 | 5 | 1 | 2 | 2 | 3 | 4 | 5 | 1 |

| Stability factor (Fs) | 1.126 | 1.214 | 1.172 | 1.231 | 1.198 | 1.235 | 1.078 | 1.275 | 1.225 | 1.084 | 1.132 | 1.172 |

According to the range calculation, the range value of each influencing factor on slope stability is shown in Table 3 below.

Table 3 Range analysis of single factor sensitivity

| Various level parameters | A     | B     | C     | D     | E     |
|--------------------------|-------|-------|-------|-------|-------|
| \( K_{ij} \)             | 1.247 | 1.2306| 1.1694| 1.1288| 1.2116|
| \( K_{ij} \)             | 1.2092| 1.2136| 1.1938| 1.158 | 1.2092|
| \( K_{ij} \)             | 1.1872| 1.1968| 1.2036| 1.1996| 1.202 |
| \( K_{ij} \)             | 1.1828| 1.1854| 1.2106| 1.244 | 1.191 |
| \( K_{ij} \)             | 1.1776| 1.1774| 1.2264| 1.2734| 1.19  |
| \( R_j \)                | 0.0694| 0.0532| 0.057 | 0.1446| 0.0216|

Order of sensitivity: D>A>C>B>E

Analysis of Table 3 shows that the primary and secondary order of the sensitivity of each factor to slope stability is: internal friction angle of residual soil > rainfall intensity > cohesion > rainfall time > severe. The maximum range of internal friction angle is 0.1508, which is significantly greater than the range of other influencing factors, indicating that the internal friction angle \( \phi \) of residual soil has the greatest impact on slope stability.

3.2 Multi-factor interaction analysis

Because the slope is in a complex geological condition, the influence of various influencing factors on the slope stability is not a single effect, but it may be influenced by multiple factors. The impact of rainfall on slope stability may be that rainfall first affects the stability of the slope through the impact on the shear strength of residual soil. Therefore, on the basis of single-factor sensitivity analysis, this
paper selects the internal friction angle $\phi$, rainfall intensity and rainfall time of residual soil to further analyze the influence of multi-factor interaction on slope stability.

Refer to the single-factor orthogonal experiment plan and use $L_8(2^7)$ to arrange the test. The first column is the internal friction angle $\phi$ (X) of the residual soil, the second column is the rainfall intensity factor (Y), and the interaction between the two is set to the third columns. The fourth column arranges the rain time (Z). The fifth and sixth columns arrange their interaction with the internal friction angle and rainfall intensity. The seventh column is the empty column. For the results of multi-factor interactions, refer to the single-factor sensitivity analysis and perform a range analysis based on formulas (1)-(6). Seven factors and two levels $F_{1.0.05} = 236.768$, $F_{1.0.1} = 58.906$, the results are shown in Table 4 below.

| Various level parameters | X     | Y     | $X \times Y$ | Z     | $X \times Z$ | $Y \times Z$ |
|--------------------------|-------|-------|-------------|-------|-------------|-------------|
| $K_{1}$                  | 0.9232| 0.9806| 0.9576      | 0.9508| 0.9462      | 0.9448      |
| $K_{2}$                  | 0.971 | 0.9136| 0.9366      | 0.9434| 0.948       | 0.9494      |
| $R_{j}$                  | 0.0478| 0.067 | 0.021       | 0.0074| 0.0018      | 0.0046      |
| Order of sensitivity     | I     | II    | III         | IV    | VI          | V           |

Analysis of Table 4 shows that the order of sensitivity is: internal friction angle > rainfall intensity > interaction of internal friction angle and rainfall intensity > rainfall time > interaction of internal friction angle and rainfall time > interaction of rainfall intensity and rainfall time. The influence of the interaction between factors on the slope stability can’t be ignored. In actual early warning and prevention, multiple factors and their interaction should be fully considered.

4. Conclusion

(1) The range of single factor’s sensitivity indicates that all five factors have a high significant impact on slope stability. The primary and secondary order of sensitivity is: residual friction angle in residual soil > rainfall intensity > rainfall time > cohesive force > heavy.

(2) The results of multi-factor interaction sensitivity range analysis show that the order of sensitivity is: internal friction angle > rainfall intensity > internal friction angle and rainfall intensity interaction > rainfall time > internal friction angle and rainfall time interaction > rainfall intensity and rainfall time interaction. Therefore, the influence of interaction on slope stability can’t be ignored, and various factors and their interaction should be considered in the early warning and prevention of slopes.

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