Factorial experiment of slope stability under slope-top loading and heavy rainfall

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Abstract: Because the slope-top loading and heavy rainfall are both important factors inducing slope landslides and another geologic hazard, it is necessary to analyze factorial experiment of the slope stability under the slope-top loading and heavy rainfall. Taking a slope engineering of a municipal roads as an example, the stability of the slope was calculated based on the strength reduction method with FEM and Midas-GTS (SRM), and then the double-factor factorial experiment with repeated tests was used to analyze the stability of the slope. The stability results show that, when rainfall conditions remain unchanged, the slope-top loading is applied, and the safety coefficient is reduced by 16%~21%. When the slope-top loading remains unchanged and the rainfall is strengthened, the security coefficient decreases by 10%~19%. The analysis shows that the maximum shear strain of the slope is significantly affected by the slope-top loading and rainfall on the top of the slope. The effect of the slope-top loading on the maximum horizontal displacement of the slope is not significant. The effect of heavy rainfall on the maximum displacement of slope is very significant. The combined effect of slope-top loading and heavy rainfall on the maximum horizontal displacement of the slope is significant. Generally speaking, heavy rainfall is the main factor affecting the slope safety. Under the interaction of two factors, the slope stability is poor. In the future, attention should be paid to some local projects such as slope drainage in landslide control and prevention.

1. Introduction

On the one hand, with the continuous development and expansion of urban scale, building various buildings on the slope becomes an effective way to utilize land resources. On the other hand, when the slope as a rock and soil body is susceptible to rainfall and other effects, resulting in soil landslide, ground collapse and other geological disasters. Many scholars have done a lot of research on slope stability under rainfall or roof load [1-5]: Cao jie et al.[6] believed that the increase of slope deformation could be caused by the increase of roof load, while the concentrated generation and development of deformation caused slope failure. Deng yun et al. [7] believed that as the slope increased, the negative impact of roof load on slope stability increased. The sliding scale factor is positively correlated with the increase of load on the top of slope. Xu han et al. [8] believed that the degree of slope deformation was positively correlated with rainfall intensity. Liu xin-xi et al. [9] showed that when the precipitation intensity was 200mm/d, the slope of high fill embankment would be unstable. The above studies focused on the slope stability under the single factor of roof load or rainfall respectively, and did not analyze the possible interaction of multiple factors on the landslide under complex working conditions. The existence of interaction can make different combination results of different factors produce different effects. Based on previous studies, this paper takes a cutting slope project as an example. Based on the finite element strength reduction method, the slope stability analysis and two-factor factor test analysis.
were carried out to observe the significance effect of different factors and their interaction on slope stability. It can provide reference for the prevention and control of landslide and other geological disasters.

2. research technique

2.1. A two-factor factorial test with repeated trials

The main purpose of this experiment is to study the significance of the impact of heavy rainfall and roof load on the slope stability, Factor \( A_m \) is used in the experiment to indicate whether there is roof load, and factor \( B_n \) is whether there is heavy rain. \( A_m \times B_n \) is used to represent the interaction between the roof load and heavy rainfall on the slope. The two factors have two horizontal \( m=n=2 \): dead weight \((A_1)\), slope top load \((A_2)\), no rain \((B_1)\), heavy rain \((B_2)\). There are four horizontal combinations of \( A_m \) and \( B_n \), and each combination is repeated twice. In this experiment, \( x_{ijk} \) is used to represent the test results. Where \( i \) represents the level corresponding to factor \( A \), \( j \) represents the level corresponding to factor \( B \), and \( k \) represents the KTH experiment at the combination level. Factorial test arrangements are shown in table 1.

Basic calculation method of two-factor anova with repeated tests:

\[
F \text{ value of } A_m : F_A = \frac{s_A^2}{s^2} = \frac{Q_A}{m-1},
\]

\[
F \text{ value of } B_n : F_B = \frac{s_B^2}{s^2} = \frac{Q_B}{n-1},
\]

In the above equation: \( Q_A \) is the sum of squared deviations of factor \( A \); \( Q_B \) is the sum of squared deviations of factors \( B \); \( s^2 \) is the sum of squared errors; \( s^2 \) for variance.

| no rain \((B_1)\) | heavy rainfall \((B_2)\) |
|------------------|-----------------------------|
| dead load \((A_1)\) | \( x_{111} \), \( x_{112} \) | \( x_{121} \), \( x_{122} \) |
| slope-top loading \((A_2)\) | \( x_{211} \), \( x_{212} \) | \( x_{221} \), \( x_{222} \) |

Where \( F \) value is subject to the \( F \) distribution of \( (df_A, df_e) \), The level of significance given is \( \alpha = 0.05 \) and \( \alpha = 0.01 \). If \( F_A > F_{0.01}(df_A, df_e) \), then factor \( A \) is very significant for the test results; if \( F_{0.01}(df_A, df_e) > F_A > F_{0.05}(df_A, df_e) \), the influence of factor \( A \) on the test result is significant; if \( F_A < F_{0.05}(df_A, df_e) \), the influence of factor \( A \) on the test result is not significant. Similarly, \( B_n \), \( A_m \times B_n \) also adopt the above principles.

3. Instance analysis of Engineering landslide

3.1. project profile

A chemical plant cooling tower is built at the top of a cutting slope. As the slope and surrounding buildings have been built for many years, and in recent years, the slope has not been supported and reinforced. The back edge of the top slope of this section is obviously cracked and in an unstable state. The slope landslide occurred after continuous heavy rainfall in rainy weather in May. According to the geological survey, the slope engineering safety level is level 3. (1) residual soil (silty clay), yellow-brown, checkered and reticulate structure, mainly composed of clay particles, with a small amount of coverage; (2) strongly weathered silty mudstone, purplish red, argillaceous structure, medium-thick layer loading structure, developed joints and fractures. Partial demonstration shows that basic weathering is in the form of soil, the original rock structure can be distinguished, the rock is broken, in the form of soil, half rock, half soil, and broken pieces, which are easy to soften when exposed to water, and easy to disintegrate after a long time. (3) medium weathered silty mudstone, purplish red, muddy structure.
3.2. Calculate parameters and boundary conditions
According to geological exploration, all parameters of rock and soil mass are determined as shown in table 2. Horizontal constraint of left and right boundaries, full constraint of bottom edge and free surface. The model dead weight was used to simulate the initial stress of the bottom layer, and then according to the field investigation, the uniform distributed load with a length of 10m and a size of 150Kn/m was applied on the slope top of the original model. The daily rainfall in this area is: \( q = 3.5 \times 10^{-6} \text{m/s} \).

| name of parameter       | silty clay | highly-weathered silty mudstone | medium-weathered silty mudstone |
|-------------------------|------------|---------------------------------|--------------------------------|
| elasticity modulus E/MPa| 4.4        | 260                             | 890                            |
| unit weight b/(kN·m⁻³)  | 18.7       | 22.0                            | 25.5                            |
| Poisson's ratio \( \mu \) | 0.31       | 0.29                            | 0.25                            |
| Cohesion C/kPa          | 20.8       | 30                              | 40                              |
| internal friction \( \phi \)/° | 19         | 50                              | 60                              |

4. Midas-GTS(SRM) calculation results and experimental analysis

4.1. Midas-GTS(SRM) calculation results
After Midas-GTS calculation, the safety coefficient, horizontal maximum displacement and maximum shear strain was obtained.

|                          | no rain \( (B_1) \) | heavy rainfall \( (B_2) \) |
|--------------------------|----------------------|----------------------------|
| dead load \( (A_1) \)    | 1.431, 1.431         | 1.211, 1.206               |
| slope-top loading \( (A_2) \) | 1.231, 1.219         | 0.988, 0.978               |

Table 4. The result of horizontal maximum displacement under the double factor test of repeated test
Unit: cm

|                          | No rain \( (B_1) \) | Heavy rainfall \( (B_2) \) |
|--------------------------|----------------------|----------------------------|
| dead load \( (A_1) \)    | 2.46, 2.46           | 31.73, 27.76               |
| slope-top loading \( (A_2) \) | 1.17, 1.32           | 37.69, 33.89               |

Table 5. The result of maximum shear strain under the double factor test of repeated test

|                          | no rain \( (B_1) \) | heavy rainfall \( (B_2) \) |
|--------------------------|----------------------|----------------------------|
| dead load \( (A_1) \)    | 0.011, 0.011         | 0.212, 0.232               |
| slope-top loading \( (A_2) \) | 0.006, 0.006         | 0.377, 0.384               |

4.2. Midas-gts (SRM) calculation results are compared and analyzed
As can be seen from table 3, the rainfall condition \( (B_n) \) remains unchanged, and the top load \( (A_2) \) is applied to change the initial dumping rock location and the distribution range of the sliding front [10], and its safety coefficient decreases by 16%~21%. The slope top load \( (A_m) \) remains unchanged, and enhanced rainfall \( (B_2) \) is applied. Due to the heavy rainfall, the soil layer is partially saturated and the soil strength is reduced, and its safety coefficient is reduced by 10%~19%. When the roof load and heavy rainfall \( (A_2+B_2) \) act at the same time, the slope safety coefficient =0.988 and is in an unstable state. Under the action of all kinds of geological forces or vibration loads of vehicles, geological disasters such as landslides, collapse and other slope instability are easy to occur. This project is during this period, the occurrence of landslides.
4.3. A two-factor factorial analysis with repeated trials

The results of maximum horizontal displacement (table 4) and maximum shear strain (table 5) obtained by numerical simulation were analyzed by two-factor anova, as shown in table 6 and 7.

Table 6. The analysis table of horizontal maximum displacement under the double factor test of repeated test

| source of variation | DEVSQ | degree of freedom | estimator of variance | F value | $F_{crit}$ |
|---------------------|-------|------------------|----------------------|---------|-----------|
| $A_m$               | 11.66 | 1                | 11.66                | 3.09    | 21.20     |
| $B_n$               | 1900.12 | 1            | 1900.12              | 475.03  | 21.20     |
| $A_m \times B_n$    | 37.72 | 1                | 37.72                | 9.98    | 21.20     |
| error               | 15.10 | 4                | 3.78                 |         |           |
| sum                 | 1964.60 | 7          |                      |         |           |

Table 7. The analysis table of maximum shear strain under the double factor test of repeated test

| source of variation | DEVSQ | degree of freedom | estimator of variance | F value | $F_{crit}$ |
|---------------------|-------|------------------|----------------------|---------|-----------|
| $A_m$               | 0.012 | 1                | 0.012                | 189     | 21.20     |
| $B_n$               | 0.171 | 1                | 0.171                | 2753    | 21.20     |
| $A_m \times B_n$    | 0.013 | 1                | 0.013                | 214     | 21.20     |
| error               | 2.49E-04 | 4          | 6.225E-05             |         |           |
| sum                 | 0.197 | 7                |                      |         |           |

(1) As can be seen from table 6, for the given significance levels $\alpha = 0.05$ and $\alpha = 0.01$, $F_A < F_{0.05}(1,4)$, indicating that the impact of roof load on the maximum horizontal displacement of the slope is not significant; $F_B > F_{0.01}(1,4)$, indicating that the effect of heavy rainfall on the maximum horizontal displacement of the slope is very significant: $F_{0.01}(1,4) > F_{A_m \times B_n} > F_{0.05}(1,4)$, indicating that the interaction between roof load and rainfall has a significant effect on the maximum horizontal displacement of the slope. The order of influence of different factors on the maximum horizontal displacement of slope is: $F_B > F_{A_m \times B_n} > F_A$.

(2) As can be seen from table 7, $F_B > F_{0.01}(1,4)$, $F_B > F_{0.01}(1,4)$, $F_{A_m \times B_n} > F_{0.01}(1,4)$. It indicates that the maximum shear strain of the slope is significantly affected by the roof load, rainfall and their interaction. The order of influence of different factors on the maximum shear strain of slope is: $F_{A_m \times B_n} > F_A$.

5. conclusion

(1) In this paper, Midas-GTS (SRM) software was used to simulate and calculate the safety coefficient of a certain slope. When the roof load remains unchanged, the safety coefficient decreases by 10%~19% with the increase of heavy rainfall. When the roof load and heavy rainfall act on the slope at the same time, its safety coefficient is 0.988, in an unstable state; The potential sliding surface position of the simulated slope is more directly reflected by the cloud diagram of horizontal displacement and maximum shear strain. The simulation results are in good agreement with the landslide on site.

(2) The double-factor analysis with repeated tests showed that the maximum shear strain of the slope was significantly affected by the roof load, heavy rainfall and their interaction. Top load on the horizontal maximum displacement of the slope is not significant, the influence of rain on the influence of the horizontal maximum displacement of slope is very significant, the interaction of the top load and rainfall on the slope significantly, the influence of the horizontal maximum displacement of the sort of impact of different factors on the maximum shear strain of slope, heavy rainfall > reciprocal action > slope top loading.

(3) Compared with traditional slope stability analysis, stability factor analysis not only analyzes the slope stability, but also compares the significance of factors affecting slope stability. The results show
that both the load on the slope top and the heavy rainfall have negative effects on the slope stability, and
the maximum effect on the slope safety. In the future, attention should be paid to slope drainage and
other local projects.

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