Seismic Stability Analysis of Loess Landslide Based on Orthogonal Test

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Abstract. A numerical model of a loess landslide is established by using numerical simulation method to simulate the stability of the loess landslide under earthquake load. The results show that the loess landslide is stable before the earthquake and unstable under the earthquake. The horizontal displacement and shear strain increment of the front part of the sliding slope increase obviously under the earthquake. At the same time, the sensitivity analysis of the seismic stability of the loess landslide is carried out by using the orthogonal test design method. The results show that the seismic action is the second factor to the internal friction angle of the sliding zone soil. With the increase of the seismic intensity, the decrease trend of the stability coefficient increases.

1. Introduction
The stability of landslide is affected by various internal factors, such as the shape of landslide, the physical and mechanical characteristics of landslide rock mass, the effect of seismic force, the change of groundwater and surface water [1, 2]. Loess landslide is one of the most serious geological disasters in the loess area of Northwest China, which often causes houses and farmland to be buried, traffic interruption, river blockage and so on. Some large earthquakes in history have induced a large number of loess landslides, resulting in huge loss of life and property. For example, in 1654, the Tianshui 8.0 earthquake in Gansu Province induced a large number of loess landslides, buried thousands of nearby villages; in 1718, the Tongwei 7.5 earthquake in Gansu Province induced more than 300 large-scale loess landslides, resulting in more than 40000 deaths and injuries in urban and rural areas [3]. In this paper, a numerical model of a loess landslide in Wenchuan earthquake area is established by using numerical simulation method, and the stability of the loess landslide under earthquake load is simulated. Finally, the sensitivity analysis of the main factors affecting the stability of loess landslide is carried out by using the orthogonal test design.

2. Numerical simulation of loess landslide stability under earthquake
In this paper, the stability of a loess landslide under the action of earthquake force is analyzed by numerical simulation. The total displacement, horizontal displacement, shear strain increment and plastic zone of the landslide before and after the earthquake are simulated and compared.

2.1. Numerical calculation model and parameters
According to the topographic map and geological exploration data, the boundary conditions of the model are determined comprehensively. The y-axis direction of the whole calculation model is...
perpendicular to the main ditch direction, the x-axis direction is the main ditch direction, the z-axis direction is vertical upward, and the bottom elevation is 1300m. According to the structural characteristics and material composition of landslide, the model is generalized into three kinds of materials, namely sliding mass, sliding belt and sliding bed. The length of the model in x-axis direction is 1050 m, the width in Y-axis direction is 600 m, and the height in vertical direction is 290 m. The bottom of the model is set as a static boundary, and the side boundary is set as a free field boundary. The soil material of the landslide is set as elastic-plastic material, Mohr Coulomb strength criterion is adopted, local damping is adopted, and the damping coefficient is 0.15. The initial stress field produced by the Gravity stress is considered in the calculation.

The geotechnical mechanical parameters used in the model include density, internal friction angle, cohesion, modulus of elasticity, Poisson's ratio, etc. The specific parameter value is determined on the basis of indoor test, considering local experience value and combining with parameter inversion. See Table 1 for specific parameters. The bulk modulus (K) and shear modulus (G) are calculated as follows:

\[ K = \frac{E}{3(1-\mu)} \]  \hspace{1cm} (1)

\[ G = \frac{E}{2(1+\mu)} \]  \hspace{1cm} (2)

In the formula: E is the modulus of elasticity; \( \mu \) is the Poisson's ratio.

| Name of rock and soil mass | Bulk density (KN/m\(^3\)) | Modulus of elasticity E/Mpa | Poisson's ratio \( \mu \) | Cohesion C(kPa) | Internal friction angle \( \phi(°) \) |
|---------------------------|---------------------------|---------------------------|------------------------|---------------|-------------------------|
| Sliding mass              | 20.7                      | 85                        | 0.28                   | 20            | 12.5                    |
| Slip zone                 | 19.6                      | 75                        | 0.27                   | 19            | 12                      |
| Slide bed                 | 25                        | 800                       | 0.25                   | 570           | 38                      |

According to the No.1 amendment to the national standard of seismic ground motion parameter zoning map of China (GB110386-2001) implemented in June 2008, the seismic intensity of landslide area is VIII degree, and the design basic seismic acceleration is 0.20g. In this paper, the input seismic wave of numerical simulation ground motion loading is Kobe wave, and the representative 9 s-long seismic wave in the time history curve of Kobe seismic horizontal acceleration is taken as the seismic dynamic input. Considering the actual situation of the landslide area, the peak acceleration is adjusted to 0.2g, and input after filtering and baseline correction.

2.2. Analysis of calculation results

2.2.1. Analysis of deformation characteristics of landslide before and after earthquake. Figure 1 shows the isoline cloud map of the total displacement of the landslide before and after the earthquake.
Figure 1. Isoline nephogram of total displacement of landslide.

It can be seen from Figure 1 that the overall deformation of the landslide is relatively small and the front deformation is relatively large. The deformation shows the distribution characteristics of decreasing from the surface to the inside of the slope. The maximum displacement before the earthquake is about 0.57M, and the maximum displacement under the earthquake is 1.51m, all of which appear in the front of the slope. It shows that the whole landslide is relatively stable before the earthquake and after the earthquake, and the front of the landslide may slide and destroy. This is in accordance with the actual situation that the front edge of the landslide mass produced violent sliding during the "5.12" earthquake.

2.2.2. Analysis of shear strain increment before and after earthquake. A large number of theoretical and engineering analysis results show that the shear strain increment concentration zone is usually the area where deep deformation and failure occur. Figure 2 shows that the maximum value of shear strain increment in the slope before the earthquake is $5.9 \times 10^{-2}$, and the shear strain increment concentrated in the front of the landslide. Under the action of earthquake, the maximum value of shear strain increment is $4.0 \times 10^{-1}$, which is greatly increased before the earthquake. The shear strain increment concentration zone is distributed in the front and back edge of landslide, and the penetration rate is increased before the earthquake.

Figure 2. Isoline nephogram of shear strain increment of landslide.

Through the comprehensive analysis of the numerical simulation results before and after the earthquake action of a landslide, it can be seen that the displacement of the front edge of the landslide under the earthquake action of deformation increases greatly compared with that before the earthquake; The shear strain increment concentration zone is mainly distributed in the front of the landslide. Under the earthquake action, the shear strain increment value is obviously increased compared with that before the earthquake, and the penetration rate is also increased. The comprehensive analysis shows
that the whole landslide is in an unstable state under the action of earthquake, and the front deformation is the largest. The numerical simulation results are consistent with the actual situation of violent sliding of the front of landslide mass during the “5.12” Wenchuan earthquake.

3. Sensitivity analysis of factors affecting seismic stability

3.1. Design principle of orthogonal test

Orthogonal experiment design is a mathematical method to arrange multi factor experiments. Orthogonal experiment design method is also called orthogonal experiment method. It is a method of arranging multi factor experiment by using orthogonal table. It selects some representative points from the comprehensive experiment for experiment. These representative points are uniform and tidy. Orthogonal test design is the main method of partial factor design, with high efficiency. In the test, the results to be inspected are called indexes, the factors to be inspected that may have influence on the test indexes are called factors, and the specific conditions to be compared for each factor in the test are called levels [4].

Each factor considered in the experiment should occupy a column number in the orthogonal table, and the number of levels of the factor should be equal to the number of levels that the column number of the factor can accommodate, that is, r level factor should be placed on the column number with r level, and the number of level of column number r corresponds to the number of level of the factor. If we want to consider the interaction between factors, we should regard the interaction between factors as a new factor and arrange it on the corresponding column number according to the same rule.

When it is not required to make quantitative conclusion, only to identify the sequence analysis of the significant influence of factor variable X, on Index Y, the method to find the range R is as follows:

Set A, B Indicates the different factors in the test; r is the level number of each factor; A_i is the ith horizontal value of factor A, i=1,2,……r; X_{ij} is the ith horizontal value of factor j, i=1, 2,…..r, j=A, B…. n tests were carried out under X_{ij} to obtain n test results Y_{ijk}, k=1,2,…,n. The calculation parameters are as follows:

\[ K_{ij} = \sum_{k=1}^{n} Y_{ijk} \]  \hspace{1cm} (3)

In the formula, K_{ij} is the statistical parameter of factor j at level i; n is the test times of factor j at level i; Y_{ijk} is the k test index value of factor j at Level i. In conclusion, the calculation formula of the parameter range R_j of the significance of evaluation factors is as follows:

\[ R_j = \max \left\{ K_{ij}, K_{ij}, \ldots \right\} - \min \left\{ K_{ij}, K_{ij}, \ldots \right\} \]  \hspace{1cm} (4)

The greater the range R_j, the greater the influence of the level change of this factor on the test index. The biggest difference is the most important factor. Although the factor with smaller range can not be said to be unimportant, it can be determined at least that when the factor changes within the selected range, it has little influence on the test index compared with other factors.

3.2. Steps of orthogonal test design

In the sensitivity analysis of factors affecting the stability of loess landslide, the first step is to determine the analysis object. The so-called analysis object is the key quantity that can measure the stability degree of landslide, which refers to the stability coefficient of landslide. We are concerned about how the stability coefficient of the landslide will change when the factors change, and how its change range. In this paper, Morgenstern price method is used to calculate the stability coefficient of the Loess Landslide in sensitivity analysis.

Select important parameters as sensitivity analysis factors. When selecting sensitive factors, we should carefully consider them to avoid complicating the problem. In order to reduce the amount of calculation without affecting the analysis results, the combination of factors and events that are rarely likely to occur should be excluded before calculation.

Calculate the rate of change. In sensitivity analysis, according to the pre-determined change range, change one analysis factor, while other factors remain unchanged, calculate the impact of the change
of this factor on the analysis object, and compare with the original index to find out the change range (or change rate), and then carry out the same comparison calculation for the other factor.

3.3. Sensitivity orthogonal test analysis of factors affecting the stability of a loess landslide
Taking a loess landslide as an example, sensitivity analysis is made on the factors influencing the stability of the landslide. The sensitivity analysis was carried out by selecting four main factors, namely, horizontal seismic acceleration coefficient $J_H$, internal friction angle $\phi$, cohesion $c$ and bulk density $\gamma$. According to the design idea of orthogonal test, $L_{25}(5^4)$ orthogonal table is selected, and the factor level is shown in Table 2. According to the design and calculation scheme of orthogonal table, the stability coefficient of loess landslide is calculated by unbalanced force transfer method, and the calculation results are shown in Table 3.

Table 2. Table of factors.

| Factor | Horizontal acceleration coefficient $J_H$ | Internal friction angle $\phi$ (/°) | Cohesive force $c$/kPa | Bulk density of sliding mass $\gamma$/KN.m$^{-3}$ |
|--------|------------------------------------------|-------------------------------------|------------------------|-----------------------------------------------|
| Level 1 | 0                                        | 7                                   | 9                      | 13                                            |
| Level 2 | 0.025 (VI degree)                        | 9                                   | 12                     | 15                                            |
| Level 3 | 0.05 (VII degree)                        | 11                                  | 15                     | 17                                            |
| Level 4 | 0.075 (VIII degree)                      | 13                                  | 18                     | 19                                            |
| Level 5 | 0.1 (IX degree)                          | 15                                  | 21                     | 21                                            |

Table 3. Calculation results of orthogonal test.

| Experimental scheme | $c$/kPa | $\phi$ (/°) | $\gamma$/KN.m$^{-2}$ | $J_m$/KN.m$^{-3}$ | Stability coefficient |
|---------------------|---------|-------------|----------------------|------------------|-----------------------|
| 1                   | 9       | 7           | 13                   | 0                | 0.709                 |
| 2                   | 9       | 7           | 13                   | 0.025            | 0.768                 |
| 3                   | 11      | 7           | 15                   | 0.05             | 0.826                 |
| 4                   | 13      | 7           | 19                   | 0.075            | 0.875                 |
| 5                   | 15      | 7           | 21                   | 0.1              | 0.930                 |
| 6                   | 12      | 9           | 15                   | 0.05             | 0.566                 |
| 7                   | 12      | 9           | 17                   | 0.075            | 0.633                 |
| 8                   | 12      | 11          | 19                   | 0.1              | 0.691                 |
| 9                   | 12      | 13          | 21                   | 0                | 1.230                 |
| 10                  | 12      | 15          | 13                   | 0.025            | 1.292                 |
| 11                  | 15      | 7           | 17                   | 0.1              | 0.475                 |
| 12                  | 15      | 9           | 19                   | 0.1              | 0.891                 |
| 13                  | 15      | 11          | 13                   | 0.025            | 0.990                 |
| 14                  | 15      | 13          | 21                   | 0.05             | 1.002                 |
| 15                  | 15      | 15          | 15                   | 0.075            | 1.055                 |
| 16                  | 18      | 7           | 19                   | 0.025            | 0.648                 |
| 17                  | 18      | 9           | 21                   | 0.05             | 0.715                 |
| 18                  | 18      | 11          | 13                   | 0.075            | 0.909                 |
| 19                  | 18      | 13          | 15                   | 0.1              | 0.858                 |
| 20                  | 18      | 15          | 17                   | 0                | 1.476                 |
| 21                  | 21      | 7           | 21                   | 0.075            | 0.530                 |
| 22                  | 21      | 9           | 13                   | 0.1              | 0.651                 |
| 23                  | 21      | 11          | 15                   | 0                | 1.146                 |
| 24                  | 21      | 13          | 17                   | 0.025            | 1.161                 |
| 25                  | 21      | 15          | 19                   | 0.05             | 1.175                 |

Use the range analysis method to analyze the calculation results of the orthogonal test. The analysis results are shown in Table 4.
Table 4. Range analysis table.

| Parameter        | Factor |   |   |   |
|------------------|--------|---|---|---|
|                  | Cohesive force | Internal friction angle | Bulk density of sliding mass | Horizontal acceleration coefficient of earthquake |
| $k_3$            | 4.108  | 2.928 | 4.551 | 5.452 |
| $k_2$            | 4.412  | 3.658 | 4.393 | 4.859 |
| $k_1$            | 4.413  | 4.562 | 4.571 | 4.284 |
| $k_4$            | 4.606  | 5.126 | 4.28  | 4.002 |
| $k_5$            | 4.665  | 5.928 | 4.407 | 3.605 |
| $K_3$            | 0.8216 | 0.5856 | 0.9102 | 1.0904 |
| $K_2$            | 0.8824 | 0.7316 | 0.8786 | 0.9718 |
| $K_1$            | 0.8826 | 0.9124 | 0.9142 | 0.8568 |
| $K_4$            | 0.9212 | 1.0522 | 0.856  | 0.8004 |
| $K_5$            | 0.9326 | 1.1856 | 0.8814 | 0.721  |
| $R_f$            | 0.111  | 0.600 | 0.0582 | 0.3694 |

It can be seen from Table 4 that the internal friction angle of the sliding zone soil has the greatest influence on the stability coefficient of a loess landslide, and the seismic action is the second only to the internal friction angle of the sliding zone soil. Moreover, with the increase of the seismic intensity, the decrease trend of the stability coefficient of the landslide increases.

4. Conclusion

Through the comprehensive analysis of the numerical simulation results before and after the earthquake action of a loess landslide, it can be seen that the whole landslide is in an unstable state under the action of earthquake, and the front deformation is the largest. The numerical simulation results are consistent with the actual situation of violent sliding of the front of landslide mass during the "5.12" Wenchuan earthquake. The sensitivity analysis of the seismic stability of the loess landslide is carried out by using the orthogonal test design method. The results show that the seismic action is the second factor to the internal friction angle of the sliding zone soil. With the increase of the seismic intensity, the decrease trend of the stability coefficient increases.

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