Stability evaluation method for assessing bedrock and overburden layer slope (BOLS) under seismic load

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Abstract. Seismic load is a type of dynamic load that can easily induce the failure of the foundation slope. Using the continuum-based discrete element method in continuum mechanics, herein, the rupture degree and permanent displacement are defined and their evaluation steps are proposed. The sensitivity of rupture degree and the permanent displacement of overburden under seismic force are also analyzed. A new stability evaluation method for an overburden layer under seismic load, which considers rupture degree and permanent displacement, is established. The results showed that the overburden layer and the interface between bedrock and overburden are damaged to a certain extent under the action of a small-intensity earthquake (a_{peak} = 0.03–0.06 g), although the overburden surface is not damaged. With the increase of seismic frequency and slope height, the permanent displacement of overburden decreases, although it increases with the increase of peak acceleration and slope angle. Furthermore, duration has little to no influence on the permanent displacement of the overburden under the condition of a small or moderate earthquake. In the case of a large earthquake, the permanent displacement of overburden increases linearly with the increase in duration.

1. Introduction

Currently, the main methods for conducting stability analysis of high and steep slopes are the qualitative and quantitative analyses. Qualitative analysis methods include engineering geological interpretation, the graphic method, the engineering analogy method, and so on (Song et al., 2011). Quantitative analysis methods include limit equilibrium analysis methods, such as the Sarma method; block limit equilibrium method; and transfer coefficient method, the Newmark displacement analysis method, and the finite element numerical calculation method, among others (Terzaghi et al., 1967; Fredlund & Delwyn, 2006; Zhang, 2007).

The methods of slope stability analysis under earthquake action are mainly conducted using quantitative calculation via a quasi-static method based on limit equilibrium analysis, the Newmark method based on cumulative displacement criterion, and dynamic numerical simulation (Leshchinsky et al., 1994; Feng et al., 2012; Luan et al., 2013). The pseudo static method was first applied to slope stability analysis (Terzaghi et al., 1967) in 1950. The main idea is to simplify a seismic action into a
constant acceleration action in the horizontal and vertical directions. Then, all the forces existing on the potential sliding body are decomposed along the sliding surface direction according to limit equilibrium theory. In this way, the safety coefficient along the sliding surface is obtained. The advantage of this method is its simple calculation, while its disadvantage is its failure to consider the dynamic characteristics of earthquakes, rocks, and soil, such as the vibration frequency, vibration times, and duration. The Newmark method mainly uses acceleration time history double integral with the value of transcendental domain; however, only the cumulative displacement can be given.

Meanwhile, dynamic numerical analysis includes the response spectrum analysis method and the time history analysis method (Huang, 2000). The response spectrum analysis method, which uses a relatively simple calculation, determines the seismic parameters according to the statistical response spectrum curve accumulated in the annual observation. However, the ground behavior under earthquake action is very complex, and the selected mode combination is only the average value in the statistical sense, which is not strict in a theoretical sense. At the same time, it is difficult to consider its influence on the time history analysis method.

The time history analysis method can fully consider the three elements of amplitude, frequency spectrum, and duration of earthquake (Fu et al., 2017; Chen et al., 2020). At the same time, it fully considers the dynamic and damping characteristics of the slope rock and soil, as well as reflects the stress and deformation of the slope with the seismic action time. However, it has two disadvantages: it cannot easily measure the input of site seismic wave and its calculation is relatively cumbersome.

Based on the continuum-based discrete element method (CDEM) in continuum mechanics, this paper systematically studies the definition and evaluation steps of rupture degree and permanent displacement. Then, the sensitivity analyses of rupture degree and permanent displacement of overburden are conducted. Finally, an evaluation method of bedrock and the overburden layer slope (BOLS) stability under seismic load is established, considering rupture degree and permanent displacement.

2. Definition and evaluation of rupture degree

2.1. Definition of rupture degree

Rupture degree is a quantitative index that is used to describe the damage degree of the overburden layer of BOLS (Guo et al., 2016). It physically represents the ratio of the number of ground fissures existing in the study slope to the number of ground fissures formed during a disaster. Currently, there are different ways to define the rupture degree when evaluating slope stability by numerical calculation. For instance, the rupture degree may be defined using the ratio of the number of current failure elements to the number of failure elements at the time of disaster. Moreover, given that there are different definitions for the description of disaster formation in numerical calculation, the rupture degree can also be defined by the ratio of the number of current interface elements destroyed to the total number of interface elements in the calculation model. These definitions of rupture degree indicate that it can be considered the evaluation index of the state of landslide damage in which the greater the rupture degree, the more severe the slope damage and the greater the possibility of instability. Here, rupture degree $= 0$ implies no damage, while rupture degree $= 1$ implies complete damage.

In the concept of rupture degree, CDEM is used to perform dynamic calculation. As mentioned above, the CDEM program can realize the process of material transformation from continuous to discontinuous through the failure of an interface unit. According to this, the failure number of interface spring in the model can be calculated to represent the state of the slope. Therefore, three kinds of rupture degrees are defined as follows: total rupture degree ($T_b$), sliding surface rupture degree ($I_b$), and surface rupture degree ($D_b$), where $0 \leq T_b, I_b, D_b \leq 1$.

2.2. Steps in evaluating rupture degree
The process of using the evaluation index of rupture degree to evaluate the slope stability can be divided into four steps, which are described in detail below.

Step 1. Determine the important factors affecting slope stability

The influence of an earthquake on BOLS can be classified into either a cumulative or a triggering effect. A “cumulative effect” refers to the damage caused by an earthquake to the rock and soil structure of slope, the occurrence of small discontinuity surface, or the original structural surface penetration, among others, which are eventually reflected in the reduction of material strength and in slope disasters caused by engineering disturbance, precipitation, and other external factors. For such landslides, the influence of a seismic action is reflected in the reduction of material strength. Slope body stability under gravity can be calculated by the reduced strength, thus facilitating the evaluation of slope stability after an earthquake. Meanwhile, the “triggering effect” refers to the strong stress wave generated by the earthquake, which directly leads to the fatal damage of the slope structure, eventually resulting in slope collapse and instability during an earthquake. For this kind of landslide, the influence of earthquake action is reflected in the action of boundary load; hence, slope stability under dynamic load must be calculated.

Step 2. Determine the numerical simulation scheme by combining with the actual situation

Taking the later landslide as an example, the calculation models of BOLS are shown in Figure 1 and Table 1, respectively. Then, the tensile strength, cohesion, and the internal friction angle of overburden material are modified and the material cohesion is assumed to be always consistent with the tensile strength. Finally, the rupture degree of BOLS under the action of gravity is calculated for different strength combinations.

![Figure 1. Calculation model of the rupture degree of BOLS.](image)

Step 3. Create the distribution chart of the statistical rupture degree

As shown in Figure 2, the change rule of rupture degree with different influencing factors can be drawn based on the statistical calculation results under different working conditions. In Figure 2, the higher the tensile strength (cohesion), the smaller the rupture degree of the foundation slope under the action of gravity. Simultaneously, the larger the internal friction angle, the smaller the BOLS under gravity. When the strength decreases gradually, the value of rupture degree tends to 1. This shows that it is feasible to use the rupture degree as an evaluation index under the static action of the foundation slope.
Step 4. Determine the current state of the slope and preliminarily evaluate the stability of the slope.

The main material parameters of rock and soil can be obtained through field investigation, while the current rupture degree of the slope can be determined by comparing it with others in the rupture degree distribution chart (Figure 2), which can be used to perform a preliminary evaluation on the stability of the slope. The reasonable rupture degree of the slope can be obtained if the reasonable strength of the material after earthquake is provided.

2.3. Sensitivity analysis of rupture degree of the overburden layer

The load characteristics are determined as the research object for the same landslide occurring in an earthquake. Based on static calculation, the intermittent shear stress load is inputted at the bottom of the model to investigate the change of the rupture degree of the overburden with the peak acceleration ($a_{\text{peak}}$) and load period (T). The calculation model is shown in Figure 1, and the material parameters are shown in Table 2. In addition, the calculation results are shown in Table 3, where the interface rupture degree refers to the ratio of the number of broken springs on the interface between bedrock and overburden to the total number of springs on the interface. The surface rupture degree represents the ratio of the number of damaged springs on the slope surface to the total number of springs on the slope surface. The variation laws of rupture degree of the overburden, interface rupture degree, and surface rupture degree with load period are shown in Figure 3.

### Table 1. Geometric dimensions of the calculation model.

| Length (m) | Height (m) | Slope height (m) | Slope gradient ($^\circ$) | Maximum distance in the horizontal direction of overburden (m) | Maximum vertical distance of the overburden (m) |
|------------|------------|------------------|--------------------------|-------------------------------------------------------------|-----------------------------------------------|
| 75         | 40         | 20               | 30                       | 15                                                          | 13                                            |

### Table 2. Material parameters of the calculation model.

| Layers | Density (g/m$^3$) | Elastic modulus (kPa) | Tensile strength (kPa) | Cohesion (kPa) | Internal friction angle ($^\circ$) |
|--------|-------------------|-----------------------|------------------------|----------------|----------------------------------|

Figure 2. Distribution of total rupture degree under different strength combinations.
As shown in Figure 3(a), the rupture degree of the foundation and cladding increases with the load cycle and the damage degree of the overburden layer also increases when the peak acceleration $a_{\text{peak}}$ varies from 0.03 g to 0.24 g. When the loading period reaches 0.3 s, the rupture degree of the overburden layer gradually tends to be stable and the damage degree of the overburden layer essentially reaches a stable state. When the peak acceleration $a_{\text{peak}}$ reaches 0.48 g, the rupture degree of the overburden layer becomes larger and changes linearly with the load cycle; in this case, the damage degree of the overburden layer also becomes larger.

It can be seen from Figure 3(b) that the variation law of the rupture and damage degrees of the interface between bedrock and overburden with the load cycle is consistent with that of the overburden layer. As shown in Figure 3(c), surface rupture degree is 0 when the peak acceleration $a_{\text{peak}}$ varies from 0.03 g to 0.06 g and there is no damage on the surface of the overburden layer. When the peak acceleration $a_{\text{peak}}$ varies from 0.12 g to 0.48 g, the variation of the surface rupture degree with the load cycle is consistent with that of the overburden layer.

Meanwhile, Figure 4 shows that the overburden layer and the interface between bedrock and overburden are damaged to a certain extent under the action of a small-intensity earthquake ($a_{\text{peak}}$ = 0.03 g). The degree of damage varies with the load cycle, and the degree of damage of the overburden layer is lower than that of the interface between bedrock and overburden layer.

### Table 3. Calculation results.

| Peak acceleration (g) | Stress amplitude (MPa) | Load period (s) | Action time (s) | Rupture degree of overburden (%) | Interface rupture degree (%) | Surface rupture degree (%) |
|-----------------------|------------------------|-----------------|-----------------|---------------------------------|-----------------------------|---------------------------|
| 0.03                  | 0.187                  | 0.1             | 0.5             | 0.8                             | 8.9                         | 0.0                       |
| 0.06                  | 0.461                  | 0.3             | 1.5             | 21.3                            | 33.9                        | 0.0                       |
| 0.12                  | 1.122                  | 0.5             | 2.5             | 16.3                            | 43.8                        | 0.0                       |
| 0.24                  | 1.87                   | 0.1             | 1.0             | 51.1                            | 64.3                        | 1.4                       |
| 0.48                  | 4.045                  | 0.5             | 2.5             | 78.1                            | 82.0                        | 82.5                      |

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0.03–0.06 g), although the overburden surface is not damaged. Furthermore, the damage of the overburden, the interface between bedrock and overburden, and overburden surface all increase with $a_{\text{peak}}$.

![Variation of the rupture degree with load cycle](image)

**Figure 3.** Variation of the rupture degree with load cycle.
3. Definition and evaluation of permanent displacement

3.1. Definition of permanent displacement

“Permanent displacement” refers to the irrecoverable deformation (plastic deformation) or slip on the surface and inside of a slope after an earthquake. As a dynamic load, the effect of the load disappears after an earthquake; however, the additional stress produced by the earthquake acts on BOLS, which causes the sliding force of the BOLS to exceed the antisliding force at some specific time. As a result, the BOLS has a certain slip. However, after the earthquake, the additional stress produced by the earthquake disappears and the deformation of the BOLS stops, as shown in Figure 5.

In the field of engineering, the concept of permanent displacement is used to describe the damage effect of an earthquake on a slope, wherein the larger the permanent displacement, the more serious the slope damage. The allowable permanent displacement of slope is related to the allowable displacement of engineering structure. Currently, permanent displacement has been completely or partially adopted in the seismic design of large structures, such as dams and ports.

3.2. Steps in evaluating permanent displacement

For the low slope, whose slope height is less than 10 m, the simple integral of seismic acceleration time history curve can be used to calculate the permanent displacement. The permanent displacement of the slope is shown in Eq. (1), in which the critical pseudo static acceleration leading to slope sliding...
and the seismic time history curve of the design area are represented by $a_c$ and $a(t)$, respectively. The calculation diagram is shown in Figure 6.

$$D = \int_{0}^{t} (a(t) - a_c)dt$$

(1)

### Figure 6. Schematic diagram of obtaining permanent displacement value using the simple integration method.

The dynamic time history method (numerical analysis method) should be used to check the permanent displacement of the high slope, whose slope height is more than 10 m.

**Step 1.** Determine the physical and mechanical parameters of the slope.

**Step 2.** The input waveform (including amplitude, dominant frequency, and duration) should be determined according to the seismic intensity in the design area. The input waveform should be classified as a sine, El Centro, or synthetic wave in the design area.

**Step 3.** Ensure that the numerical model is stable in the elastic and plastic calculation under static force.

**Step 4.** Impose the boundary conditions of no reflection and free field, and input the preset seismic wave for dynamic calculations.

**Step 5.** Analyze the calculation results, including the maximum displacement position and maximum displacement value of the overburden. If there is a retaining structure, the rigid displacement and the rotation of the retaining structure should be analyzed.

### 3.3. Sensitivity analysis of permanent displacement of the overburden layer

#### 3.3.1. Influence of earthquake frequency and peak acceleration

As shown in Figure 7 (the slope height is 60 m), the permanent displacement of the overburden gradually decreases with the increase of seismic frequency; moreover, the permanent displacement suddenly changes near the resonance point. Furthermore, the permanent displacement increases gradually with the increase of peak acceleration.
Figure 7. Effect of seismic frequency and peak acceleration on permanent displacement of slope.

3.3.2. Influence of earthquake duration

3.3.3. As shown in Figure 8 (slope height is 20 m, and earthquake frequency is 2 Hz), duration has no influence on the permanent displacement of the overburden under the condition of a small earthquake. Under the condition of a moderate earthquake, the influence of duration on the permanent displacement of overburden is small, and there is a critical duration. In the case of a large earthquake, the permanent displacement of the overburden increases linearly with the increase in duration.

Figure 8. Influence of earthquake duration.

3.3.4. Influence of slope geometry size

As shown in Figure 9 (earthquake frequency is 5 Hz), with the increase of slope height, the permanent displacement of the overburden layer decreases in general, however it increases locally near the resonance point. Furthermore, with the increase of the slope angle, the permanent displacement of the overburden layer increases gradually.
4. Conclusions
(1) Based on the CDEM in continuum mechanics, this study proposes a new method for evaluating the seismic stability of overburden slope. The current state of BOLS is determined according to the principle of “high is not low.”
(2) The overburden layer and the interface between the bedrock and overburden are damaged to a certain extent under the action of a small-intensity earthquake ($\alpha_{\text{peak}} = 0.03–0.06$ g), although the overburden surface is not damaged. The damage of the overburden, interface between bedrock and overburden, and overburden surface all increase with $\alpha_{\text{peak}}$.
(3) The permanent displacement of overburden gradually decreases and increases with the increase of seismic frequency and peak acceleration, respectively. Meanwhile, with the increase of slope height or angle, the permanent displacement of the overburden layer either decreases or increases in general.
(4) Duration has little to no influence on the permanent displacement of overburden under the condition of a small or moderate earthquake. In the case of large earthquakes, the permanent displacement of overburden increases linearly with the increase in duration.

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