Seismic input model of high slope and its test verification

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Abstract. The Seismic input model of high slope is proposed, in which the Lagrangian discontinuous deformation analysis (LDDA) is adopted to simulate faults, cracks and structural surfaces, and the viscoelastic boundary is used as the energy absorbing boundary to reflect the influence of infinite foundation radiation damping. Due to employing the wave analysis method, the propagation and amplification effect of seismic waves in the slope can also be included. In order to verify the rationality of this calculated model, a slope dynamic model test of a large earthquake simulation shaking table was also carried out. From the results of experiment and numerical calculation, it can be seen that the acceleration of seismic response and its amplification effect, the slope base frequency and the opening degree of the simulated faults are comparable. The calculation model presented in this paper provides a good tool for correctly evaluating the seismic stability of the high slope near dam.

1. Introduction

The seismic stability of the high slope near the dam has a significant impact on the safe operation of the reservoir dam. In order to mitigate the damage of this natural disaster to the dam, it is necessary to analyze and study the dynamic response of the high slope. At present, in the slope design of hydropower projects in China, the quasi-static method based on the principle of plane rigid body limit equilibrium is the basic analysis method for slope stability analysis of seismic action, and the seismic stability of slope is evaluated by safety coefficient according to the corresponding specifications [1]. Obviously, it is necessary to use numerical method to analyze the deformation stability of important or high slope with complex engineering geological conditions. Due to the complexity of dynamic amplification mechanism, dynamic response and dynamic instability mechanism of high slope under the action of earthquake, the research in this field is not perfect at present. The key technical problems include: a) the problem of slope ground motion input, and the ideal earthquake input method, which should reflect the seismic wave propagation and amplification effect along the mountain; b) the dynamic stability analysis method of the slope should take into account the radiation damping effect of the infinite foundation and the nonlinear mechanical characteristics of faults, main joints and inter-layer dislocation zones that form the boundary of the sliding block; c) slope seismic stability evaluation index and safety standard, the strength reserve safety factor in the static finite element slope stability analysis can be used as the evaluation index of the dynamic stability, for dynamic stability research, but also should study the "overload safety factor" of the overdesign seismic action. This paper will focus on the slope seismic stability of the above three key problems, put forward the seismic input model of high rocky slope, in which the time domain wave method is used to better reflect the dynamic process of seismic wave transmitted by deep bedrock up, Lagrange discontinuous deformation analysis
deformation analysis (LDDA) [2-4] is adopted to simulate faults, cracks and structural surfaces, and viscoelastic boundary is applied to absorb outward-spaying scattering waves. In order to verify the reliability of this model, the rock high slope dynamic tests have been carried out in the large earthquake simulation shaking table. The analysis of the amplification effect of ground motion along the slope, the time history of seismic response of key points, and the time history of structural plane opening shows that the numerical results of the model presented in this paper are in good agreement with the model test.

2. High slope seismic input model

2.1. High slope seismic input method

The calculation of earthquake action on slope varies according to the analysis method. For the limit equilibrium of rigid body, the action of earthquake is generally applied to the landslide body as a quasi-static load whose magnitude and direction do not change with time. To this end, the seismic action coefficients k_v and k_s are introduced, which are numerically equal to the ratio of horizontal or vertical acceleration to gravitational acceleration. Although the seismic action coefficient has a certain correlation with the peak ground acceleration (PGA), the two are not equal. It is generally considered that the seismic action coefficient is 0.3 to 0.5 times that of PGA [5]. Obviously, the pseudo-static assumption of seismic action in rigid body limit equilibrium analysis is relatively rough. In order to overcome the limitations of the quasi-static hypothesis and obtain the residual displacement of the post-earthquake slope, the Newmark sliding block analysis method [6] is a good choice. The seismic input of the Newmark sliding block analysis method is the acceleration time history. When the earthquake motion exceeds the critical acceleration, the acceleration of the block is integrated twice to obtain the displacement. In the whole time history calculation, the displacement obtained by integration above is the cumulative sum. Model test and calculation and analysis of natural slope [7-9] prove that Newmark sliding block analysis method can predict the seismic permanent displacement of slope quite accurately when the geometric characteristics of slope, soil mechanical characteristics and seismic ground motion are known. Although the Newmark sliding block analysis method uses the ground motion acceleration time history, it has not found an effective scheme for rational selection of seismic ground motion in the seismic stability evaluation of engineering slopes. In addition to the propagation characteristics of ground motion in slope media, the spatial and temporal distribution of ground motion in slope media is also different.

A better method to solve the problem of slope ground motion input is to adopt time-domain wave analysis as shown in Figure 1, which has been successfully applied in seismic analysis of high dams [4,10]. Specifically, the following steps are included: 1) determine the design response spectrum of engineering site through seismic risk assessment and generate the corresponding artificial seismic acceleration time history a(t); 2) at the engineering site, it is assumed that seismic waves are vertically incident from deep bedrock. The theoretical basis of this hypothesis is the wave propagation theory in seismic engineering [11], because the rock layer in the earth's crust is generally harder and harder, so when the seismic wave propagates from bottom to top, its propagation direction is passed through each interface. The angle of intersection with the vertical line is reduced. When it reaches the surface, the seismic wave is nearly perpendicular to the incident. In order to obtain the artificial seismic wave a(t) of step 1) at the site surface, it is only necessary to fold the input ground motion acceleration time a(t)/2 at the bottom of the slope. In order to simulate the propagation of seismic waves outside the artificial boundary, viscoelastic boundary is applied to the model boundary, which requires the boundary conditions of force. The following finite equations are obtained by LDDA[4]:

$$\mu_\delta + C_\delta + K_\delta = F_\delta + F + GA$$  \hspace{1cm} (1)

The $F_\delta$ is the total dynamic load vector generated by the vertical incident seismic wave on the artificial boundary. It is composed of the dynamic load vectors $F_i$ of the boundary node $i$.

Let the free field displacement vector at the boundary node $i$ outside the viscoelastic boundary be
\( \mathbf{u}^f \), the free field velocity vector be \( \hat{\mathbf{u}}^f \), the free field stress tensor be \( \sigma^f \), the spring coefficient constituting the viscoelastic boundary be \( K_i \), and the damping coefficient be \( C_i \), the force vector acting on the spring damper at the boundary node \( i \) is:

\[
F_i = K_i u^f_i + C_i \dot{u}^f_i + \sigma^f_i n_i
\]

where \( A_i \) is the influence area of free field grid nodes, \( n \) is the cosine vector of the normal direction outside the free field boundary. The \( K_i \) and \( C_i \) are 3 by 3 diagonal matrices. The magnitude of the component varies as a longitudinal or shear wave.

For the P-wave:

\[
K_p = A_i \frac{E}{2r_i} \quad C_p = \rho c_p A_i
\]

For the S-wave:

\[
K_s = A_i \frac{G}{2r_i} \quad C_s = \rho c_s A_i
\]

where \( E \) and \( G \) are the modulus of elasticity and the modulus of shear respectively. \( \rho \) is the mass density, \( c_p \) and \( c_s \) is the P wave and S wave velocity respectively, and \( r_i \) is the distance from the scattering source to the artificial boundary.

Figure 1. Seismic input model for slope stability analysis.

2.2 Shaking table seismic wave input principle

Slope seismic simulation shaking table test is an important aspect of slope stability research. Although there are certain limitations, such as difficulty in satisfying the strict similarity of stress, deformation and material properties, there are corresponding advantages, which can simulate the dynamic response of the experimental structure under real seismic record, and the inertial force and boundary conditions of substructure. For large-scale engineering projects, it is often used as a qualitative and macroscopic failure phenomenon analysis, or used for the experimental verification of computational models. The realization of the above-mentioned slope seismic input method in the earthquake simulation shaking table test is shown in Figure 2. Due to the limitation of the vibration table scale, the high slope model test is a scale test, and the prototype slope has a larger geometric scale than the model slope. For the prototype slope, the incident ground motion from deep bedrock can be calculated by the above numerical simulation, and the acceleration response at any depth in the surface and strata can be obtained. The acceleration response at the position corresponding to the bottom edge of the test model is selected in the prototype slope as the seismic excitation of the vibration table. At the same time, the shear damper boundary of polymer viscous liquid developed by China Institute of Water Resources and Hydropower Research is used around the model slope to simulate the influence of radiation.
damping of infinite foundation.

Figure 2. Shaking table seismic wave input principle diagram.

3. Test verification of high slope seismic input model

3.1. Test model design
In order to verify the correctness of the above-mentioned slope seismic input model, a dynamic model test based on the actual engineering slope was carried out on the earthquake simulation shaking table of the China Institute of Water Resources and Hydropower Research. The basic characteristics of the shaking table are shown in Table 1. The test simulates a wedge-shaped block and some surrounding rock masses. The height of the prototype slope is close to 400 m, and the length scale between prototype and model is 200. The time scale between prototype and model is 20. The slope body (including the wedge-shaped block) is made of special weighted rubber. Considering the heterogeneity of the slope material, the slope and the nearby rock mass materials are generalized into three categories, and the corresponding dynamic materials of the model materials are: 78, 117, 169 MPa. The length, width and height of the model are 220cm, 295cm and 191cm respectively. The total volume of the model is 6.45 m³, of which the wedge-shaped block volume is 0.174 m³. The wedge-shaped slider is composed of a bottom sliding surface LS337, a side sliding surface f114, and an upper cracking surface J110. It is known from kinematic analysis that the potential sliding direction of the block is along the line of intersection of the bottom sliding surface and the side sliding surface. The block structure surface parameters are shown in Table 2.

Table 1. Basic characteristics of shaking table.

| Parameter          | Specifications |
|--------------------|----------------|
| Table size         | 5x5m²          |
| Load capacity      | 20t            |
| Frequency range    | 0.1~120Hz      |
| Horizontal acceleration | 1.0g |
| Vertical acceleration | 0.7g |

Table 2. Block structure surface parameters.

| Structural plane | area/cm² | seepage-pressure/N | friction factor | Cohesive/Pa |
|------------------|----------|--------------------|-----------------|-------------|
| LS337            | 0.95159  | 46.63              | 0.38            | 1220        |
| f114             | 0.27988  | 0.57               | 0.50            | 500         |
| J110             | 0.54051  | 0.87               | 0.15            | 0.00        |
3.2. Design seismic acceleration and vibration table input waves

The test adopted the bedrock peak acceleration with a probability of 5% over the 50-year period as the designed seismic acceleration, that is, the designed horizontal peak acceleration was 2.12m/s², and the vertical peak acceleration was 2/3 of the horizontal acceleration, that is, 1.41m/s². According to the response spectrum specified in the “Specifications for seismic design of hydraulic structures”, two horizontal and one vertical artificial wave acceleration time histories are generated, as shown in Figure 3, which corresponds to the absolute seismic response of the ground surface in Figure 2. The input wave of the shaking table model time can be obtained from the time scale and the 2.2-section principle as shown in Figure 4.

![Figure 3. Design seismic acceleration time histories.](image)

![Figure 4. Shaking Vibration table input wave (model time).](image)

3.3. Layout of accelerometer and displacement meter

A total of 56 measurement channels were used in this test, namely, accelerometer and LVD displacement meter. Accelerometer is used to measure the acceleration response of slope and wedge block surface. See figure 5 for the installation position. Due to the large geometrical scale of the experimental model, in order to reduce the influence of the sensor on the model, the sensors installed on the slope surface are of light weight type.

14 LVD contact displacement meters are arranged along the periphery of the wedge-shaped block (see figure 6). Wherein, 4 pieces are arranged on the slope corresponding to the sliding surface J110 to measure the opening degree of the sliding surface; In the slope surface exposed on the bottom sliding surface LS337, six are arranged, mainly measuring the tangential slip and taking into account the measurement normal opening; On the slope surface of the side slip surface f114, the other four were arranged to measure the opening and slipping.

![Figure 5. Accelerometer installation location diagram.](image)

![Figure 6. Displacement meter installation location diagram.](image)
3.4. Numerical calculation of the experimental model
In order to test the rationality of the calculation method and calculation model of Section 2, the LDDA calculation analysis of the experimental model is carried out. The coordinate system is the right hand system, X is the slope direction, Y is the transverse slope direction, and Z is the vertical direction. The meshing of the experimental model is shown in Figure 7. The model has 8838 nodes, 7760 elements and 26514 degrees of freedom. The calculated damping ratio is determined by the test, which is about 10%, and the calculation time step is $1.5 \times 10^{-7}$ s due to the smaller grid scale.

![Figure 7. Finite element mesh of the experimental model.](image)

4. Comparison of calculation and test results
Table 3 shows the comparison between the calculated value of slope fundamental frequency and the measured value. As can be seen from the table, the calculated value of slope fundamental frequency is close to the measured value, and the relative errors between the calculated value and the measured value in the direction of slope, transverse slope and vertical direction are 7.07%, 3.95% and 5.81% respectively.

![Figure 8.](image)

Figure 8 shows the distribution of the maximum acceleration along the slope height and the slope seismic amplification coefficient, and the calculated value is basically close to the measured value. However, there are some differences between the middle and lower elevation calculations and experiments. The main reason is that the topographic and geological conditions are more complicated, and the finite element mesh is evenly difficult. In the finite element dynamic analysis, if the mesh size is too small, the calculation time step is required to be small; if the mesh size is too large, the high frequency components of the seismic wave are filtered. The finite element mesh size generally requires no more than 1/8~1/12 wavelength, the model shear wave velocity is about 140m/s, and the maximum mesh size is about 0.15m, then the seismic wave above 95Hz is filtered. Therefore, if only the experimental results are compared with the numerical calculation of the experimental model, the experimental results are more reasonable for the local amplification of the acceleration. The slope seismic amplification coefficient is defined as the ratio between the maximum seismic acceleration response and the designed seismic peak in the corresponding direction.

![Figure 9.](image)

Figure 9 is a comparison of the calculated values of the three-component acceleration time history and the measured values near the center of the wedge block (Figure 5 measurement channels 22x, 23y, 24z). It can be seen from the figure that the two have good comparability.

![Figure 10.](image)

Figure 10 is a comparison of calculated and measured opening values of measuring points LVD-1~LVD-4. The calculated and measured results show that the opening degree is in good agreement.

| Table 3. Comparison between calculated and measured values of slope fundamental frequency (Hz). |
|---|---|---|---|---|---|---|---|
| Along slope | Transverse slope | Vertical |
| value of calculation | measured value | error (%) | value of calculation | measured value | error (%) | value of calculation | measured value | error (%) |
| 17.47 | 18.80 | 7.07 | 20.81 | 20.02 | 3.95 | 38.05 | 35.96 | 5.81 |
5. Discussion

The main purpose of this paper is to verify the rationality of the computational model by comparing the model test with the numerical calculation. The model test is based on the near dam slope of a hydropower project in the western region. For this specific engineering slope, the design earthquake is located at the top of the slope, not all slopes. Therefore, the following issues need to be further explored:

(1) The influence of the location of the design earthquake on the seismic amplification factor needs to be further studied.

(2) The fundamental frequency of the slope is the experimental model and is the fundamental frequency of the finite range of slopes. The purpose is to compare the difference between the calculated and measured values. For repeated trials, the degree of damage to the slope can be assessed by measuring the change in the fundamental frequency of the slope.

(3) The structural surface parameters of the block are the measured values of the static conditions. Under dynamic conditions, the structural surface parameters may change. This is a problem worthy of further investigation.

6. Conclusions

The seismic input calculation model of rock slope proposed in this paper, in which the viscoelastic boundary is applied on the side to absorb the external wave, and LDDA is used to simulate the fault,
fracture and structural surface, and the wave analysis method is employed to solve the dynamic response of the slope under the action of earthquake.

In order to verify the reliability of the calculation model, a large-scale shaking table model test of rock slope was also carried out.

From the fundamental frequency of the model slope, the seismic acceleration time-history response of the key points, the distribution of the seismic response acceleration peak along the slope height, and the upper cracking surface J110's opening history, it can be seen that the calculation and test results have better comparability, the calculation model can better simulate the propagation of ground motion in the slope medium.

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