Study on Ultimate Seismic Capacity of Concrete Gravity Dam- Superhigh Face Rockfill Dam Compound Structure

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Abstract. Based on a very high for the project of the concrete face rockfill dam, by three-dimensional finite element analysis method, from the seismic permanent deformation, stress, deformation and stability of dam slope angle of joint panel, this paper demonstrates the ultimate seismic capacity of concrete gravity dam - superhigh face rockfill dam compound structure, the research results show that the dam seismic permanent deformation limit aseismic capacity from 0.65 g to 0.72 g, panel stress seismic limit of 0.7 g, joint dislocation limit of 0.8 g, dam slope stability of aseismic capacity limit is 0.43 g. The seismic ability of concrete gravity dam - superhigh face rockfill dam compound structure is strong and can meet the local fortification intensity requirements.

1. Introduction
Concrete face rockfill dam is a dam type widely used in water conservancy projects because it is easy to adapt to terrain, geology and climate conditions, can use local materials, fast construction speed, safe operation and easy maintenance, etc., and has accumulated rich experience in the engineering practice of concrete face rockfill dam. With the development of the dam construction technology towards the direction of ultra-high face rockfill dam, the problems of ultra-high face rockfill dam are large deflection of face slab and difficult maintenance of the face slab [1]. Usually, in the design of high or extra-high face dam, most studies are carried out from the aspects of anti-seepage system, dam body zoning, filling standard, joint water stop, construction steps, etc., and relevant measures are proposed to strengthen anti-seepage and drainage structure, reduce dam deformation, improve face slab stress and control joint displacement [2]. Northwest engineering corporation limited in the design process of Yangqu and Cihaxia face rockfill dam, proposes a new kind of compound structure of concrete gravity dam - face rockfill dam [3], adopted at the dam heel of measures, such as concrete dam not only shorten the length of the concrete face, panel to the lowest level in the reservoir with a comprehensive maintainability, and set in the concrete dam corridor, thus further improving the maintainability at the bottom of the dam body.

The purpose of this paper is to demonstrate the ultimate seismic capacity of concrete gravity dam - superhigh face rockfill dam compound structure, from the seismic permanent deformation, stress, deformation and stability of dam slope angle of joint panel analysis. The site seismic wave with the exceedance probability of 1% in 100 years is used for the calculation, and the seismic acceleration
peak is amplified to analyze the ultimate seismic capacity, which provides a reference for the construction and technical development of extra-high face slab dam.

2. Model construction

2.1. Project overview
The dam crest length is 681.0 m, and the maximum dam height is 257.5 m. The basic intensity of the dam site area is VII, and the fortification intensity is normal. The peak acceleration of the bedrock with a probability of exceedance of 1% in 100 years is 0.337g. The type of concrete gravity dam - superhigh face rockfill dam compound structure is chosen by comparison and selection: dam height 80 m, dam top width 12 m, upstream dam slope 1:0.2, downstream dam slope 1:0.7, and its typical section is shown in Figure 1.

![Figure 1. Seismic wave.](image1)

![Figure 2. Typical dam profile.](image2)

2.2. Analysis model
In this paper, the integral three-dimensional finite element calculation is used. When finite element method is used to analyze the dynamic response characteristics of high rockfill dam in earthquake, it can be divided into two categories according to the different types of constitutive models for dam construction materials. One method adopts the constitutive model based on the equivalent viscoelastic model. The other is the constitutive model based on (viscoelastic) plasticity [4]. At present, the commonly used method is the equivalent linear analysis method based on equivalent viscoelastic model, its basic principle is through a series of linear operation multiple iterations to obtain the approximate solution of the nonlinear dynamic response of soil, clear concepts, easy to use, the method in the determination of parameters and application has accumulated abundant experimental data and rich experience in engineering, study shows that the analysis results can be achieved practical precision, to provide a reference on the macro structure design [5]. The dynamic calculation model in this paper adopts the equivalent viscoelastic analysis method. The model has 10 parameters. The calculation parameters are shown in Table 1. \( \lambda \) is the maximum damping ratio, \( \nu \) is Poisson's ratio, and the rest are test parameters. The calculation model is shown in Figure 3.
Table 1. Calculated parameters.

| Location                  | $\lambda$ | $\nu$  | $k_1$ | $k_2$ | $n_2$ | $c_1$ | $c_2$ | $c_3$ | $c_4$ | $c_5$ |
|---------------------------|-----------|--------|-------|-------|-------|-------|-------|-------|-------|-------|
| Concrete slab             | 5         | 0.167  | 0     | 85900 | 0     | 0     | 0     | 0     | 0     | 0     |
| Concrete gravity dam      | 5         | 0.167  | 0     | 85900 | 0     | 0     | 0     | 0     | 0     | 0     |
| Main pile stone area      | 18        | 0.33   | 23.5  | 2733  | 0.332 | 0.0041| 0.73  | 0     | 0.0391| 0.8   |
| Secondary rockfill area   | 21        | 0.33   | 21.5  | 1910  | 0.33  | 0.0083| 0.86  | 0     | 0.0087| 0.99  |

Figure 3. Finite element model.

3. Seismic capacity of dam

3.1. Earthquake permanent deformation

It is generally believed that when the maximum earthquake subsidence exceeds 0.7% ~ 0.8% of the height of the dam, obvious earthquake damage will occur and serious consequences will result. In this paper, the site seismic wave waveform based on the exceedance probability of 1% in 100 years is calculated, and gradually magnified the peak acceleration of seismic wave to form gradually strengthened seismic waves, and the seismic permanent deformation of the dam under the action of different levels of strong earthquakes is calculated. Taking 0.7% ~ 0.8% of the maximum seismic depression above the dam height as the standard, the ultimate seismic capacity of concrete gravity dam-face rockfill dam is analyzed.

The calculation results show that the maximum seismic subsidence of concrete gravity dam-face rockfill dam increases gradually with the increase of the site wave acceleration peak value. When the seismic wave acceleration peak value is 0.71 g, the maximum seismic subsidence of the dam is 1.99 m, which reaches 0.77% of the dam height. Figure 4 and Figure 5 respectively show the distribution map of permanent deformation contour of typical transverse section and longitudinal section of concrete gravity dam-face rockfill dam after an earthquake with a peak acceleration of 0.71 g. Figure 6 shows the relationship between the maximum seismic subsidence and the peak acceleration of input seismic waves after an earthquake, indicating that the ultimate seismic capacity of concrete gravity dam-face rockfill dam is between 0.65g and 0.72g.

(a) Vertical residual deformation contour.  
(b) Horizontal residual deformation contour.

Figure 4. Calculation results of cross section after earthquake (m)
3.2. Panel stress

According to the data of Zipingpu concrete slab dam during the "5.12" Wenchuan earthquake, the concrete slab mainly showed compression failure. It is difficult to determine the ultimate seismic capacity from the point of view that the slab stress exceeds the limit, because even in the case of low earthquake intensity, there are areas where the tensile stress locally exceeds the limit, but the tensile crack area is relatively high and easy to repair. With the increase of earthquake intensity, the compressive stress of the slab increases, and when the compressive stress exceeds the dynamic strength of the concrete, the concrete slab will be crushed, which is more harmful than the tensile crack failure. Therefore, from the point of view of the panel stress, the ultimate seismic capacity of the panel is analyzed with crushing failure as the standard. Figure 7 and Figure 8 show the maximum slope and axial stresses of the panel under different peak accelerations.

As can be seen from Figure 7, when the peak acceleration reaches 0.70 g, the maximum compressive stress of the panel reaches the limit value of the dynamic compressive strength of C 30 concrete. From the point of view of the slab stress, the ultimate seismic capacity of the dam slab is about 0.70 g. In this case, the compressive stress of the panel is within the allowable range, but the tensile stress of the panel is far beyond the allowable value. The area where the tensile stress exceeds...
the standard is located in the higher position of the slope on both sides of the bank. It is easier to repair the earthquake cracks.

3.3. Joint displacement
Due to the influence of the earthquake permanent deformation, the displacement of the surrounding cracks increases after the earthquake, and increases with the increase of the earthquake intensity. Figure 9 shows the calculated three-way displacement characteristic values of panel periphery joints dislocation, settlement and opening under different peak accelerations after earthquake.

During the construction of Shuibuya face slab dam, a new type of water stop structure with peripheral joints was studied. The relevant research results show that the water stop structure will not be damaged under the condition of 50 mm dislocation, 100 mm subsidence and 50 mm opening. Combined with the calculation results, the seismic capacity of the displacement limit of the dam joint is set as 0.8g.

![Figure 9. Relation diagram of maximum subsidence displacement and peak acceleration.](image)

4. Seismic capacity of dam slope

4.1. Calculation of parameters
The stability of dam slope is analyzed by simplified Bishop method, and the analysis section is the standard design section. The material strength index used is shown in Table 2.

| The material         | Density (g/cm³) | φ₀ (°) | Δφ (°) | c (kPa) |
|----------------------|-----------------|-------|--------|---------|
| Main pile stone      | 2.23            | 52.5  | 7.9    | 0       |
| Minor pile stone     | 2.24            | 51.9  | 8.4    | 0       |
| Concrete             | 2.40            | 60    | 0      | 2000    |

The horizontal seismic acceleration is designed using 0.2844 g, the horizontal seismic acceleration is checked using 0.3364 g, and the vertical seismic acceleration is taken as 2/3 of the horizontal seismic acceleration. In order to calculate the ultimate seismic capacity of the dam slope, the horizontal earthquake accelerations of 0.4 g, 0.5 g, 0.6 g, 0.7 g, 0.8 g and 0.9 g are taken to check the calculation. The search method for the critical slip surface is as follows: first, the global simplex method is used to search for a false number of initial slip surfaces, then the local enumeration method is used to optimize the search near the critical slip surface found by the former, and the one with the minimum safety factor is the final critical slip surface.

4.2. Safety factor
Table 3 shows the stability calculation results under each seismic acceleration. The minimum safety factor allowed by the code is 1.2, and the seismic acceleration is 0.6, which does not meet the requirements of the code. Factor of bedrock earthquake acceleration magnified effect, according to the three dimensional finite element calculation results of acceleration amplification factor, within the scope of the landslide on the acceleration amplification coefficient average, calculated under different...
damage forms suggest the pseudo-static method input level of horizontal seismic acceleration and the bedrock peak ground motion acceleration corresponding relation, as shown in Table 4.

Table 3. Stability calculation results.

| Safety factor | Seismic acceleration (g) | Downstream slope | Upstream slope |
|---------------|--------------------------|------------------|---------------|
|               |                          | Partial failure  | General failure |       |
| 0.2844        | 1.512                    | 1.584            | 1.453          |
| 0.3364        | 1.419                    | 1.489            | 1.355          |
| 0.50          | 1.201                    | 1.251            | 1.119          |
| 0.60          | 1.096                    | 1.146            | 1.012          |
| 0.70          | 1.014                    | 1.060            | 0.923          |
| 0.80          | 0.946                    | 0.989            | 0.848          |
| 0.90          | 0.888                    | 0.929            |               |

Table 4. The correspondence between the input acceleration of quasi-static method and the dynamic peak acceleration of bedrock.

| Seismic acceleration input by pseudo-static method (g) | The dynamic peak acceleration of the corresponding bedrock (g) |
|--------------------------------------------------------|---------------------------------------------------------------|
|                                                        | Partial failure on the downstream slope | General failure on the downstream slope | Upstream slope |
| 0.35                                                   | 0.63                                      | 0.55                                      | 0.50          |
| 0.4                                                    | 0.68                                      | 0.60                                      | 0.55          |
| 0.45                                                   | 0.74                                      | 0.66                                      | 0.60          |
| 0.5                                                    | 0.79                                      | 0.72                                      | 0.66          |
| 0.55                                                   | 0.86                                      | 0.79                                      | 0.72          |
| 0.6                                                    | 0.92                                      | 0.86                                      | 0.78          |

If the safety factor is less than 1.0 as the failure criterion, the dynamic peak acceleration of bedrock corresponding to the ultimate seismic capacity of local failure at the top of downstream dam slope is 0.43 g, and the ultimate seismic capacity of global failure at downstream dam slope is 0.54 g. The ultimate seismic capacity of the upstream slope is 0.46 g without considering the favorable effect of hydraulic stress. Therefore, the limit seismic capacity of dam slope stability is set as 0.43 g.

5. Conclusion

By relying on the project of the concrete gravity dam - face rockfill dam seismic permanent deformation, stress, deformation and stability four aspects the limit of seismic capacity analysis, the dam seismic permanent deformation limit aseismic capacity from 0.65 g to 0.72 g, panel stress seismic limit of 0.7 g, joint dislocation of aseismic capacity limit is 0.8 g, dam slope stability of aseismic capacity limit is 0.43 g, in conclusion, determine the limit of seismic capacity of 0.43 g. The seismic ability of concrete gravity dam - face rockfill dam is strong and can meet the local fortification intensity requirements.

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