Analysis and seismic behavior verification of Zipingpu concrete faced rock-fill dam during Wenchuan Earthquake

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Abstract: Based on the seismic damage of the Zipingpu dam in Wenchuan earthquake, the stochastic finite fault method with dynamic corner frequency is used to reconstruct the ground motion input acceleration time history of the Zipingpu dam in Wenchuan earthquake, and the dam-base-water seismic response analysis model is established. After analyzing the causes of dam deformation and panel joint dislocation after the earthquake, this paper suggested the comprehensive anti-seismic measures to improve the panel stress. These measures have important theoretical and practical significance for preventing the slab damage caused by extreme earthquakes in the concrete faced rock-fill dam (CRFD).

1. Research background
China's water resources are unevenly distributed in the scale of time and space, and 80% of the country's water resources are concentrated in the western areas with high-intensity of earthquake. In the strategy of western region development, a large number of hydropower projects will be constructed. In the construction of these high rock dams, high earth-rock dams account for a considerable proportion, such as the dam of Zipingpu, Pubugou, Daliushu, Gongboxia, Nuozadu, Lianghekou, Shuangjiangkou and Gushui. These high dams bring great benefits to the society, but also have many hidden dangers at the same time. Once they are damaged by the earthquake, they will have unimaginable consequences. Whether these high-dams built in high-intensity areas can resist strong earthquakes, and how safe they are under earthquakes, seismic research on high earth-rock dams has become a hot spot in the dam industry.

As the most commonly used dam type in earth-rock dams, it is difficult for panel rock fill dams to solve the seismic problems of complex concrete faced rockfill dams based on traditional experience concepts and methods. New concepts and methods must be tested by strong earthquakes. Before the 5.12 Wenchuan earthquake, China's concrete panel rock fill dams with more than 100 meters never experienced a strong earthquake that exceeded its designed standards. Therefore, by analyzing the earthquake damage of Zipingpu panel rock fill dam, it can open up new ideas and study new methods of ground motion input and permanent deformation analysis. It has important theoretical and practical significance to prevent the catastrophic failure of high concrete faced rock-fill dams during extreme earthquakes.
2. Overview of Zipingpu concrete faced rock-fill and its damage situation in Wenchuan earthquake in 2008

The Zipingpu Dam is the water retaining building of the Zipingpu Water Conservancy Project. It is located in the upstream of the Minjiang River, 60km northwest of Chengdu, Sichuan Province. The project was completed at the end of 2006. The dam crest elevation is 884.00m, the minimum construction elevation of the panel toe is 728.00m, the maximum dam height is 156.00m, the axial length of the dam crest is 663.77m, the upstream dam slope ratio is 1:1.4, and the downstream dam slope ratio is 1:1.4~1:1.5, set up a three-level dyke. The normal water level is 877.00m, the designed flood level is 871.20m, and the check flood level is 883.10m. The designed basic seismic intensity of the dam site is 7 degrees, and the base rock is set at 7 degrees. In the 50 years of the base period, the horizontal peak acceleration of the bedrock with a 10% surpassing probability is 0.12g; the dynamic peak acceleration with 2% of the overtaking probability in 100 years is 0.26 g. The floor plan and typical section are shown in Figure 1 (a, b).

In the Wenchuan earthquake, the water level of the Zipingpu dam was 828.65m and the water depth was about 100.00m. It is about 17km away from the epicenter of the Wenchuan earthquake and only 8km away from the seismogenic fault. It is located in the X-intensity area. After experiencing the 8.0-level shallow source near-seismic, which is much higher than its design level, the main structure of the dam is complete. However, earthquake damage such as dam damage, panel voiding and staggered towers have also been generated, which provides valuable information for seismic research of concrete faced rock-fill dams.

![Figure 1. Layout and sectional view of Zipingpu CRFD](image)

3. Dam site ground motion input

In the Wenchuan earthquake, the Zipingpu panel rock fill dam in the strong earthquake area failed to obtain the recorded strong earthquake record. The reconstruction of the ground motion input of the Zipingpu dam in the Wenchuan earthquake was the primary prerequisite for the earthquake detection. Zhu Xi [1] and other peripheral stations recorded and the attenuation relationship given by Haiying [2], etc., considering the upper and lower disk effect, the peak acceleration of the bedrock of the Zipingpu dam at the time of the main shock was 0.52g. Considering the surrounding station records and the attenuation relationship given by Yuhaiying [2], and considering the upper and lower disk effects. Zhu Xi et al. derived that the peak acceleration of the Zipingpu dam bedrock level during the main shock was 0.52g. This paper intends to reconstruct the ground motion input of the Zipingpu dam site in the Wenchuan Earthquake by using the random finite fault method with the dynamic corner frequency introduced from the Wenchuan earthquake composite source rupture mechanism.

3.1. Composite source rupture mechanism of Wenchuan earthquake

According to the main shock rupture surface model of the global seismic network far-field seismic waveform collected by the China Earthquake Administration and the USGS and other research
institutions, the focal mechanism solution, fault model and parameters of the Wenchuan earthquake are analyzed. The Wenchuan main rupture surface model given by the California Institute of Technology [3] tectonic movement observation group shown in Figure 2 is representative. The results show that the Wenchuan earthquake seismogenic fault is located in the central main fault zone of Longmenshan, with a rupture surface extending at 229 degrees, a dip angle of 33 degrees, a rupture surface length of 260 km, a width of 28 km, and a rupture velocity of 3 km/s. The source is 103.270 degree east longitude and 31.104 degrees north latitude. There are two main asperities on the rupture surface.

![Figure 2. Major fracture plane model](image_url)

3.2. Solving 3D surface source seismic mechanism using "improved stochastic finite fault method"

Due to the uncertainties such as the location of the earthquake and the nonlinear characteristics of the wave propagation medium and diffusion, it is difficult to use the deterministic model for solving the seismic mechanism of the 3D surface source. Therefore, the "random limited fault method" is often used.

This method is the semi-theoretical semi-empirical deterministic method first proposed by Beresnev and Atkinson [4] for simulating near-field strong ground motion. In the calculation, the source spectrum model with dynamic corner frequency [5] is selected to effectively eliminate the dependence of the simulated ground motion amplitude level on the sub-fault size, and ensure that the far-field radiation energy is not affected by the sub-fault size. The main step [6] is:

- Based on the seismic hazard analysis results commonly used in engineering earthquakes at home and abroad, the main faults in the potential sources that may lead to the most confidence earthquakes are selected as the seismogenic faults. According to the empirically summarized relationship, the magnitude, intensity, inclination, and the length and width of the fault plane are determined by the magnitude of the energy release.
- Divide the fault plane into sub-fractures that can be used as point sources, and assign non-uniform shift weights to each sub-fracture by setting its possible rupture mode and the speed of rupture propagation and the geometric relationship between the sub-source and the site.
- Based on seismology theory, determine the relevant parameters of the respective faults as point sources in the frequency domain. These include seismic spectrum models, geometrical diffusion and seismic wave propagation effects of inelastic and non-uniform scattering associated with quality factors, amplification from deep source to surface, and energy loss effects. Then, after selecting the random phase uniformly distributed in the [0-2π] interval, the effects in the frequency domain are integrated into the ground motion acceleration time history of the sub-fracture in the time domain.
- Considering the rupture mode and time history, the ground motion time history of each sub-fracture of the sub-fracture is integrated into the ground motion parameters of the dam site.
3.3. Verification of the reliability of the 3D surface source synthesis method for adding dynamic corner frequencies

According to the research of Zhang Yong [7] and Zhao Cuiping [8], the rupture process of the Wenchuan earthquake can be divided into four successive sub-rupture events. The time, distance and moment magnitude are shown in Table 1. Using the research methods of Wells and Coppersmith, the whole fault is divided into 65×7 sub-sources of 4km×4km.

Table 1. Parameters of sub fracture plane model in Wenchuan earthquake

| Event | Time (s) | Distance (km) | Moment magnitude (Mw) |
|-------|----------|---------------|-----------------------|
| Event 1 | 0-16 | 0-80 | 7.1 |
| Event 2 | 17-42 | 0-220 | 7.7 |
| Event 3 | 43-68 | 100-320 | 7.6 |
| Event 4 | 68-100 | 220-320 | 7.3 |

3.3.1. Determination of subsurface parameters. Among the parameters required for random synthesis of ground motion, the attenuation effect of ground motion with propagation distance is expressed by a three-line geometric attenuation model [9]. The regional quality factor $Q(f) = Q_n f^n$, which expresses the hysteretic decay effect, is obtained by analyzing the coda wave of the seismic record. There are many researches on quality factors in Sichuan area. Among them, Hua Wei et al. [10] gave two corresponding quality factors $206.7f^{0.836}$ and $274.6f^{0.423}$ for the plains and mountainous areas of Sichuan and Chongqing. In the simulation of this paper, according to the calculation point or the geographical location of the station, the corresponding two of the above quality factors are selected for calculation. The parameter $k_o$ of the filter expressing the high-band spectral attenuation at the local site is taken as 0.04 as recommended by Boore [11]. Due to the small amount of geological exploration data in the epicenter of the Wenchuan main earthquake, the local site amplification function still empirically uses the amplification function of the general bedrock site and general soil site given by Boore and Joyner. The stress drop is a key parameter for controlling the amplitude of the high frequency band of the simulated ground motion, and usually refers to the static stress drop associated with the length of the fracture and the average amount of slip. According to Zhang Yong et al. [12], the average stress on the main seismic fracture surface of Wenchuan Earthquake is reduced to 180 bars, and the maximum stress drop is 530 bars. Therefore, the stress drop in this simulation is 180 bars. According to the related research of Cheng Wanzheng, Yu Xiang et al [13,14], the shear wave velocity $\beta$ in the source region is taken as 3500 m/s.

3.3.2. Selecting a calibration station. The main station records were obtained at 7 stations near the Zipingpu Dam, and the station information for obtaining the measured acceleration records near the dam site [7] is shown in Table 2. Among them, Wenchuan Wolong and other stations were laid on the soil layer and was not built on the bedrock like the Zipingpu dam; The Pixian Zoushishan and Chengdu Zhonghetai stations are located in the lower part of the fault, and the main shock is the peak acceleration of the earthquake and it is only around 0.1g. As a station in the far-field area, its main shock ground vibration contains too many low-frequency components, so it should not be used as a calibration station; The location of the Maoxian station is 26km away from the fault, and the peak acceleration of the ground motion during the main earthquake is 0.3g. It can be considered that the Maoxian County Station is a near-field regional station, and it is in the same upper plate of the seismogenic fault as the Zipingpu dam site. Therefore, the Maoxian station is selected as the calibration station.

Table 2. Information of station near dam site

| Station name | latitude | longitude | Geological type | Peak acceleration along river/g |
|--------------|----------|-----------|----------------|-------------------------------|
| Wenchuan wolong | 31.0N | 103.2E | Soil | 0.96 |
| Mianzhu qingping | 31.5N | 104.0E | Soil | 0.82 |
| Maoxian nanxin | 31.6N | 103.7E | Soil | 0.42 |
According to the above model parameters, the stochastic finite fault method with dynamic corner frequency is used to synthesize the acceleration time history of the Maoxian station, compare the synthetic and measured seismic waves, and verify the parameters of the seismogenic model.

### 3.3.3 Analysis and comparison

Acceleration response spectra of sub-source sizes 1*1, 2*2, 4*4 were synthesized by random finite fault method with static corner frequency and dynamic corner frequency, respectively, and compared with the actual recorded results, such as Figure 3.3 shows.

| Location         | Latitude | Longitude | Type  | Distance |
|------------------|----------|-----------|-------|----------|
| Shenqi bajiao    | 33.3N    | 104.0E    | Soil  | 0.56     |
| Maoxian diban    | 31.7N    | 103.9E    | Rock  | 0.31     |
| Bixian zoushishan| 30.9N    | 103.8E    | Rock  | 0.12     |
| Chengdu zhonghe  | 30.6N    | 104.1E    | Rock  | 0.08     |

It can be seen from Figure 3 that the acceleration response spectrum synthesized by the static corner frequency decreases with the increase of the sub-source size under the short period of 1 s; The amplitude of the long period of more than 1s increases with the increase of the size of the sub-source. When the sub-source size reaches 4 km, the acceleration response spectrum synthesized according to the static corner frequency is still quite different from the actual recorded result. In contrast, the acceleration response spectra of different sub-source sizes synthesized using the dynamic corner frequency are not much different. The acceleration response spectrum synthesized by the static corner frequency is well fitted in the high frequency part, and the amplitude is underestimated in the low frequency part. The dynamic corner frequency is better fitted in both the high frequency and low frequency parts. The source spectrum model based on the dynamic corner frequency avoids the underestimation of the high frequency range of the source source spectrum due to the decrease of the corner frequency with the increase of the rupture area, which can effectively eliminate the dependence of the simulated ground motion amplitude level on the sub-fault size, and ensure that the far-field radiation energy is not affected by the sub-fault size. The validity and reliability of the dynamic corner frequency synthesis method adopted in this paper are also verified.

This paper considers the non-reactive surface source properties of the point source model and solves the seismic mechanism of the three-dimensional surface source. The seismic acceleration time history and the point source method without considering the surface source characteristics are synthesized by considering the method of surface source characteristics. The comparison between the two methods and the measured acceleration record is shown in Figure4.
Figure 4. ground motion synthesizing comparison of actual and this paper used model

It can be seen from Figure 4 that the acceleration time history synthesized by the method is closer to the measured acceleration time history, which reflects the multiple rupture of Wenchuan earthquake and the long duration.

3.4. Earthquake input of the Zipingpu dam site in the Wenchuan earthquake
Using the method of this paper, the ground motion of the Zipingpu dam site in the Wenchuan earthquake was reconstructed using the verified model parameters. The researchers randomly synthesized 20 acceleration time courses with an average PGA of 0.52 g.

4. Earthquake deformation analysis of dam-base-water system
In order to prevent damage to the face rock fill dam during strong earthquakes, it is necessary to establish a realistic seismic response analysis model and ground motion input mechanism, and determine the quantitative determination standard of the overall instability of the dam system to truly reflect the damage process of the dam in the earthquake. [15].

4.1. Dynamic interaction between dam body, foundation and reservoir water
Due to the large amount of sediment in rivers in China, it is unlikely that the resonance phenomenon of compressible reservoir water occurs [16], and the hydrodynamic pressure of the dam surface can be considered as an additional quality.
4.2. Considering the influence of structure on ground motion input, mainly the dissipation of seismic wave energy to the far ground foundation

The artificial transmission boundary of the incident displacement wave is directly input from the boundary of the near-field foundation. The near-field foundation boundary is set to a local artificial boundary satisfying the condition of the one-way outgoing wave \( f(x-ct) \), where \( x \) is the normal direction outside the boundary. The artificial transmission boundary theory is based on ensuring that the propagation properties of the externally scattered wave unidirectional propagated at the artificial wave velocity in the vertical boundary direction at the artificial boundary interface are consistent with those in the original continuous medium. That is, when the wave passes through the artificial boundary interface, there is no reflection effect, but complete transmission occurs. Combining the inner point motion equation of the finite element with the extrapolation method of the artificial boundary node, the finite process model can be used to simulate the wave process in the infinite medium. After the incident wave is subtracted from the total response of the solution, the outer wave is obtained, and the process of the outer wave passing through the artificial boundary from the inside of the finite model is simulated directly on the boundary. Think of the near-field foundation and the dam as a whole, and directly input the artificial transmission boundary at the boundary of the near-field foundation.

4.3. Earthquake input mechanism along the dam foundation space

The existing seismic design of the dam project is approximated to the concentrated parameter in the time domain after obtaining the dynamic impedance matrix of the foundation along the dam foundation. When inputting ground motion to the dam foundation surface, it is obviously lack of theoretical basis to replace the scattered wave field of the dam front valley with a uniform surface design ground motion. According to the assumption of the plane-shaped wave propagating in a uniform elastic medium, the horizontal ground motion of the flat surface superimposes the reflected wave of the free boundary. Therefore, the amplitude of the ground motion input from the depth of the source to the base of the near-field can be taken as 1/2 of its surface.

5. Modeling and seismic deformation analysis of Zipingpu concrete rock fill dam

5.1. Modeling and Calculation

According to the actual situation at the time of the earthquake, the static load such as reservoir water, seepage field, self-weight and initial ground stress is applied, and the viscous damping boundary of the panel joint and the near-field foundation is considered. The static calculation uses the Duncan Zhang E-B model. When calculating, the dam body is layered and the dam body material is loaded by layer and by weight. Simulated construction process, the actual filling is divided into three phases, the dam began to filled on March 1, 2003, and the first phase of the dam was completed to 810.00m elevation on December 28, 2003; On July 31, 2004, the second phase of construction was completed to 850.00m elevation; On April 30, 2005, the third section was filled to 880.00m elevation on the left side; On June 16, 2005, the third section was filled to 880.00m elevation. The water level before the earthquake was 828.65m. The power calculation uses the Shenzhujiang equivalent linear model. The static and dynamic parameters are based on the test results of Zipingpu dam [17]. The main parameters are shown in Table 3 and Table 4. The concrete panel is calculated using a linear elastic model with a density of 2.4t/m³, an elastic modulus of \( E=2.8*10^5 \) Mpa, and a Poisson's ratio of 0.167. The permanent deformation calculation uses the improved Shenzhujiang model [18], considering the influence of residual body strain on the permanent deformation of earth-rock dams. The parameters are the permanent deformation parameters introduced by Zhu Xi [1]. The main parameters are shown in Table 5. The Fortran language is used to program the Shenzhujiang permanent deformation model considering residual strain, and the analysis of permanent deformation of earth-rock dam in Abaqus software is realized.
Table 3. Dam material parameters of Duncan model

| Dam materials       | $γ_d$ | $K$  | $K_b$ | $n$  | $R_f$ | $Δφ$ | $m$  | $φ_0$ |
|---------------------|-------|------|-------|------|-------|------|------|-------|
| Rockfill materials  | 21.6  | 1089 | 95    | 0.33 | 0.79  | 10.6 | 0.21 | 55    |
| Bedding materials   | 23.0  | 1274 | 1276  | 0.44 | 0.84  | 10.7 | 0.03 | 58    |
| Transition materials| 22.5  | 1085 | 1084  | 0.38 | 0.75  | 11.4 | 0.09 | 58    |

Table 4. Dynamic equivalent Viscoelastic model parameters of dam materials

| dam materials       | $k_1$ | $n$  |
|---------------------|-------|------|
| Rock fill materials | 3784.4| 0.416|

Table 5. Permanent degeneration parameters of dam materials

| Dam materials       | $C_1$ | $C_2$ | $C_3$ | $C_4$ |
|---------------------|-------|-------|-------|-------|
| Rock fill materials | 0.49  | 0.59  | 0.80  | 0.35  |

5.2. Analysis of calculation results

Static power finite element analysis and permanent deformation analysis obtained the settlement value of the dam body during the construction period and after the earthquake, the strain field and shear strain field of the dam body after the earthquake, and the stress field of the panel after the earthquake.

5.2.1. Analysis of settlement results during the construction period. During the completion period, the displacement along the river is basically displaced upstream and downstream along the dam axis. The maximum displacements of the upper and lower reaches are 11.5cm and 12.8cm respectively, and the maximum settlement of the dam is 73.0cm. The maximum settlement is located near the 1/2 dam height, and the maximum settlement is 0.45% of the dam height.

The maximum stress of the dam body during the construction period appears at the bottom of the dam. The maximum principal stress and the small principal stress are respectively 2.35 MPa and 1.35 MPa, and the major principal stress contour is basically parallel with the dam slope. The maximum principal stress and the small principal stress are 2.35 MPa and 1.35 MPa respectively, and the major principal stress contour is basically parallel with the dam slope. The comparison between the dam's completion period and the measured sedimentation after the earthquake [13] and numerical calculations are shown in Figure 5. The calculated value is basically consistent with the monitored value, which is consistent with the deformation law of the rock fill dam.

Figure 5. Comparisons between numerical calculation during completion period and measured settlement process
5.2.2 Analysis of post-earthquake settlement results. The results of permanent deformation indicate that the dam shrinks inwardly as a whole, and the settlement increases with the increase of the dam height, which reflects the shearing characteristics of the rock fill body. It reflects that there is no dissipation in the dam after the earthquake, and the overall density increases, which is conducive to the stability of the dam. The measured settlement after the earthquake [19] is compared with the numerical calculation. As shown in Figure 6, the calculated displacement value is larger than the measured value, but it is basically close. The calculated settlement value of the dam crest is 946.3mm, which is basically consistent with the monitoring value of 944.3mm. The measured range has been monitored to the maximum settlement value near the dam axis of the 850m elevation. It can be seen from the calculation results that the position where the maximum contraction occurs coincides with the position of the maximum vertical settlement. This is because the confining pressure and acceleration are relatively large here, and the rock mass is repeatedly sheared and broken under high confining pressure, resulting in a large volume change.

5.2.3 Analysis of downstream slope damage after earthquake. The earthquake caused the rock mass on the downstream slope near the dam crest to be partially loose and accompanied by a downward shift, as shown in Figure 7. It can be seen from the strain field of D0+251 in Figure 8 that the body strain dilatancy appears in the area above 850m above the dam crest. This is because the confining pressure of the dam crest area is smaller and the acceleration is larger. Under the action of low confining pressure, the rock fill material repeatedly shears the dilatation which crosses each other, causing structural damage of the rock fill body. During the vibration, the rock fill material of the dam body will roll down along the dam slope.

5.2.4 Panel extrusion damage analysis. The earthquake caused different degrees of damage to the panel. The vertical joints of the 5#-6# panel at the left end of the dam and the 23#-24# panel in the middle of the dam were severely damaged, and the panel suffered severe crushing and rupture damage (Figure 9). After the damaged concrete was cut out, the panel was found to be staggered. The middle part of the panel was stretched and bent by “Z” shape. The concrete of the third stage was pulled down by the concrete under the force rib, and the concrete on the contact surface was broken. From the panel stress field analysis in Figure 10, the maximum stress along the axial direction of the dam is located at the top of the dam near the center of the dam, between the 23# and 24# panels. Under the action of earthquake,
the deformation of the rock fill body from upstream to downstream and from the two banks to the riverbed, the frictional force acting on the dam axial direction of the dam, result in excessive axial stress of the CRFD, where the vertical joint is prone to crush. This is basically consistent with the actual earthquake damage phenomenon.

5.2.5. Analysis of the staggered panel after the earthquake.

The 845m elevation Phase II and Phase III concrete slab construction joints are displaced in the upstream direction (shown in Figure 11). The maximum misalignment value is 170mm, involving 26 panels, and there is a void between some concrete panels and the cushion. It can be seen from the strain field near the fault platform (shown in Figure 8) that the dam slope has dilatancy, and the shear strain here is the largest (shown in Figure 12). It can be seen that the main cause of the misalignment is that the shear strain is too large, which is consistent with Kong Xianjing’s opinion. [20]. From the analysis of the shear strain calculation principle, we can see that the shear strain value is proportional to the water level height, and the higher the water level, the higher the position of the fault. It can be seen from the panel stress field that the second and third stage construction joints are subjected to large slope-direction dynamic tensile stress, which causes a certain degree of damage to the panel. From the dam horizontal displacement distribution map, it is seen that the relative slip occurs between the third panel and the surrounding cushion material after the earthquake, and the maximum slip occurs at the top of the dam, and the slip amount reaches 12.8 cm. This is due to the large plastic deformation caused by the overall settlement of the dam under strong earthquakes. The deformation produces downward friction on the panel. In addition, the second and third panel construction joints are weak and the panel joints are horizontal construction joints, which causes the panels to be staggered here. In order to study the influence of the construction joint direction on the staggered platform, the direction of the second and third panel construction joints was changed to be perpendicular to the panel, and the finite element calculation shows that the amount of misalignment at the construction joints of the second and third panels after the earthquake is small. In order to effectively reduce the staggered phenomenon of the panel during strong earthquakes, the panel construction joints should take appropriate measures: changing the direction of the panel construction joints, increasing the panel reinforcement at the construction joints, and improving the shear strength of the panel construction joints. These measures can effectively alleviate the misalignment of the panels.
6. Conclusion

This paper reconstructs the ground motion input of the Zipingpu dam in the Wenchuan earthquake, and establishes a model considering the interaction between the dam-base-water model. Through the finite element calculation, the residual vertical strain, body strain, shear strain and residual strain of the downstream slope of the panel and dam are obtained, which explains some seismic damage of the dam, and proposes comprehensive seismic countermeasures to improve the panel stress. The main conclusions:

- The reconstructed input ground motion more accurately describes the acceleration time history of the main shock, reproduces the process of the dam encountering strong earthquakes, and explains the phenomenon of dam body subsidence and panel misalignment after the earthquake.
- The maximum seismic subsidence of the dam occurs near the height of the 2/3 dam. The area where the dam is dilating is above 1/3 of the dam crest. The seismic measures in this area should be strengthened.
- The main reason for the horizontal construction of the panel is that the residual shear strain of the rock fill material is too large. The direction of the construction joint should be changed or the panel reinforcement at the construction joint should be increased.

With the current development of advanced technology, China, as a big dam construction country, urgently needs to deepen the key issues of high-dam seismic safety on the basis of high-tech achievements, and put forward a more practical, effective and feasible new method of seismic research, leading the world trend of high dam technology.

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References

[1] Zhu Cheng,Yang Ge,Zhou Jianping(2010)Back Analysis on Static and Dynamic Characteristics of Zipingpu CFRD Under “5.12”Wenchuan Earthquake.JOURNAL OF SICHUAN UNIVERSITY,42(5):113-119.
[2] YU Haiying,WANG Dong,YANG Yongqiang.(2009)The preliminary analysis of strong ground motion records from the M 8.0 Wenchuan Earthquake.JOURNAL OF EARTHQUAKE AND ENGINEERING VIBRATION,29(1):1-13.
[3] Sladen A.(2008).Preliminary Result:05/12/2008(Mw7.9),East Sichuan[DB/OL].
[4] Beresnev I A,Atkinson G M.(1998)Stochastis finite-fault modeling of ground motions from the 1994 Northridge,California,earthquake I. Validation on rock sites[J].Bullrtion of the Seismological Society of America,88(6):1392-1401.
[5] Motazedian D,Athinson G M. (2005)Stochastis finite-fault modeling based on a dynamic corner frequency[J]. Bullrtion of the Seismological Society of America,95(3):995-1010.
[6] CHEN Houqun,LI Deyu,GUO Shengshan.(2015)Analysis and verification of seismic behavior of Shapai RCC Arch Dam During 2008 Wenchuan Earthquake.46(6):1-9.
[7] ZHANG Yong, XU Li-Sheng, CHEN Yun-Tai. (2009) Spatio-temporal variation of the Source mechanism of the 2008 great Wenchuan earthquake. 52(2):379–389.
[8] Cuiping Zhao, Zangli Chen, Lianqing Zhou. (2009) Study on Source Rupture Process of Wenchuan Mw 8.0 Earthquake: Segmentation feature, Chinese Science Bulletin, 54 (22): 3475-3483.
[9] CHEN Houqun. (2006) Discussion on seismic input mechanism at dam site. 37(12): 1417-1423.
[10] Athison G M, Boore D M. (1995) Ground-motion relations for eastern north America[J]. Bulletin of Seismological Society of America, 85(1): 17-30.
[11] Hua W, Chen Z L, Zheng S H. (2009) A study on segmentation characteristics of aftershock source parameters of Wenchuan M8.0 earthquake in 2008. CHEMICAL JOURNAL OF GEOPHYSICS, 52(2):365-371.
[12] Yong zhang, Wanpeng Feng, Lisheng Xu. (2008) Rupture process of the 2008 Wenchuan earthquake, SCIENCE CHINA Earth Sciences, PP. 38 (10) :1186-1194.
[13] CHENG Wan-zheng, CHEN Xue-zhong, QIAO (2006) Hui-zhen. Research on the radiated energy and apparent strain of the earthquakes in Sichuan province. PROGRESS IN GEOPHYSICS, 21(3): 692-699.
[14] Ruan xiang, 2007, Research of focal parameter of medium and small earthquakes in Yunnan and Sichuan (Thesis for Master's Degree), China Earthquake Administration Lanzhou Institute of Seismology, Lanzhou.
[15] CHEN Hou-qun, XU Ze-ping, LEE Min. (2008) Wenchuan Earthquake and seismic safety of large dams. SHULI XUEBAO, 39(10): 1158-1167.
[16] Liu Xiaosheng, Wang Zhongning, Wang Xiaogang. (2005) Model test and dynamic analysis of large vibration table for panel dam. China WaterPower Press, Beijing.
[17] Chen Shenghui, Shen Zhiqian. (1990) Study on earthquake-induced permanent deformation of CFRD, HYDRO-SCIENCE AND ENGINEERING, 1990(3):277-286.
[18] SONG Yan-gang, DENG Liang-sheng, CAI De-wen. (2006) Monitoring for Concrete Faced Rockfill Dam Settlement during Construction of Zipingpu Project, 25 (1): 21-27.
[19] Chengdu engineering corporation limited of HydroChina, 2008, Brief monitoring reports of Zipingpu concrete faced rock-fill dam in Sichuan province during 5.12 Wenchuan M8.0 earthquake, Chengdu engineering corporation limited of HydroChina, Chengdu.
[20] KONG Xian-jing, LIU Fu-hai, LIU Jun. (2012) Shaking table model tests on face-slab dislocation of concrete faced rock-fill dams under earthquakes. Chinese Journal of Geotechnical Engineering, 34(2): 258-266.