Assessment of the Post-earthquake Safety and the Maximum Anti-Seismic Capability of Zipingpu Concrete Face Rockfill Dam

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Content of Presentation

- Review of the earthquake damages of Zipingpu CFRD in Wenchuan Earthquake
- Seismic analysis and safety evaluation of the dam subjected to Design Earthquake and Check Earthquake
- Study on the effects of Pre-earthquake on the aseismic capacity for the dam
- Study on the Maximum Anti-Seismic Capability of Zipingpu CFRD
Review of the earthquake damages of Zipingpu CFRD in Wenchuan Earthquake

- Location: Sichuan, China
- Height: 156m

Zipingpu dam is CFRD with height of 156m located in Sichuan China. The Zipingpu CFRD became more famous because of Wenchuan Earthquake.
It's only 17 km from zipingpu dam to the epicentre. The dam suffered more stronger earthquake far than the original designed level. The dam was safe on the whole while the earthquake damages were obvious.
Earthquake-induced permanent deformation

- The deformation of dam after the earthquake
- The differential settlement between dam and right abutment (spillway)
Earthquake-induced permanent deformation

- The distribution of settlement of dam top after the earthquake
- Recorded maximum settlement was 81cm
- The distribution of internal settlement of 0+251.0 dam section along elevation after the earthquake
Damages of the concrete face: separation between the concrete face and cushion layer, the crushed damage of the vertical joints and the dislocation of the construction joints of the concrete face.

- The crushed damage of the vertical joint between concrete face No.23 and No.24.
- The separation and dislocation of the construction joints of the concrete face between 2nd stage and 3rd stage.
the earthquake damages of downstream dam slope
Damages of wave protection wall and dam top pavement

The cracks between curb and top pavement

The crushed damage of the wave protection wall
the changes of seepage amount

10. 38 L/s to 18.82 L/s
Seismic analysis and safety evaluation of the dam subjected to Design Earthquake and Check Earthquake

- After Wenchuan earthquake, in order to rehabilitate Zipingpu CFRD, the dynamic analysis and seismic safety evaluation of the dam was performed in accordance with related national laws and regulations, in order to meet the requirements of "repairable under design earthquake and no dam break under check earthquake" and to provide reference for post-earthquake rehabilitation.
Earthquake Parameter

- According to the latest seismic hazard analysis after Wenchuan Earthquake, the peak ground accelerations of the dam site are as follows:
  - Exceeding probability of 10% in 50 years is 185gal
  - 2% in 100 years is 392gal, which is taken as design earthquake
  - 1% in 100 years is 485gal, which is taken as check earthquake.
3-D Authentic Nonlinear Dynamic Analysis and seismic Safety Evaluation Method of High CFRD

- Based on the proposed 3-D authentic nonlinear dynamic constitutive model of soil, a 3-D authentic nonlinear effective analysis method for seismic response calculation of CFRD is developed.
3-D Authentic Nonlinear Dynamic Analysis and seismic Safety Evaluation Method of High CFRD

◆ The interface between concrete face and rockfill is simulated by 3-D anisotropic thin interface elements.

◆ Using seismic safety factor of the elements to evaluate the seismic safety of the elements and partial area. The seismic safety factor can be obtained by the ratio of the maximum resist shear stress to the whole shear stress for each soil element.
In order to evaluate the dynamic stability of dam slope on the basis of FEM seismic response results, the dynamic time history line method and dynamic equivalent method are developed.

\[ F_s = \sum \sigma'_{ni} \tan \phi' l_i + \sum \frac{c' l_i}{\sum \tau_{nt} l_i} \]
Seismic analysis and safety evaluation

- The geometry and FEM mesh of the dam is shown in followed fig. It is composed of 31879 nodes and 28414 elements.
- In the case of normal reservoir water level (877m).
Acceleration response

- In the case of design earthquake, the maximum response acceleration which occurs in the dam crest in the up-downstream direction is biggest. The maximum response accelerations are 10.43m/s², 9.96m/s² and 6.85m/s² respectively in the up-downstream direction, axial direction and vertical direction.

Contour of the maximum response acceleration in the up-downstream direction
Acceleration response

- The amplification factors are about 2.66 times, 2.54 times and 2.62 times respectively in three directions. Thus, the reinforced measures for the dangerous zones where the biggest response acceleration was above 1g should be considered seriously.

Contour of the maximum response acceleration in the up-downstream direction
Dynamic shear stress and seismic safety of elements

- The maximum of dynamic shear stress in the dam can be up to 588.4 kPa. It can be seen that the anti-seismic safety factor of few elements which located at the downstream near dam crest could be below 1.0.
The maximum slab stress in the direction of along the dam slope occurs at the upper of slab face. The maximum of dynamic press stress are 5.44MPa and 5.82MPa respectively in the direction of along dam slope and axial. The maximum of dynamic tension stress are 5.16MPa and 5.41MPa respectively in the above two directions.
Slab stress

- Considering the coupled effects of static stress and dynamic stress in the concrete slab elements, the maximum press stress are up to 17.27MPa and 19.88MPa respectively in the two directions, the maximum tension press are up to 2.65MPa and 2.75MPa respectively in the two directions.
Dynamic displacement of Joints

- The maximum dynamic displacement of Peripheral Joints in the design earthquake are 13.1mm (tension), 14.2mm (settle) and 11.3mm (shear dislocation) respectively.

- The maximum dynamic displacement of vertical joints in the design earthquake are 7.5mm (tension), 6.7mm (settle) and 8.5mm (shear dislocation) respectively.
Liquefaction potential of foundation overburden layers

- The maximum ratio of pore-pressure in the overburden layers is up to 0.51 as ignoring the effect of dissipation of pore-pressure. The maximum ratio of pore-pressure in the overburden layers is 0.12 as considering the effect of dissipation of pore-pressure. Thus, there's no liquefaction occurred in the overburden layer as the dam subjected to the design earthquake.
Earthquake-induced permanent deformation

- The maximum deformation in the up-downstream direction are 30.3cm (downstream) and 13.5cm (upstream), in the axial direction is 22.3cm (left bank) and 13.1cm (right bank) and in the vertical direction is 74.2cm respectively. The ratio of settle displacement to the height of dam is up to 0.48%.
Dynamic stability analysis of the dam slope

- From the stability analysis results for the dam slope obtained by the dynamic time history method and dynamic equivalent method, we can see that the minimum safety factor are 1.05 and 1.17 respectively. Both the minimum safety factors are above 1.0. Thus, the dynamic stability of dam slope under the design earthquake can meet the essential requirements.

![Time history of the minimum safety factor of downstream dam slope](image1)

![Sketch of the most dangerous potential sliding surface in dam](image2)
Seismic analysis and safety evaluation of the dam subjected to **Check Earthquake**

- According to the results of dynamic analysis, the seismic response phenomena for the check earthquake are similar to design earthquake, while the magnitudes are different.
- The dam can meet the requirements of “no dam break under check earthquake”.
Seismic analysis and safety evaluation of the dam subjected to Design Earthquake and Check Earthquake

- From the dynamic response of the dam, the seismic stability of the dam can meet the new aseismic design requirements.
- The amplification effect at the dam crest and nearby area is apparent. It is noted that shear failure and the shallow surface sliding would occur at downstream dam slope near the crest, especially under the check earthquake, thus the necessary reinforcement measures should be adopted for the above potential dangerous areas.

Contour of anti-seismic safety factor of element
Seismic analysis and safety evaluation of the dam subjected to Design Earthquake

- The dynamic stress of concrete face slab is relatively large. Coupling with the static stress, the biggest press stress of slab occurs in the middle of valley, in addition, there is greater tensile stress around the peripheral slab and larger displacement in the peripheral joints. Therefore, consideration should be given in the corresponding position to take reasonable measures to prevent extrusion damage and damage due to the cracks caused by the earthquake.
Study on the Effects of Pre-earthquake on the Aseismic Capacity for the Dam

- Being different from the safety evaluation of general earth dam, effect of pre-earthquake should be considered in the post-earthquake dynamic analysis and safety evaluation of the Zipingpu CFRD, for it had been subjected to the “5.12” WenChuan earthquake. In order to study the effect, the dynamic tests and numerical analysis had been performed.

- The large-scale tri-axial dynamic tests had been performed to studied the above effect on residual strain properties for the main rockfill materials in Zipingpu CFRD.
The large-scale tri-axial dynamic tests

100T large scale cyclic triaxial testing machine

Specimen size: $\phi 30cm \times h \ 75cm$
Maximum axial loading capacity: 1000kN
Maximum confining pressure: 3.0Mpa
Frequency range: 0.01-10Hz

Laser measuring system for recording micro strain of rockfill
Study on the Effects of Pre-earthquake

- The below Fig. gives the relationships of residual strain and vibration times under different shear stress ratio and different vibration tests for the rockfill materials used in the Zipingpu dam.
Study on the Effects of Pre-earthquake

- *vibration test 1*: first vibration test which means normal vibration test
- **vibration test 2**: second vibration test which means the following vibration test after first vibration test for the same soil sample.
Study on the Effects of Pre-earthquake

- Based on the above studies and laboratory results, the effects of pre-earthquake on the dynamic response of post-earthquake are demonstrated by the results obtained by the three dimensional authentic nonlinear dynamic analysis method.
- Under the design earthquake, the maximum seismic permanent deformations in three directions in two cases are listed in Table 1.

<table>
<thead>
<tr>
<th>Case</th>
<th>permanent horizontal deformation/cm</th>
<th>permanent deformation in transverse direction/cm</th>
<th>Vertical permanent deformation/cm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Downstream</td>
<td>Upstream</td>
<td>Left bank</td>
</tr>
<tr>
<td>1*</td>
<td>30.3</td>
<td>13.5</td>
<td>22.3</td>
</tr>
<tr>
<td>2**</td>
<td>5.8</td>
<td>2.7</td>
<td>4.6</td>
</tr>
</tbody>
</table>

*Case1: ignoring the effect of pre-earthquake; **Case2: considering the effect of pre-earthquake
Study on the Effects of Pre-earthquake

From the above comparisons, the earthquake-induced permanent deformation reduced obviously if the effects of pre-earthquake were considered. And on the single viewpoint of deformation, the anti-seismic capacity of the dam would be improved based on the assumption that the effect of pre-earthquake on the each element is consistent.

Table 1  Earthquake-induced permanent deformation for two cases

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*Case 1: ignoring the effect of pre-earthquake; **Case 2: considering the effect of pre-earthquake
Study on the Effects of Pre-earthquake

- It is noted that the residual deformation of CFRD will decrease greatly as the dam subjected to another strong earthquake. However, the post-earthquake dynamic analysis is built on the follow assumption, that is, the effect of pre-earthquake on the each element is consistent.

- This assumption is still different from the real state, the further investigation on the non-consistent effect on the rockfill materials should be studied in accordance with laboratory tests, theory and method of dynamic analysis, dynamic model test and collection and analysis of earthquake damage data.
Study on the Maximum Anti-Seismic Capability of Zipingpu CFRD

An analysis method is proposed to evaluate the maximum anti-seismic capability of high rockfill dam. The method is based on the 3D authentic nonlinear effective stress dynamic analysis. The focus is on the decisive factors of the seismic safety of rockfill dam, i.e. stability, deformation and safety of the impervious system (slab system).
The Maximum Anti-Seismic Capability

- In order to study the maximum anti-seismic capability of Zipingpu CFRD, based on the dynamic analysis of the dam under the design and check earthquake, some more peak accelerations including 0.55g, 0.60g, 0.65g and 0.7g are taken as the input motion of bedrock.

- A comprehensive analysis on the calculations of the dam slope dynamic stability, the earthquake-induced permanent deformation, the liquefaction potential, the element aseismic safety as well as the sand seismic safety of impervious slab under these input motions is carried out.
The Maximum Anti-Seismic Capability

◆ From the viewpoint of dynamic stability of dam slope, the maximum anti-seismic capability of the dam can be considered as 0.55g-0.6g.

◆ From the viewpoint of earthquake-induced deformation, the maximum anti-seismic capability of the dam can be considered as 0.60g-0.65g.
The Maximum Anti-Seismic Capability

- From the viewpoint of **Seismic safety of impervious body (slab system)**, including the stress and deformation of concrete slab, the possibility of cavity between slab and cushion materials and displacement of joint, the maximum anti-seismic capability of the dam can be considered as
  
  0.55g-0.60g

- From the viewpoint of **seismic safety of elements and liquefaction potential of foundation**, the maximum anti-seismic capability of the dam can be considered as
  
  0.55g-0.60g
The Maximum Anti-Seismic Capability

- Based on the above analysis, the maximum anti-seismic capability of the dam can be taken as 0.55g-0.60g in accordance with the results of stability, deformation and safety of imperious body, etc.

- In view of the complexity of the problem, the further discussion and research on this topic should be conducted in conjunction with earthquake damage data analysis and dynamic model tests in the future.
The situation of Zipingpu CFRD after rehabilitation

The rehabilitation of concrete face slab
The situation of Zipingpu CFRD after rehabilitation

The rehabilitation of downstream dam slope
Thank You!
谢谢！

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