Seismic damage analysis and reinforcement measure research for earth dams after a strong earthquake

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Abstract. At present, there are more than 98,000 reservoirs and dams in China. Most of these projects are earth dams. As unexpected disasters and events occur frequently, emergency response problems facing reservoirs and dams are increasingly prominent. Especially during a strong earthquake, the dangerous problems of these dams will be more serious, which is a serious threat to people’s lives and property downstream. Therefore, the seismic damages and the measures of reinforcement need to be studied. Basic data of 379 reservoirs at high-risk or at dam-break risk, as well as the damage situations of medium and small earth dams damaged in the Wenchuan earthquake, are collected and presented in this paper. Several main failure modes of earth dams during the earthquake are analyzed and summarized. For practical engineering, some reinforcement measures for the typical failure mode of an earth dam are also proposed. The Wenjiajiao earth dam, a typical medium reservoir in the high-risk category, located in Cangxi County, Sichuan Province, is selected as the analysis example. The dam safety and seismic stability are calculated and analyzed by the finite element software program ANSYS. The results indicate that the biggest permanent deformation caused by the earthquake occurred in the dam crest; the maximum deformation is mainly a downward subsidence of 21.8 cm. As the thickness of the dam top part decreases, the dynamic displacement and vibration velocity of the dam crest increases. This calculation is consistent with the actual situation where the parapet wall of a dam crest was seriously incline and the upper slope collapsed and cracked. The research results can provide a reference for the danger control and reinforcement of similar earthquake damaged reservoirs.

1. Introduction
At present, there are more than 98,000 reservoirs and dams in China, ranking No. 1 in the world [1]. Most of these projects are earth dams, and they have played an important role in flood control, farmland irrigation, water supply, power generation, etc. As unexpected disasters and events occur frequently, emergency response problems facing reservoirs and dams are increasingly prominent [2]. Especially during a strong earthquake, the dangerous problems of these dams will be more serious.
Some dams will be at the high-risk or at the dam-break risk, which is a serious threat to people's lives and property downstream. Therefore, measures of reinforcement need to be studied.

At 14:28, May 12, 2008 (Beijing time), a magnitude 8.0 earthquake occurred in Wenchuan County, Sichuan Province. The maximum intensity reached 11 degrees in the epicenter, resulting in large disasters in the quake-stricken area, especially in the scope of the epicenter [3-4]. The earthquake had large influence on water conservancy projects. Focusing on the 379 high-risk reservoir dams, this paper collected and analyzed the data of dangerous reservoirs after the Wenchuan earthquake. Then, main failure modes of earth dams damaged in the earthquake were analyzed and carefully summarized according to the typical failure modes. Some reinforcement measures and suggestions for earth dams after earthquake were presented. In addition, the Wenjiajiao clay core rockfill dam, a typical medium reservoir in a high-risk category, located in Cangxi County, Sichuan Province, is selected as the analysis example. The dam safety and seismic stability are calculated and analyzed using the finite element software ANSYS. The results of the calculation were compared with the actual seismic damage situation and the corresponding reinforcement measures were presented. The research results provide a reference for the danger control and reinforcement of similar earthquake damaged reservoirs.

2. Basic situation of damaged reservoirs in the Wenchuan great earthquake

Sichuan Province is a province with a large number of reservoirs in China. In the “5.12” Wenchuan earthquake, the water conservancy projects in Sichuan Province were greatly affected. Many reservoirs in Sichuan had been suffered varying degrees of damage, and some reservoirs were at “high-risk” and “dam-break risk” categories. The earthquake damaged reservoirs distributed in Chengdu, Deyang, Mianyang, Guangyuan, and 17 other cities and 96 counties (city, area). The quake affected more than 60 cities across the county, as well as more than 1630 villages and towns. The population of approximately 16.865 million people and more than 5 million acre of arable land were affected. By the end of 2008, the number of earthquake-damaged reservoirs around the province was 1996, which amounts to 30% of the provincial reservoir quantity. There were 69 at dam-break risk category, 310 reservoirs at high-risk reservoir category, 1617 reservoirs at secondary high-risk and generally dangerous reservoir categories. The degree of damage to the reservoirs is shown in figure 1.

![Figure 1. The damage degree of the damaged reservoirs.](image)

Among the 379 reservoirs at the dam-break risk and at the high-risk, there are three main dam types: earth dam, rockfill dam and core wall or inclined wall dam. The specific number and damaged condition are shown in table 1.

| Dam type                        | Earth dam | Rockfill dam | Core wall/inclined wall dam |
|---------------------------------|-----------|--------------|-----------------------------|
| Total number of damaged (seats) | 358       | 6            | 12                          |
| Earthquake damage type          | crack     | leakage      | landslide                  |
| Numbers (seats)                 | 308       | 80           | 56                          |
| Percentage (%)                  | 87        | 22           | 16                          |
| Earthquake damage type          | crack     | leakage      | landslide                  |
| Numbers (seats)                 | 3         | 5            | 5                           |
| Percentage (%)                  | 33        | 25           | 25                          |

Table 1. Damaged situation of different dam types.
3. Study of the main seismic damages and reinforcement measures of earth dams

3.1. The influence of an earthquake on earth dams

Earth dams are more sensitive to the seismic shock. Seismic shocks produce movements in the horizontal and vertical directions that increase the periodic load even though the duration time of the earthquake is not very long. The periodic load, the dam body and foundation may form the excessive pore water pressure, which can decrease the shear strength and deformation modulus and cause the permanent (plastic) deformation of the dam body and foundation. Eventually, the settlement failure may occur in the dam body and the crack failure in the dam crest. Seismic activity, dam foundation, topographic conditions, dam type and scale are the main factors affect these engineering problems [5]. Crack damage is common on sandy soil dams and cohesive soil dams due to the earthquake actions. Permanent deformation of the dam crest including settlement and horizontal displacement may occur under a strong earthquake. To ensure the safety of the dam, we must control the dam deformation within a certain range.

In this paper, 379 high-risk reservoir dams that were damaged in the Wenchuan earthquake were chosen for examination, and the main seismic damages are “dam crack”, “dam leakage” and “landslide” [6-7].

3.2. Crack: The first main seismic damage

3.2.1. Investigation and analysis of the crack. Through the investigation and analysis, in an earthquake-damaged reservoir, 85% of the risk of damage to the dam is related to the crack. According to the distribution forms, the dam cracks can be divided into longitudinal and transverse cracks. Longitudinal and transverse cracks will harm the integrity of the dam body and reduce the bearing capacity of the dam. Transverse cracks can cut or pull apart the impervious body and cause dam leakage as the cracking depth is large, which endangers the dam safety. Therefore, special attention should be paid to these types of cracks. From the analysis of the dams, when the number and size of the longitudinal cracks are greater than the transverse cracks, the longitudinal cracks are mostly near the crest of the superficial cracks and will not endanger the dam safety. However, landslides often follow when a large longitudinal portion of the dam has many cracks. Some dams have even declined and instability since seismic shock, and these dams are quite dangerous. Figure 2 shows longitudinal creaks on dam crest of Xinyoufang reservoir dam in the Hanwang town of Mianzhu city. The length of this creaks are approximately 90% of the dam axis, and the width of a single crack is about 20cm. This has greatly endangered for the dam safety.

Figure 2. Crest longitudinal creaks of Xinyoufang reservoir in Hanwang Mianzhu.
3.2.2. Crack treatment method. The main crack treatment methods include the excavation and backfill method and the grouting method. The excavation and backfill method is a thorough method for shallow surface cracks and leakage site cracks. For longitudinal cracks caused by uneven settlement, the treatment method of only closing the creak or excavation backfill should be chosen based on the width and depth of the cracks. Because transverse cracks will produce leakage along the dam seam and cause dam perforation, no matter what size, must be thorough handling. When the soil dam has very deep or amount of cracks that cause difficulty in excavating or influence the stability of the dam, the grouting method is a perfect treatment method. The grouting method is also used for internal cracks in the dam. For longitudinal creaks, grouting pressure should be carefully controlled to prevent excessive grouting pressure from producing a dam landslide.

3.3. Leakage: The second main seismic damage

Earth dam leakages are usually divided into three types: dam body leakage, dam foundation leakage and leakage around the dam. In the seismic analysis of this paper, the leakage accounted for 23.7% of the seismic damage. The most serious leakage problems are dam body leakage and leakage around the dam, and the dam foundation leakage is relatively slight. A portion of the reservoirs also showed the soil flow and the piping disaster. A typical leakage condition is shown in figure 3.

3.3.1. Investigation and analysis of the leakage. The main reason that water leakage occurs downstream or new water leakage points appear after an earthquake is cracks (e.g., cracks through the dam, cracks around the drainage facilities, dam abutment and loose foundation rock). If the leakage point is located in the dam body, a drain leakage channel may form in the dam, and the dam soil particles could be removed by the leakage of water. A continuous expansion of leakage channels will cause leakage piping of soil, leading to a dam break. Therefore, the drain leakage in the dam must be monitored.

3.3.2. Leakage treatment method. The treatment principle of dam leakage is “blocking upstream and drainage downstream”. Two specific measures include (a) blocking the leakage entrance and cutting off the leakage pathway on the upstream side and (b) using a leakage guide and drainage measures on the downstream side. These measures ensure that the dam reaches a leakage steady state. The actual projects use the “blocking upstream” measure or “drainage downstream” measure or those measures consider the causes of the leakage and the specific project circumstances.

The main treatment methods of dam body leakage include the inclined wall method, grouting method, anti- leakage wall method, guide leakage ditch method, guide leakage and thickening method, and leakage control material method. The main treatment methods of dam foundation leakage include a clay cutoff trench, a concrete anti- leakage wall, curtain grouting, a clay blanket, a dam leakage
guide and pressure leakage platform. The main treatment methods of leakage around the dam include cutoff wall, anti-leakage material wall, clay blanket, lining, curtain grouting, blockage and backfill, leakage diversion and drainage.

3.4. Landslide: The third main seismic damage

3.4.1. Investigation and analysis of the landslide. Dam landslides account for 16.8% of the seismic damages. A landslide is a serious seismic disaster because the water-retaining section becomes smaller after a dam landslide, which may directly influence the safety of the dam. If a landslide occurs on the upstream side of a clay sloping core earth dam, it will damage the dam impervious body, and the upstream slope may decline, which can lead to a dam-break disaster.

The vertical vibration of an earthquake will cause the dam to accelerate upward, increasing the soil’s downward volume force. A dam landslide may occur due to this downslide force. When the dam accelerates downstream, the reservoir water force will change from pressure to suction force, and the water contained in the dam soil will apply an upstream force to the dam. A typical landslide condition is shown in figure 4.

![Figure 4. Landslide of the Fengyu reservoir after earthquake](image)

3.4.2. Landslide treatment method. Control the reservoir level: When evidence of landslide appears upstream of the dam, the reservoir water discharging speed should be controlled to prevent landslides caused by the reservoir level quickly dropping. When evidence of landslide appears downstream, the reservoir level should be lowered appropriately to decrease the infiltration line and reduce the leakage pressure to prevent a dam landslide from developing. (i) Decrease the dam height and add a parapet wall: The main purpose of these efforts would be to increase the dam crest width and reduce the upper load. (ii) Lower the dam slope: When the dam slope is too steep, all or the lower portion of the uplifted sliding soil should be excavated. Alternatively, the dam body sections that have not slid should be increased appropriately to prevent a dam landslide. If the dam slope is lowered, the high quality of toe drainage facilities must be built. (iii) Riprap above water: This method is also used to lower the upstream slope for an earth dam with an instability risk. Reinforced earth can also be used to give the earth dam a steep slope. The methods of weighting the solid dam toe, dredging drainage and ditching guide leakage are also used to treat dam landslides.

4. The finite element seismic calculation of a typical earth dams based on ANSYS

4.1. Project introduction
Wenjiajiao reservoir is located in Wenjiajiao Village, Shimen Town, Cangxi County. It is a medium-sized water conservancy project. It predominantly used for irrigation, flood control and comprehensive utilization. The dam has a clay core, a crest elevation of 588.92 m, and a height of 37.7 m.

Through the site inspection after the 5.12 Wenchuan Earthquake, it is found that the project had been destroyed: the stone revetment of the upstream dam shell was loose and collapsed; the upstream dam shell was cracked near dam crest; the dam leakage around the dam at the right side was serious and reached 8.8 L/s; a large area of parapet wall was cracked and damaged; the wall of spillway collapsed and water came from the right side of the spillway wall with a leakage quantity of approximately 0.1 L/s; the base slab of stilling pool at the inlet was cracked; the wall of the water shaft was cracked vertically.

4.2. The seismic analysis method

The seismic stability evaluation of an earth dam is a complex geotechnical earthquake engineering problem. Many scholars have made great efforts to research this issue [8-10]. Presently, calculation methods of the seismic effect mainly include the pseudo-static method and dynamic method.

This paper uses the mode-superposition response spectrum method and the ANSYS FEM dynamic method to calculate the seismic effect on the earth dam. First, this method makes a modal analysis to analyze the dam vibration characteristic. Then the response spectrum, modal expansion and modal merge are analyzed, and a post-processed analysis is performed. Finally, the deformation of dam is obtained. The specific procedures are as following: (i) First, carry out modal analysis, and obtain the first n-stage natural vibration period $T_j$ of the structural, vibration $\{\Phi\}_j$ and modal participation factors $\gamma_j$; (ii) Next, determine the first n $\beta_j$ corresponding to $T_j$ based on the design response spectrum (damping coefficient, $\xi=0.05$).

In practical application, engineers often use the seismic response coefficient $\beta$ spectrum curves corresponding to the average spectra as the basis for calculating the seismic effect. The response spectrum is shown in figure 5 according to the site classification and natural vibration period, $T_j$, of the structure. The maximum of the design response spectrum, $\beta_{max}$, and the characteristic period, $T_j$, of site classification are determined by the specification values.

![Figure 5. Design response spectrum](image)

According to the theory of the response spectrum, with $\{U\}_j = \left\{ \frac{\beta_j}{\omega^2_j} \right\}_j \{\Phi\}_j \gamma_j g$, the maximum response displacement $\{U\}_j$ of the vibration mode action can be obtained.

4.3. The calculation parameters And FEM

According to Seismic Ground Motion Parameter Zonation Map of China (GB18306-2001) and Seismic PGA, Seismic response spectrum characteristic period Zonation Map of Sichuan, Gansu,
some regions of Shanxi published by the China Earthquake Administration in June 2008, the peak acceleration of ground motion in the engineering area is 0.05g, and the seismic intensity is rated as VI. The engineering design intensity is 6, assuming that the seismic wave input in the horizontal direction is along the stream. The representation of the horizontal direction design seismic acceleration is $a_h = 0.05g$. The representation of vertical direction design seismic acceleration is $a_v = \frac{2}{3}a_h = 0.033g$. The representation of the maximum earth-rock dam design response spectrum $\beta_{max} = 1.60$. Based on the building site classification, the dam site classification is I; therefore, the characteristic period is $T_g = 0.20$ s.

The earth dam is simplified to a linear model calculation in the modal analysis while processing the dam seismic performance analysis. ANSYS ignores the material nonlinearity by default, so the dam seismic analysis uses a linear model. The model only requires definitions of the dam material properties, such as its density, elastic modulus and Poisson’s ratio. The concrete calculation parameters are as show in table 2.

| Position          | Compression Modulus $E_s$ (MPa) | Elastic Modulus $E_d$ (MPa) | Poisson’s Ratio $\mu$ | Density (kg/m$^3$) |
|-------------------|---------------------------------|----------------------------|-----------------------|-------------------|
| Dam body          | 8.54                            | 68.32                      | 0.26                  | 2050              |
| Core wall         | 6.69                            | 53.52                      | 0.28                  | 1980              |
| Dam foundation    | 6.78                            | 8000                       | 0.28                  | 2000              |

This paper uses the finite element software ANSYS to establish a 3-D numerical model for calculating the response. One calculation boundary is the dam foundation length, and for the depth of the upstream or downstream sides, the boundaries are twice the dam height. The dam and dam foundation rock are developed with an 8-node isoparametric hexahedron element, 2398 nodes and 2276 elements. The bottom of the model is constrained in three directions; the upstream and downstream are constrained in the normal restraint. The coupling reaction between the dam and reservoir water is based on the additional mass method. The finite element model is shown in figure 6.

The X direction represents the direction along the river, where a positive value represents a downstream displacement and a negative value represents an upstream displacement; the Y direction represents the vertical direction, where a positive value represents an upward displacement and a negative value represents a downward displacement.

4.4. Calculation result and analysis

4.4.1. Results of the modal analysis. The modal analysis of the dam is studied by ANSYS. Every natural frequency and vibration mode is obtained through the modal analysis. Figures of the vibration
mode of the dam are obtained from the calculation. Typical vibration mode figures are shown in figure 7 and figure 8.

The displacement of the dam in the X direction contour map, and the stress and strain contour map are also obtained. The maximum displacement distribution of the dam in the X direction during the earthquake is shown in table 3.

![Figure 7. First vibration mode of the dam.](image1)

![Figure 8. Tenth vibration mode of the dam.](image2)

| Vibration mode | 1st | 2nd | 3rd | 4th | 5th | 6th | 7th | 8th | 9th |
|----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Maximum displacement in X direction /mm | 0.65 | 0.18 | 0.73 | 0.58 | 0.6 | 0.36 | 0.5 | 0.59 | 0.53 |

Table 3. The maximum displacement distribution of every vibration mode in the X direction.

Because the modal analysis by ANSYS ignores the nonlinear aspect of the material and the constitutive model lacks the Duncan-Chang model, which is the conventional model for calculating of earth dam behavior, the response spectrum analysis comes only from the damage of the dam vibration trend analysis. There is only reference significance of the displacement values. The following conclusions come from the calculation results shown in table 3. The maximum displacement of the dam for the 1st, 3rd and 7th vibration modes in the X direction appeared at the dam crest, with a maximum value of 0.73 mm. The maximum displacement of the dam for the 2nd, 6th and 9th vibration modes in the X direction appeared on the upstream dam slope, with a maximum value of 0.53 mm. The maximum displacement of the dam for the 5th and 8th vibration modes in the X direction appeared on the upstream dam slope and drainage arris body in the downstream dam slope, with a maximum value of 0.6 mm. The maximum displacement of the dam for the 4th vibration mode in the X direction appeared on the downstream dam slope, with a maximum value of 0.58 mm. Obviously, the dam crest and the upstream and downstream dam slope are liable to damage. The dam crest is cracked easily, and the parapet wall is badly destroyed by a collapse. The protection provided by the upstream and downstream dam slopes is easily lost due to tension caused by a slope landslide during the earthquake. This situation is almost the same as the field observations of the earthquake damage.
4.4.2. Results of the response spectrum analysis. The response spectrum analysis is conducted after the modal calculation and is depended on the modal calculation for the seismic response spectrum analysis. The seismic effect of every vibration mode is combined by the square root of the sum square method (SRSS). The ultimate displacement of the dam body after earthquake is shown in figure 9 and figure 10.

Figure 9 shows the displacement in the X direction. The maximum displacement occurs in the upstream dam slope, toward the right, with a value of 3.2 cm. Because the upstream dam slope is influenced by the water pressure load, the pressure on the slope surface due to the water in the reservoir changes into suction during an earthquake. The earth-rockfill dam has operated for many years, so there is more moisture in the soil within the dam. The soil forces applied to the upstream side by water within the earth dam cause the upstream dam slope to slide easily. From the on-site inspection, it was found that the upstream stone revetment was incomplete, broken, irregular, and local slope stone was loose. The calculation result is in agreement with this practical situation.

Figure 10 shows the displacement in the Y direction. The maximum displacement occurs at the dam crest, as shown in the blue area, in the downward direction, with a value of 21.8 cm.

The comprehensive analysis shows that the biggest dam displacement occurred at the dam crest, mostly subside downward, with a maximum value of 21.8 cm. Because part of the dam crest is thinner, the dynamic displacement and vibration velocity of the dam crest is large. The serious tilt of the parapet wall on the dam crest and the seismic subsidence and fracture on the dam slope, accord with the actual damage situation of the dam crest.

For the above seismic damage, some suggestions are proposed as follows: a detailed survey of the dam abutment, dam foundation and dam body should be taken; methods such as the excavation and backfill methods should be adopted for reinforcement of the fracture site; determine the leakage site and analyze the causes of leakage; thoroughly evaluate the dam; increase the height of the dam crest, reset the parapet wall, and ensure the dam meet the requirements of the flood control standard. The above measures have been taken to reinforce the project, and the reservoir is running well.

5. Conclusions
Through statistical analysis of 379 reservoirs in Sichuan Province damaged in the Wenchuan earthquake, including all 69 at the dam-break risk and 310 at the high-risk categories, it can be concluded that there are three typical damage modes of earth dams in earthquakes: cracks, leakage and landslides. The crack is the most common form of damage, accounting for approximately 84.8% of the earthquake damaged dams. The longitudinal crack is the worst crack compared to the transverse cracks. The second typical damage mode is leakage, which occurred in approximately 23.7% of the earthquake damaged dams. The severe leakage problems lie in the dam body leakage and the leakage around the dam; the dam foundation leakage is relatively slight. Dam landslides account for 16.8% of
the seismic damages, and two-thirds of the landslides were occurred on the upstream side. Based on
the three typical damage modes, some reinforcement measures and suggestions for earth dams after
the earthquake were also proposed.

ANSYS finite element analysis software was used to perform the calculations for a typical
earthquake damaged dam, the Wenjiajiao clay core rockfill dam. This dam was in the high-risk
category after the Wenchuan earthquake. The natural vibration characteristics as well as the vibration
characteristics of the dam in the earthquake were analyzed. The results indicate that the largest
permanent deformation caused by the earthquake occurred in the dam crest. The maximum
deformation is mainly a downward subsidence of 21.8 cm. As the width of the top of the dam
decreases, the dynamic displacement and vibration velocity of the dam crest increases. This result is
consistent with the actual seismic damage situation, and the corresponding reinforcement measures
were presented. These results provide a reference for the control of dangerous dams and the
reinforcement of the similar earthquake-damaged reservoirs.

Acknowledgments
This work was financially supported by the National Natural Science Foundation of China (Nos.
51609163), and National key R & D projects with grant No. 2016YFC0401908. The authors would
like to express their gratitude to the reviewers for their constructive comments and suggestions.
Additionally, valuable information and data from the field inspection were obtained with the help of
the water conservancy management departments of the local government and reservoir managers in
Sichuan Province, who helped us with this research.

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