Study on influence of dam foundation damage on seismic safety of gravity dam under combined action of main shock and aftershock

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Abstract. The existing seismic design codes for hydraulic structures have not yet required to consider the impact of strong aftershocks on the secondary damage caused by the main shock. However, the actual earthquake damage indicates that the impact of strong aftershocks cannot be ignored. In order to study the seismic safety of concrete gravity dam subjected to strong earthquakes, this paper constructs a constitutive model that reasonably reflects the dynamic damage evolution process of dam concrete based on damage mechanics theory. According to the similarity of concrete and rock material, the concrete damage model is extended to the rock mass material. Based on this, taking the gravity dam as an example, the overall damage mechanics model of the dam body and the dam foundation is established. According to the characteristics of the dam site and the characteristics of ground motion, the artificial seismic wave with time-frequency non-stationary characteristics is synthesized considering the attenuation law of ground motion duration and intensity envelope function. The effects of main shock and strong aftershock on the whole damage of gravity dam are studied. The results show that the strong aftershock after the main shock has different cumulative effects on the overall damage and plastic strain of the gravity dam. The gravity dam will further expand in the damaged area when subjected to strong aftershocks. The cumulative effect of the aftershock on the damage and plastic strain of the foundation is more significant than that of the dam. Therefore, it is necessary to consider the plastic damage of the dam and the dam foundation in the seismic analysis of the dam.

1. Introduction

The western region is home to China’s major hydro-energy resources. In modern China, over 80% of the strong earthquakes occurred in the west [1]. Therefore, China’s construction of high dams and large reservoirs faces unavoidable seismic safety issues. The measured data show that when strong earthquakes occur, a large number of aftershocks are often accompanied. The main shock will cause irreversible damage to the dam, while the strong aftershock will further increase the damage. In China’s existing seismic design codes and earthquake disaster prediction work, the main consideration is still the role of the main shock, ignoring the secondary damage caused by the strong aftershocks after the main shock to the dam structure. Correct understanding of the impact of aftershocks on the nonlinear dynamic damage of gravity dams is of great significance for comprehensive and accurate evaluation of large-scale dam engineering’s ability to withstand earthquakes.
With the understanding of the destruction of strong aftershocks, some scholars have studied the cumulative damage effects of dams under strong aftershocks. Alliard. et al. [2] evaluated the seismic safety of concrete gravity dams under the influence of aftershocks. Zhang J.K. et al. [3] studied the cumulative effect of gravity dam damage under the action of single main shock and main aftershock. Wang C. et al. [4] studied the damage evolution characteristics and energy dissipation mechanism of gravity dam under the main aftershock. Wang G.H. et al [5] the cumulative damage effect of concrete gravity dam under single main shock, single aftershock and main aftershock sequence analysed. At present, the elastic-plastic model is mainly used to study the seismic damage of the dam. The damage mechanics model has not been used to study the overall damage evolution law of the dam body and dam foundation under the combined action of the main and aftershocks. In this paper, the concrete damage model proposed by Lee and Fenves [6] under cyclic loading is used for the dam body. For the dam foundation, the concrete damage model is extended to the rock mass material according to the similarity of concrete and rock materials [7]. Taking a concrete gravity dam in the strong earthquake zone in the west as an example, the overall damage mechanics model of the concrete gravity dam body-dam foundation was established. Considering the attenuation law of ground motion duration and intensity envelope function, the phase difference spectrum obeying the normal distribution is used to replace the random phase spectrum produced by the random function [8], and the main aftershock time-frequency non-stationary artificial seismic wave is synthesized. The gravity dam is subjected to detailed analysis of the cumulative damage of strong aftershocks after the main shock. In particular, the impact of dam foundation dynamic damage on the overall safety of gravity dams is studied.

2. Analysis theory and method

2.1. Plastic damage model of concrete

Constitutive relation of concrete plastic damage model [1]

\[ \sigma = (1-d)D_0^{el} \left( \varepsilon - \varepsilon^{pl} \right) \]  

(1)

Where \( \sigma \) is stress; \( d \) describes damage variable (0 \( \leq \) \( d \) \( \leq \) 1), parameters \( \varepsilon \) and \( \varepsilon^{pl} \) are contingency and plastic strain, parameters \( D_0^{el} \) describes nondestructive elastic stiffness.

The modulus of elasticity after damage is expressed as:

\[ E = (1-d)D_0^{el} \]  

(2)

The model uses the yield function proposed by Lee and Fenves to consider the different strength evolution under tension and compression. The evolution of yield surface is controlled by variable tensile plastic strain and compressive plastic strain. The yield equation is as follows:

\[ F = \frac{1}{1-\alpha} \left( \bar{q} - 3\alpha \bar{p} + \beta (\varepsilon^{pl})_{\max} \right) - \gamma \left( \bar{\sigma}_{\max} - \bar{\sigma} \right) (\varepsilon^{pl})_{\max} = 0 \]  

(3)

\[ \beta = \frac{\sigma_{\max}}{\varepsilon^{pl}_{\max}} (1 - a) - (1 + a) \]  

(4)

Where \( \alpha \) and \( \gamma \) are size-independent material constants (0 \( \leq \) \( \alpha \) \( \leq \) 1, \( \gamma \) default value is 3), \( \bar{p} = -\frac{1}{3} \bar{\sigma} \), parameters \( \bar{q} \) is equivalent stress for effective Mises, \( \bar{\sigma}_{\max} \) is the maximum effective principal stress.

2.2. Energy dissipation equation

The plastic damage model used in this paper can consider both plastic energy dissipation and damage energy dissipation [9]. The equation is expressed as follows:

\[ E^p = \int_0^T \int_V \sigma^e \varepsilon^{pl} dV dt \]  

(5)
\[
E^d = \int_0^\tau \int_0^y \frac{d_T - d}{1 - d} \sigma' e^{cl} dV dt
\]  

(6)

Where \(E^d\) denotes damage dissipation energy, \(E^p\) denotes plastic dissipation energy. \(d_t\) is the damage value at time \(T\). \(\sigma'\) is a nonlinear recovery stress. \(e^{cl}, e^{pl}\) denotes elastic strain and plastic strain.

2.3. Earthquake input parameter method considering strong aftershock

2.3.1 Statistical relationship between magnitude of strong aftershocks and main shocks

Due to the unpredictability of earthquakes, we are still not very clear about the mechanism of earthquake occurrence. We cannot accurately infer the magnitude relationship of the main aftershocks. The literature [10] uses 81 main shocks of \(M_s \geq 5.0\) in the southwest region of China from 1900 to 2008, the seismic sequence data of 203 aftershocks obtained the empirical relationship between the largest strong aftershock \(M_a\) and the main shock \(M_m\) within one month:

\[
M_a = 0.72M_m + 1.05
\]  

(7)

Where, the standard deviation of \(M_a\) and \(M_m\) is 1.05 and 1.24.

2.3.2 Attenuation law of ground motion intensity envelope function

The non-stationary strength of the ground motion process can be obtained by multiplying a stationary Gaussian process \(x(t)\) by a deterministic time-varying intensity envelope function \(f(t)\), and using the ground motion \(a(t)\) and the stationary process \(x(t)\) to have the same spectral property assumptions, the expression of \(a(t)\) as \([11]\):

\[
a(t) = x(t) \cdot f(t)
\]  

(8)

Where the expression of \(f(t)\) is:

\[
f(t) = \begin{cases} 
(t/t_1)^2 & 0 \leq t < t_1 \\
1 & t_1 \leq t < t_2 \\
e^{-c(t-t_2)} & t_2 \leq t < t_d 
\end{cases}
\]  

(9)

Where, \(t_1\) and \(t_2\) represent the first and last moments of the stable stage of the ground motion. \(t_2-t_1\) is the peak stationary period \(t_s\), \(t_d\) is the total holding time. \(t_d-t_2\) is the seismic amplitude attenuation period \(t_e\) (where \(t_e = -\ln k/e\), \(k\) is the ratio of the amplitude to the peak at the end of the vibration, \(k\) is generally taken as 0.2). \(c\) is the intensity attenuation coefficient.

Huo J.R. et al. \([11]\) selected a total of 457 seismic records with three stages of obvious rise, stable and decline, and made statistical analysis on magnitude, epicentre distance and other factors of all recorded envelope parameters. The regression analysis results obtained on the bedrock site as follows:

\[
\begin{align*}
\text{lg}t_1 &= -1.074 + 1.005 \text{lg}(R + 10) \\
\text{lg}t_2 &= -2.268 + 0.3262M + 0.5815 \text{lg}(R + 10) \\
\text{lg}c &= 1.941 - 0.2871M - 0.567 \text{lg}(R + 10)
\end{align*}
\]  

(10)

When constructing the main residual vibration, the intensity envelope curve \(f(t)\) of the main shock and aftershock can be determined according to the corresponding source parameters (magnitude \(M\) and epicentre distance \(R\)) of the main shock and aftershock.

3. Establishment of damage model of gravity dam and structure the main aftershock sequence

3.1. Project Overview

For a concrete gravity dam in the west, the basic seismic intensity of the project site is VIII degrees\([12]\), the PGA of the designed seismic base rock horizontal acceleration with a 100-year overrun probability of 2% is 0.316 g, the corresponding magnitude is 7.3, and the epicentral distance is 25 km. Taking the
4# bank slope section of the project as an example, the dam bottom elevation is 2384.00m, the dam top elevation is 2481.00, and the normal water level elevation is 2467.00m. C15 concrete material is used for the elevation of the dam body above 2434.00m, and C20 concrete material is used for the elevation below 2434.00m (Figure 1). Geological exploration shows that the rock mass 0~10m underground in the bedrock of the dam site belongs to class III rock. Below 10m, it belongs to the class II rock. The shear parameters of the Class II rock: $f_2 = 1.25$, $c = 1.6 \text{MPa}$. The shear parameters of the Class III rock: $f_3 = 1.10$, $c = 1.15 \text{MPa}$. The parameters of the dam concrete and dam foundation materials used in the calculation are shown in Table 1.

![Figure 1. 4# dam section material partition map](image)

| Material                           | $C_{9015}$ | $C_{9020}$ | Class II | Class III |
|------------------------------------|------------|------------|----------|-----------|
| Density (kg/m$^3$)                 | 2400       | 2400       | 2675     | 2625      |
| Dynamic elastic modulus (GPa)      | 34.50      | 37.50      | 14       | 14        |
| Poisson's ratio                    | 0.17       | 0.18       | 0.22     | 0.24      |
| Dynamic tensile strength (MPa)     | 1.20       | 1.61       | 1.04     | 0.77      |
| Fracture density (N/m)             | 90         | 120        |          |           |

3.2. Establish a finite element analysis model
In this paper, the finite element simulation analysis model is established for the 4# bank slope dam section of the above gravity dam project. The dam height is taken twice in the upstream and depth directions of the model foundation and 1.5 times dam height in the downstream direction (Figure 2). The initial geostress field is determined according to the initial stress field evaluation in the engineering rock mass grading standard. The vertical geostress is the rock mass self-weight $\gamma h$, and the horizontal geostress is $1.2 \gamma h$. Concrete and rock mass materials are considered as plastic damage models.

On the ground motion input, the viscoelastic artificial boundary is used to simulate the influence of ground radiation damping$^{[13]}$, while considering the vertical and horizontal seismic waves, the hydrodynamic pressure is applied by the Westergaard additional mass method, using Rayleigh damping, and the damping ratio is calculated as 5%. The required mass damping coefficient and stiffness damping factor. In this paper, the concrete material damage curve is correspondingly reduced corresponding to the tensile strength of the rock mass to determine the damage parameters of the bedrock material$^{[6]}$. 
3.3 Main aftershock sequence construction

Some scholars have carried out statistical analysis on a large number of main aftershock peak accelerations. The peak accelerations of the main and aftershocks accord with a certain attenuation relationship. Hatzigeorgiou et al. [14] derived the peak acceleration attenuation coefficient between the two earthquake sequences of 0.8526. In order to study the influence of the main aftershock on the damage response of gravity dam, parameters 0.8526 is selected as the main shock and aftershock peak acceleration attenuation coefficient. According to the literature [15] takes the main shock aftershock as a homologous earthquake. According to equation (7), the maximum aftershock magnitude is 6.3, and the aftershock PGA is 0.269 g. According to equation (10), the main earthquake ground motion time is 31s, and the aftershock ground motion time is 22s.

In the aspect of artificial ground motion synthesis, this paper replaces the random phase spectrum produced by the random function with a phase difference spectrum obeying the normal distribution. According to the literature [15], the maximum strong aftershock has the same spectral characteristics as the main shock. According to the horizontal acceleration response spectrum curve of the bedrock of the engineering site, the time-frequency non-stationary artificial seismic wave (damping ratio is 5%) is synthesized. Each seismic wave is independent of each other, the interval time is 10s, and then the seismic waves are combined. Due to space limitations, only the horizontal-to-main- aftershock seismic wave time-history curve is shown in this paper (Figure 3). In the figure, $T_1$, $T_2$ and $T_3$ respectively indicate the main shock duration, the main aftershock interval time and the aftershock duration (the same below). The vertical seismic wave peak acceleration takes $2/3$ of the horizontal seismic wave acceleration peak.

4. Study on damage evolution of gravity dam caused by main aftershock

4.1 Damage zone analysis of dam body-dam foundation system

Figure 4 shows the overall damage of the dam-foundation under different earthquake sequences. The results show that the overall damage location of the gravity dam body and dam foundation is roughly
the same under the combined action of the main shock and the main aftershock. The damage of the dam body is mainly concentrated near the abrupt change of downstream slope, the damage of dam foundation mainly occurs at the base rock of the dam heel and extends along the direction of depth. It can be seen from Figure 4(a) that when the main shock acts alone (PGA=0.316g), the abrupt change of downstream slope of the dam body and the dam surface below the elevation are damaged. The concrete damage zone at the abrupt change of downstream slope of the dam body is extended to the upstream by about 5.2 m and downward by about 7.5 m, and the damaged zone of bedrock at the dam heel extends down 37.2 m. It can be seen from Figure 4(b) that when the main aftershock are combined (main shock PGA=0.316g, aftershock PGA=0.269g), the damage zone of the dam body is slightly increased compared with the main shock alone, but the degree of the rock damage at the dam heel increases obviously compared with that when the main shock alone. At the end of the ground motion, the damage zone of the rock at the dam heel is extended downward by about 44.1 m.

4.2 Analysis of the overall energy characteristics of dam body-dam foundation

4.2.1 Overall energy consumption of the dam body-dam foundation

In this paper, two energy consumption indicators, damage energy dissipation (ALLDMD) and plastic energy dissipation (ALLPD), are compared and analyzed. It can be seen from Figure 5 and Figure 6 that after the main shock is completed, the overall damage energy and plastic energy consumption of the dam-dam foundation are 16.76kNm and 41.19kNm, respectively. Under the combined action of main aftershocks, the damage energy dissipation and plastic energy dissipation curves of the dam appear the secondary dissipation process. Finally, the damage energy dissipation and plastic energy dissipation are 21.02kNm and 56.36kNm, respectively. Compared with the main shock alone, under the combined action of main aftershocks, the overall damage energy dissipation and plastic energy dissipation increased by 25.4% and 36.83% respectively. Compared with the energy consumption of the damage, the aftershock effect increases the overall plastic energy consumption more obviously.
4.2.2 Individual energy dissipation of dam body and foundation

The energy dissipation of the dam body caused by the combined action of the main shock and the main aftershock is shown in Figure 7. It is not difficult to find that the main shock alone when compared with the action, the damage energy dissipation and plastic energy dissipation index of the dam body do not increase obviously under the combined action of main aftershocks. This may be due to the fact that the aftershock ground motion constructed in this paper has little effect on the damage of the dam body. The energy dissipation of the dam foundation caused by the combined action of the main shock and the main aftershock is shown in Figure 8. Compared with the main shock alone, the damage energy dissipation and plastic energy dissipation of the dam foundation under the combined action of the main and aftershocks increased by 27.8% and 38.9%, respectively. It can be seen that in the joint action of the main aftershock, the aftershock action will cause more plastic energy dissipation of the dam foundation to grow. Combined with Figure 7 and Figure 8, by comparing the damage energy dissipative and plastic energy dissipation of the dam body and dam foundation, it can be seen that under the combined action of the main shock and the main aftershock, the energy dissipation generated by the gravity dam is mainly concentrated in the dam foundation. Compared with the dam body, the cumulative effect of aftershocks on the damage and plastic strain of the dam foundation is more significant. Compared with the dam foundation damage energy dissipation, the cumulative effect of aftershock on the plastic strain of the dam foundation is more significant.

5. Conclusion

In this paper, the concrete damage model is extended to the rock mass material, and the overall dynamic damage simulation analysis model of the dam body and dam foundation is established. Based on the model damage region and energy dissipation characteristics, the damage response of main shock and main aftershock to the dam foundation and dam body in strong earthquake area is studied. The main conclusions are as follows:
(1) Under the action of earthquake, damage will occur in the rock mass of the dam foundation. The damage zone is mainly located in the rock mass of the dam heel and extends downward in the depth direction. There is no concrete damage in the dam heel and the toe slab of the dam, indicating that the plastic damage of the foundation rock releases the stress concentration at this part and avoids cracking at this part. This is consistent with the results of strong earthquake damage of many actual gravity dams, indicating the necessity of considering damage to the dam foundation during seismic analysis of gravity dams.

(2) Compared with the dam body, the cumulative effect of damage to the dam foundation under the action of the main aftershock is more significant. Among them, the cumulative effect of aftershock on the plastic strain of the dam foundation part is greater than the cumulative effect of the damage, which may lead to serious irreversible deformation of the foundation part. Therefore, the influence of strong aftershocks should be paid attention to in the seismic design of concrete gravity dams.

(3) Strong main aftershock may cause a certain range of damage and damage areas in the dam body and dam foundation, which may lead to the infiltration of reservoir water and reduce the strength of the dam foundation and dam body. Therefore, these factors should also be considered in seismic design.

In addition, it is worth noting that in the research work of this paper, the dam foundation rock mass is considered as a natural rock mass. In fact, after the dam foundation is subjected to the consolidation grouting treatment, the elastic modulus and tensile strength of the dam foundation rock mass will be improved, which should be considered in future research work.

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