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The Dynamic Response Analysis of Concrete Gravity Dam under the Earthquake

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Abstract: Based on the finite element software ABAQUS, the dynamic time history of the concrete gravity dam has been analyzed. Considering the gravity dam's action of dynamic water pressure effect under the earthquake, we made a layer of user unit and given the unit quality through the door subroutine UEL relying on additional quality law, and the unit has been attached to the dam. By the statistics and analysis about displacement, stress, damage and energy of the feature points of the dam, we can conclude that: the dam stress and displacement of the most unfavorable moment most concentrated in a fairly recent time area, corresponding the larger seismic acceleration; damage first occurred in dam heel F point, then in dam neck near downstream variable cross section D point also started to happen damage; with the continuing earthquake, damage gradually becomes transverse development , and then extended to the internal; the dam mainly depend on material damping to consume energy, inelastic dissipation and damage dissipation can only consume a small part of energy; the most unfavorable position of stress, displacement, damage and energy of the dam appeared in the dam heel F point, toe G point and downstream folding slope D point. By the research of the action of nonlinear dynamic response and failure mechanism under seismic load of the dam, some reaction laws of the gravity dam in general power load have been revealed, it has provided reference for seismic design and seismic measures for the study of the dam.

Keywords: dynamic time history analysis, dynamic water pressure, additional quality law, damage and dynamic response.

1 Introduction

There are many earthquakes happen to our country every year. China occupies 35% of earthquakes above the level of 7 all over the world from the early 20^{th} century

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[Pan (2000)]. Strong earthquake is a great disaster, especially to the huge dam. If the dam has been devastated by the earthquake, the consequences will be pretty serious. On May 12, 2008, the fierce earthquake in Wenchuan County was so horrible that caused great loss of people's life and fortune and made ruins everywhere. The reservoir dams of Sichuan Province were badly damaged as a result of the aftershocks. It is reported that 27% of reservoirs in Sichuan Province, 1803, were damaged after the earthquake. The research of water and electricity project became more and more crucial after the earthquake. Gravity dam, the primary kind of dam in China now, is safe, convenient and has simple requirements of the rock basis, so it has been used all over the world. Hence, the study of gravity dam's dynamic features, anti-seismic functions and laws, is really significant to water conservancy engineering construction [Lin (2006)].

2 Computation model and material calculation parameters

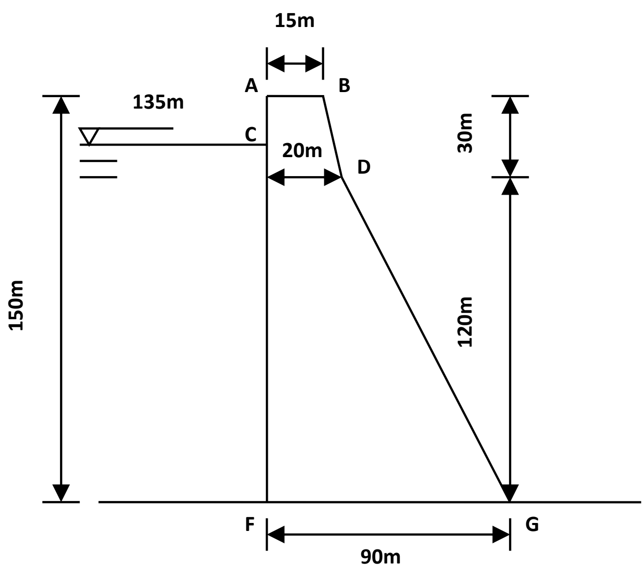

Figure 1: A schematic cross-sectional view.

A concrete gravity dam was built in hard differential bedrock, where the area seismic intensity is 8 degrees, site classification to Class II. Figure 1 is a schematic cross-section of the concrete gravity dam height 150.0m, in front of the dam water level 135m, crest elevation of 393.0m, the lowest elevation of the foundation surface 243.0m, bottom width of 90m, top width of 15m. We generally choose a

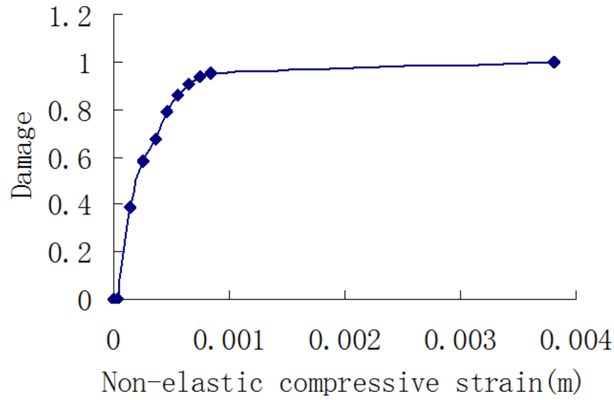

Figure 2: Tensile inelastic strain injury curve.

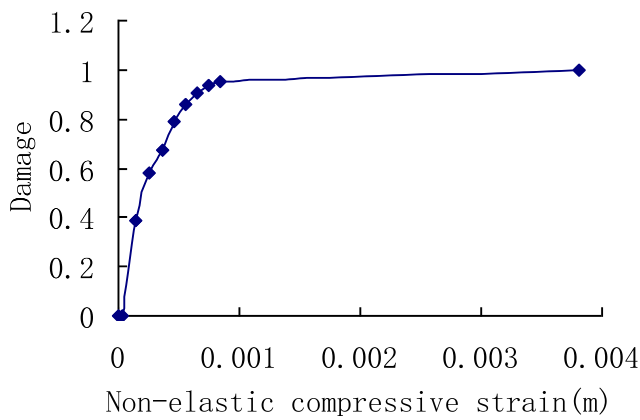

Figure 3: Compression inelastic strain injury curve.

topical monolith to take FEM analysis due to that its transverse of the river is far greater than the stiffness down the river and vertical when using the finite element method to research dynamic analysis of gravity dam. RCC dams are calculated by using elastoplastic damage plastic constitutive model. Figures 2 and 3 correspond to tensile and compressive inelastic strain and damage's corresponding relationship. Its elastic parameters: r=2500m^3 /kg, E=30000MPa, μ=0.2.

3 Dynamic time history analysis

3.1 Modal calculation overview

Modal analysis has a variety of practical algorithms. Abaqus / Standard provides three eigenvalue extraction methods, they were Lanczos method, the subspace law and AMS method. Lanczos method is very powerful, it is very effective when the extraction is of medium to large-scale model of a large number of modes. In view of the size of the dam in this article, as well as the value of feature extraction in the earthquake, the water with high-end frequency characteristics of the movement of the coupling of the dam, the Lanczos method is used. After calculation, the first 10 modal frequency and period specific parameters extracted concrete gravity was shown in Table 1.

Table 1: dam's first 10 frequency and cycle

number	1	2	3	4	5	6	7	8	9	10
frequency (HZ)	2.3124	5.7385	7.9309	10.684	15.212	16.397	16.438	17.257	17.986	18.363
cycle(S)	0.4325	0.1743	0.1261	0.0936	0.0657	0.0609	0.0608	0.0579	0.0556	0.0545

3.2 Damping

The actual project completely damped structure does not exist. Structure under dynamic loads, vibration, gradually reduced the amplitude of the vibration of the structure due to the interaction between the internal friction of the material, material hysteresis effects, as well as member, will lead to energy dissipation, and finally a complete standstill. In practical applications, in order to be able to multi-degree of freedom vibration equation formation decomposition, for a homogeneous material, or a single type of material can be further Rayleigh damping. Rayleigh damping, it is assumed that the damping matrix into mass matrix [M] and stiffness matrix [K] linear combination of form, namely:

$$[C] = \alpha\,[M] + \beta\,[K] \tag{1}$$

Where α, β is a material-specific constant. For a given mode i, the critical damping ξ_i, the Rayleigh damping coefficient α and β have the relationship of:

$$\xi_i = \frac{\alpha}{2\omega_i} + \frac{\beta\omega_i}{2} \tag{2}$$

Where ω_i represents the it modal's natural frequency. Rayleigh damping mass proportional damping part can be seen from equation (2) to play a leading role in the system in response to the low-frequency phase stiffness proportional damping some high frequency from the leading role. Take calculated for the first two order modal frequency ω_1 and ω_2, corresponding ξ_1 and ξ_2 into equation (2) can be obtained:

$$\begin{cases} \xi_1 = \dfrac{\alpha}{2\omega_1} + \dfrac{\beta\omega_1}{2} \\ \xi_2 = \dfrac{\alpha}{2\omega_2} + \dfrac{\beta\omega_2}{2} \end{cases} \tag{3}$$

Solution was:

$$\begin{cases} \alpha = \dfrac{2\omega_1\omega_2\left(\xi_1\omega_2 - \xi_2\omega_1\right)}{\omega_2^2 - \omega_1^2} \\ \beta = \dfrac{2\left(\xi_2\omega_2 - \xi_1\omega_1\right)}{\omega_2^2 - \omega_1^2} \end{cases} \tag{4}$$

When ξ_1=ξ_2=ξ,

$$\begin{cases} \alpha = \dfrac{2\omega_1\omega_2\xi}{\omega_1 + \omega_2} \\ \beta = \dfrac{2\xi}{\omega_1 + \omega_2} \end{cases} \tag{5}$$

Hydraulic structures for seismic design specification DL 5073-2000, gravity dam damping ratio can be selected in the range of 5% -10%, 5% calculated damping parameters, ξ = 0.05. Convert the vibration frequency of the dam, $\omega_1' = 2.3124$ and $\omega_2' = 5.7385$ into natural frequency $\omega_i = 2\pi\omega_i'$ and take them into (5) we can receive $\alpha = 1.0350863$, $\beta = 0.0019779$.

3.3 Added mass method

Under seismic loads, acceleration excitation's size and direction are changing over time. The dam generates corresponding reciprocating acceleration shaking to them, changing size and orientation with respect to inertial force generated between the water and the dam, and the relative sliding. Water on the role of the dam superimposed pressure can be divided into two parts: The first part of the hydrostatic pressure; inertia force of the earthquake under the second part, the hydrodynamic pressure.

Westergaard (1933), such a simplified form of added mass. Hydrodynamic pressure generated by the water at a point of the dam surface, that the body of water that is equivalent to at this point to increase a certain quality of dam together with additional inertial force generated by motion, but no longer be considered in addition to other part of the liquid at this point dam hydrodynamic pressure. Upstream dam wall to increase the mass within the unit area, gives the approximate form of expression $m = \frac{7}{8}\rho_w\sqrt{h_w z}$ for the density of water ρ_w, to design depthh_w, z is the distance to the surface [Westergaard (1933); Lee and Fenves (1998)].

Numerical Simulation Analysis of the dynamic response of the dam, the dam and water at the interface using ABAQUS / Standard finite element analysis software, ABAQUS / Standard user subroutine UEL do a layer of subscriber units attached to the dam onuses unit, to write a program to give the unit quality, and ultimately realize the added mass to the dam on. During analysis of the dynamic response of the dam, the water is no longer considered only as the dam with additional quality simulation.

3.4 Dynamic analysis

The power ring analysis is divided into three steps as follows:

1. Dam is of its own gravity, and continued to power end. The gravity analysis process is set to 1 $\times$ 10-10 seconds long.

2. Hydrostatic pressure as static load applied at the dam, and continued until the power end. The Static analysis process is set to 1 $\times$ 10-10 seconds long.

3. The role of hydrodynamic pressure, added mass method is applied to the dam on. Dynamic analysis process in the dynamic analysis of the process, in a direction of the horizontal seismic loads applied to the base of the dam. During this dynamic analysis process, ABAQUS / Standard call the user subroutine UEL, the introduction of the inertia of the water of the dam. Dynamic analysis process is set to 10 seconds long.

Concrete gravity dam in this article is in accordance with the seismic intensity of 8 degrees fortification seismic response analysis. International strong earthquake acceleration record seismic response of concrete gravity typical strong motion records selected Class II site occurred in 1952, Taft wave, and dynamic analysis studies were selected before the 10s the waveform, the time interval of 0.02s, the waveform diagram shown in Figure 4. According to the specification of the actual earthquake records peak acceleration translated into the design earthquake acceleration design seismic intensity corresponding to the representative value.

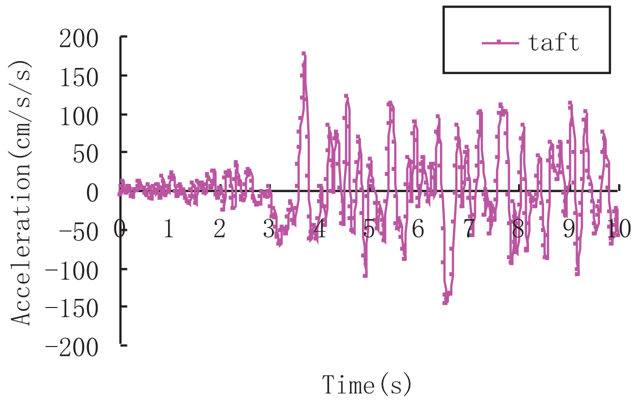

Figure 4: North and south to the Taft waveform Figure.

4 The numerical results

4.1 The relationship among displacement, stress and time

Through the dynamic analysis of the dam, we choose the Displacement time curve along the river (Figure 5) of three points, A, C, D (Figure 1) on the dam. We can know the displacement of three points A, C, D along the river are successively reduced from the figure, it suggests that the displacement of the dam on the direction along the river is increased with the increase in height of the dam. The three points' largest displacement value appears in 6.77s, the maximum displacement were 0.0577m, 0.0502m, 0.0425m. Figure 10 shows C, D, F, G four points' Mises stress time curve, from the figure it can be seen that at point D the stress concentration appeared in 5.077s, the maximum stress was 6.89MPa.

Through the displacement of dam feature points, statistics and analysis of the process curve (Figure 5, 6, 7, 8) has shown that, the stress of the dam mostly concentrated in a most unfavorable moment displacement closer time zone, corresponding at the larger value of the seismic wave velocity. As the dam's most adverse moment corresponding between 4s-8s and the seismic waves 4s-8s. Dam stress, displacement most appeared in unfavorable position in the dam heel at the point F, point downstream of the dam toe G and turned Slope D point.

4.2 The relationship between the injury and the time

As can be seen from Figure 9, 10, 11, 12, t = 3.6s when the injury first occurred in the dam heel at the point F; with the earthquake continued, when t = 4.3s, the dam heel F's injury gradually kept being horizontal development and the injury also ap-

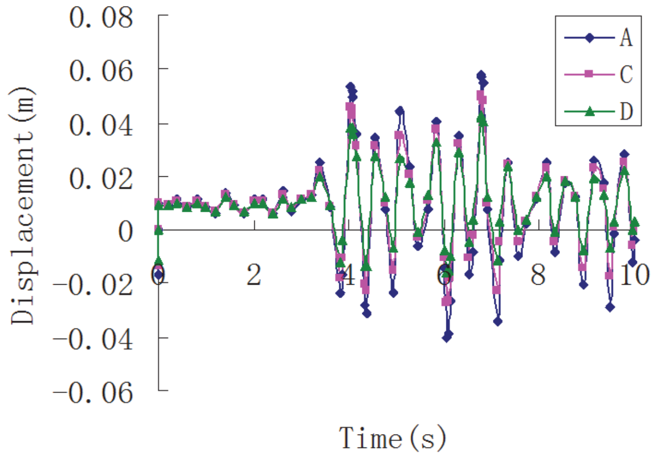

Figure 5: Displacement curve.

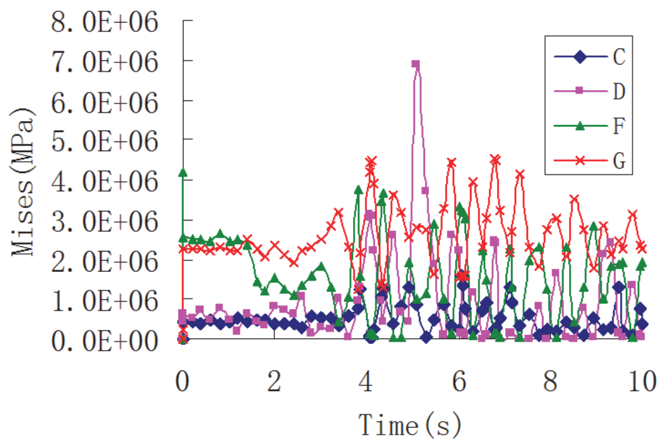

Figure 6: Mises stress time curve.

peared in downstream surface of variable cross-section D near the dam neck; when t = 5.077s, the dam heel F at the point of injury was no longer increase and the downstream surface variable cross-section D at the point of injury gradually transverse development, extended to the internal of the dam, and also began to occur at about 10m from the downstream variable cross-section point D; With the continuing earthquakes, when t=7.5s, downstream variable cross-section at the point D and the lower part of 10 meters along the horizontal development for some and then go down the lower extension to achieve the greatest degree of the injury, but in the

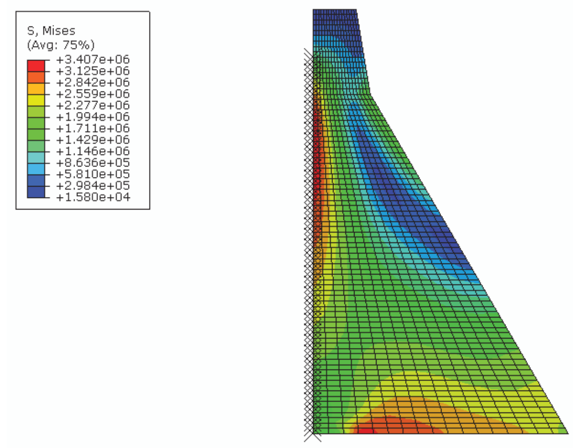

Figure 7: Mises stress cloud in 3.87s.

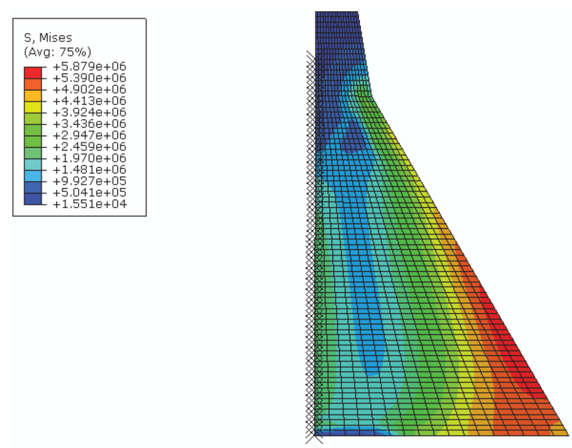

Figure 8: Mises stress cloud when t=6.77s.

final stage of the earthquake, the damage did not continue to expand. The site of injury, the development process and the actual test results are basically consistent.

Under normal circumstances, the dam dynamic stress distribution has two stress concentration areas: first is dam downstream folding slope point, and the second is the dam heel. Dam downstream folding slope point of dynamic tensile stress of two is higher, followed by the dam heel. Dam's failure mechanism is not only with the stress which is larger, but also the peak stress's order of the stress concentration area.

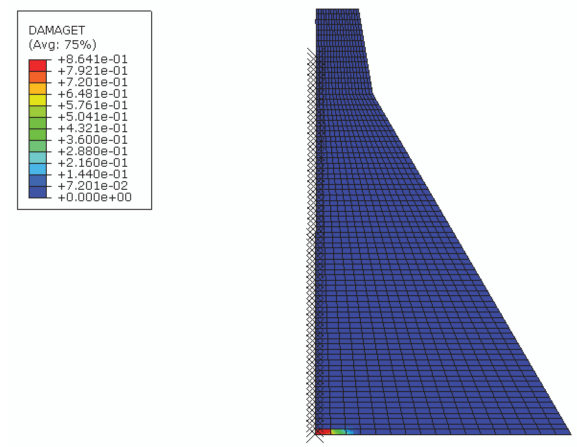

Figure 9: stretch injury state when t=3.6s

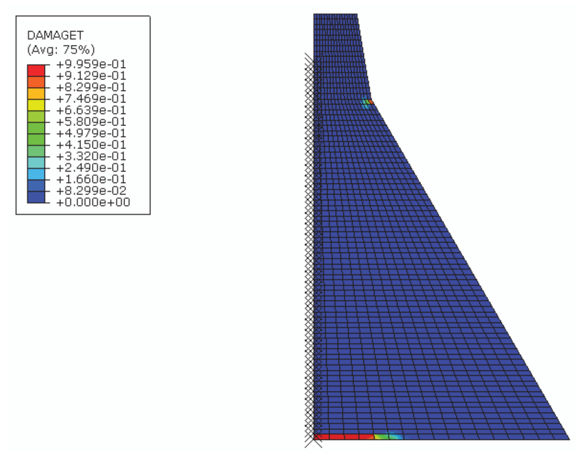

Figure 10: stretch injury state when t=4.3s

4.3 The relationship between energy and time

Shown in Figure 13, 14, 15, are the relationships between energy and time, figure ALLIE showed internal energy, ALLKE showed kinetic energy, ALLWK showed external work, ALLSE showed elastic strain energy, ALLVD showed viscous dissipation energy, ALLPD showed plastic performance, ALLDMD showed damage energy consumption. As can be seen from the figure viscous dissipation, inelastic dissipated energy and damage dissipation kept increasing with the time process and

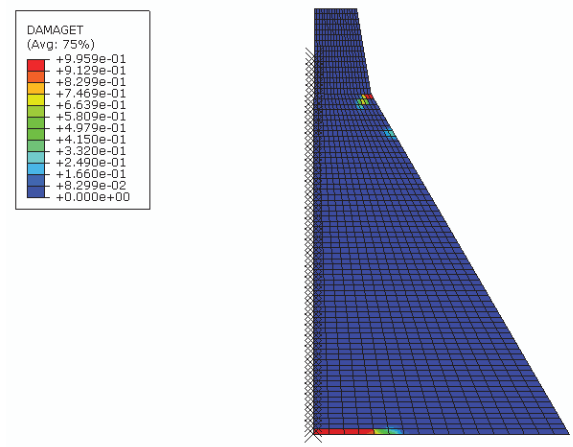

Figure 11: stretch injury state when t=5.077s

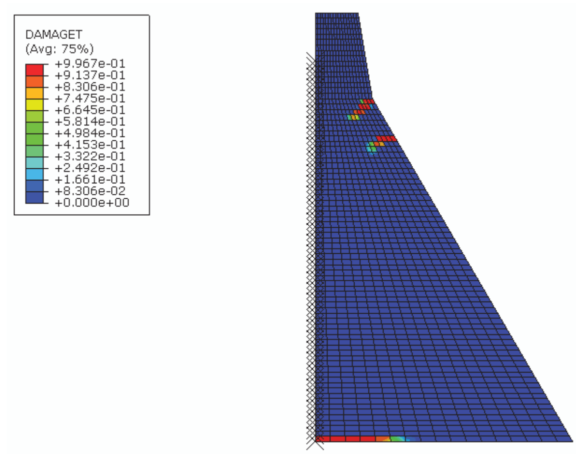

Figure 12: stretch injury state when t=7.5s

began to increase significantly after 3.7s. Viscous dissipation material damping energy accounted for the major part of the energy dissipation. Internal energy, kinetic energy and elastic strain energy had little change at the first 3.7s and after it they started up and down fluctuations around a certain value.

The dam mainly relies on material damping energy, inelastic dissipation and damage dissipation only occupy a small part of the energy consumption. The internal energy, kinetic energy and elastic strain energy are all recoverable.

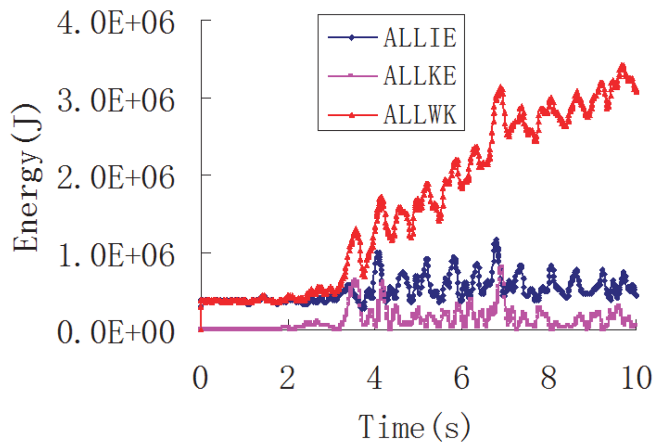

Figure 13: The relationship between energy and time.

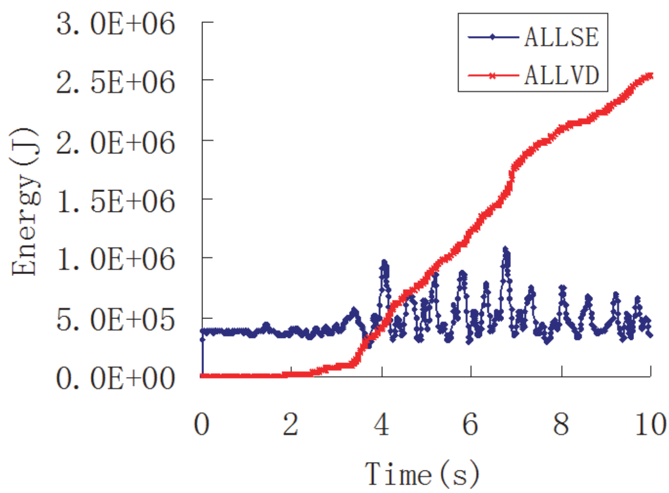

Figure 14: The relationship between energy and time.

5 Epilogue

The power of gravity was been numerical simulation based on the ABAQUS finite element software process, considering the gravity effects of hydrodynamic pressure under earthquake. The gravity's displacement, stress, injury and energy have been analyzed, and we've studied the nonlinear dynamic response under seismic loads and the dam failure mechanism obtained the following conclusions:

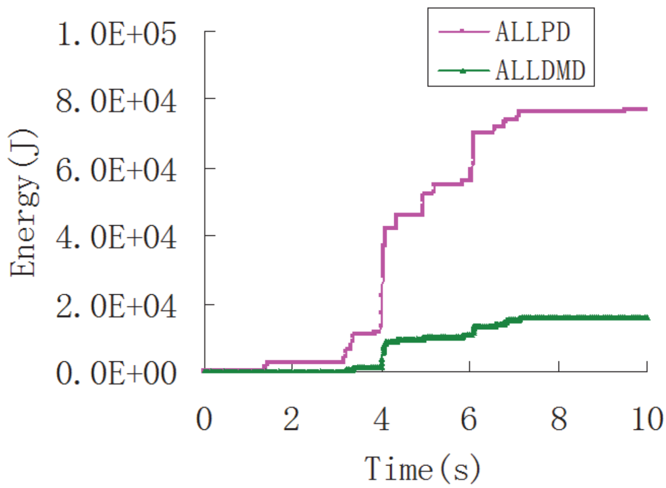

Figure 15: The relationship between energy and time.

1. Through displacement of dam feature points, statistics and analysis of the stress history curves can be drawn, the stress of the dam displacement of the most unfavorable moment mostly concentrated in a closer time zone, corresponding to the largest seismic wave acceleration values. As the dam most adverse moment is between 4s-8s, corresponding the seismic waves 4s-8s. Dam stress, displacement's most unfavorable position in the dam appears in the heel at the point F, point downstream of the dam toe G and turned Slope D point.

2. The injury first occurred at the dam heel F at the point, followed by the dam heel F's injury gradually transverse development, the downstream variable cross-section D point injury near the dam neck; With the sustained earthquake, dam heel at the point of F's injury no longer increased and downstream face variable cross-section D point damage gradually began horizontal development, extending to the dam internal and also began to occur damage at about 10m from the downstream variable cross-section point D and extended horizontally then got the period of the greatest degree; in the final stages of the earthquake, the damage did not continue to expand. Dam damage distribution has two centralized areas: The first is the dam heel and the second is dam downstream folding slope point.

3. The dam mainly relies on material damping energy, inelastic dissipation and damage dissipation only occupy a small part of the energy consumption. The

internal energy, kinetic energy and elastic strain energy are all recoverable.

Calculated by ABAQUS software analysis, obtained the key parts of the dam in the earthquake, the stress concentration and plastic strain, as well as the destruction of these key parts of the process and its morphology, attention is to be paid in the construction and design of practical engineering designed analysis has a certain reference value.

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