Study on the influence of the sediment at reservoir bottom on dynamic damage of gravity dam

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Abstract. Traditional linear elastic model or elastic-plastic DP model can hardly reflect the damage and failure law of the concrete and rock foundation when the tensile and compressive strengths exceed the limitation. Therefore, the concrete damage model is used to simulate the dynamic damage of gravity dam body. According to the similarity of concrete and rock mass materials, the damage model of concrete is extended to rock mass materials. The sediment at the bottom of reservoir is simulated by viscous and high density compressible fluid. Based on this, a multi-coupling simulation model is established, which can reasonably reflect the dynamic damage evolution process of the dam concrete and dam foundation rock mass. Based on the Koyna gravity dam project, taking the thickness of sediment at the bottom of the reservoir as a variable, FEM transient analysis is carried out in this paper. By comparing the damage areas of the model, the displacement of the key points of the dam body along the river and the energy dissipation index, the influence of different thicknesses of the sediment is quantified on the damage of the multi-coupling system of the gravity dam. The calculation results obtained are close to the actual earthquake damage, which verifies the feasibility and rationality of the calculation method. The results of the analysis also show that: the seismic damage of the gravity dam can be consistently reduced with the increase of the thickness of the reservoir bottom sediment. Compared with the dam body, the change of thickness of sediment has less influence on dam foundation damage.

1. Introduction

In the traditional seismic analysis of concrete dams, the dam concrete and rock foundation are often simulated by linear elastic model or elastic-plastic DP model, which is difficult to truly reflect the damage and failure rules of the concrete and rock foundation when the tensile and compressive strengths exceed the limitation. Combined with the theory of damage mechanics and plasticity, Lee and Fenves[1] put forward the plastic damage model under cyclic loads, which can better simulate the damage and failure process of concrete materials under reciprocating loads. Damage and failure of dam foundation are also an important part of seismic design and analysis of gravity dam. However, in the seismic research of gravity dams, the results of considering the overall non-linear damage of dam body and foundation are still less. In general, there are a lot of micro-cracks in the rock mass of dam foundation, which results in the low tensile strength of the dam foundation materials. Under the action of earthquake reciprocating, the rock of the dam foundation often cracks first, which releases seismic energy to a certain extent, thus reduces the stress concentration at the heel of the dam and prevents the dam from cracking. The observed data of gravity dams subjected to earthquakes also confirm this point. Therefore, in order to truly reflect the seismic performance of gravity dam, it is necessary to...
study the dynamic damage evolution process of the dam foundation.

In seismic design of gravity dams, the approximate solution based on rigid dam surface proposed by Westergaard is mainly used for hydrodynamic pressure. In the derivation, the incompressible water body and the non-absorbing boundary at the reservoir bottom are assumed. In fact, after long-term operation of gravity dam, a certain thickness of sediment will be formed in front of the dam body, the sediment will absorb some seismic energy and reduce the seismic response of the dam. Researchers at here and abroad have done a lot of work on how to describe the absorption characteristics of reservoir bottom and how well Westergaard’s approximate solution fits the actual hydrodynamic pressure. Fenves and Chopra[2] extended their early results to the presence of the sediment at the bottom of the reservoir. Cheng[3] studied the influence of sediment and foundation energy absorption. Yan Yizhi[4] applied the finite element method to analyze the seismic response of concrete gravity dam with two-phase porous elastic-plastic sediment at the bottom of the reservoir.

Although some scholars have studied the energy absorption effect of the sediment at the bottom of the reservoir[2-10]. However, up to now, no scholars have studied the relationship between the absorption effect of the sediment at the bottom of the reservoir and the damage characteristics of the gravity dam as a whole. In order to study the effect of sediment on dynamic damage of gravity dam, the materials of the dam body and the dam foundation are simulated with the establishment of the damage model, the sediment is simulated as viscous, high density compressible fluid[8]. Combining with the koyna gravity dam engineering example, a multi-coupling simulation model is established. Taking the thickness of sediment at the bottom of reservoir as a variable, the influence of different thickness of sediment on dynamic damage evolution of multi-coupling system of gravity dam is quantified. The research methods and results provide scientific reference for seismic design and analysis of gravity dams.

2. Computational theory and calculation method

2.1. Plastic damage model of concrete

Constitutive relation of concrete plastic damage model[1]

\[ \sigma = (1 - d)D_0^{eq} \cdot (\varepsilon - \varepsilon^{pl}) \]  \( (1) \)

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

The modulus of elasticity after damage is expressed as:

\[ E = (1 - d)D_0^{eq} \]  \( (2) \)

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:

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

\[ \beta = \frac{\tilde{\sigma} (\tilde{\varepsilon}^{pl})}{\tilde{\sigma} (\tilde{\varepsilon}^{pl})} (1 - \alpha) - (1 + \alpha) \]  \( (4) \)

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

The flow rule of plastic damage model is non-correlated flow rule, and its plastic potential function is as follows:

\[ G = \sqrt{((k\sigma_{0})_0 \tan \varphi)^2 + 1.5\rho^2 + \sqrt{\epsilon} \tan \varphi} \]  \( (5) \)

Where \( \rho = (2J_2)^{0.5} \), parameters \( k \) is the eccentricity of plastic potential function of concrete, the default value is 0.1, \( \varphi \) is the expansion angle of concrete yield surface during strengthening process.
2.2. Control equation of reservoir water-sediment model

For the coupling system of the dam body and reservoir water. Assuming that the reservoir water has no rotational disturbance and ignores the viscosity, the compressible reservoir hydrodynamic pressure (p) distribution can be calculated according to the following equation \[6\].

\[
\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\omega^2}{c^2} p = 0
\]

Assuming that the sediment is regarded as a two-dimensional viscous compressible large-density fluid, which can be calculated by the following equation.

Continuous equation:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} = 0
\]

Equation of motion:

\[
\frac{\partial (\rho u)}{\partial t} + u \frac{\partial (\rho u)}{\partial x} + v \frac{\partial (\rho u)}{\partial y} = \mu \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) - \frac{\partial p}{\partial x} + f_x \rho
\]

\[
\frac{\partial (\rho v)}{\partial t} + u \frac{\partial (\rho v)}{\partial x} + v \frac{\partial (\rho v)}{\partial y} = \mu \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) - \frac{\partial p}{\partial y} + f_y \rho
\]

Where \( t \) denotes time, \( \omega \) is the excitation frequency; \( c \) denotes the sound velocity in reservoir water, \( \rho \) is fluid density, \( v \) and \( u \) are velocity components in X and Y directions respectively, \( f_x \) and \( f_y \) are the components of the volume force in the X and Y directions respectively, parameters \( \mu \) is the dynamic viscous coefficient.

3. Effect of deposit layer at reservoir bottom on dynamic damage evolution of gravity dam

3.1. Finite element model of dam body- foundation- reservoir water and sediment

The Koyna gravity dam has been a classic example of dynamic analysis of the concrete dam. On December 11, 1967, the Koyna gravity dam in India suffered a magnitude 6.5 earthquake, earthquake caused multiple horizontal cracks in the Koyna gravity dam, the depth of the reservoir was 91.5m. In this paper, a typical dam section of the Koyna gravity dam is selected for analysis. The upper, lower and depth directions of the foundation are taken twice as dam high. The coupling model of the dam body- reservoir water -sediment-dam foundation is established (Figure 1), \( h \) denotes the thickness of sediment. The Abaqus acoustic unit is used to simulate the water compressibility of the reservoir, and the sediment is modelled as a viscous, high-density compressible fluid \[8\]. The centre line of the anti-seepage curtain in the model is 7m from the upstream surface of the dam, and the depth of the curtain is 1/2 of the water level in front of the dam, which is 45.5m.

![Figure 1. Dam body- foundation- reservoir water - sediment model.](image-url)
Considering both vertical and horizontal seismic waves, the peak acceleration of horizontal seismic wave \( \text{PGA} = 0.474 \text{g} \) (Figure 2) and that of vertical seismic wave \( \text{PGA} = 0.312 \text{g} \) (Figure 3). In analysis, the viscoelastic damping boundaries were used\(^{[1]}\). Assuming that reservoir water is an inviscid, irrotational compressible ideal fluid, water density \( \rho = 1000 \text{kg/m}^3 \) and bulk modulus \( K = 2 \text{GPa} \); Assuming that the sediment at the bottom of reservoir is regarded as viscous compressible high density fluid. According to the dry density of sediment (2640 kg/m\(^3\)), reservoir water density and porosity \( \phi = 0.6 \), the material parameters for the sediment were taken as density \( \rho = 1656 \text{kg/m}^3 \), bulk modulus \( K = 3.33 \text{GPa} \), and the kinematic viscosity coefficient of the sediment is 4.5\(^{[8]}\). The material parameters for the dam foundation were taken as tensile strength \( f_t = 2c \cdot \cos \phi / (1 + \sin \phi) = 1.28 \text{MPa} \) (\( \phi = 54.46^\circ \), \( c = 2.0 \text{MPa} \)), original elastic modulus \( E_0 = 20 \text{GPa} \), specific fracture energy \( G_f = 88 \text{N/m} \). The material parameters for the dam concrete were taken as follows: Original elastic modulus \( E_0 = 31 \text{GPa} \), density \( \rho =2643 \text{kg/m}^3 \), tensile strength \( f_t = 2.9 \text{MPa} \), poisson ratio \( \mu =0.2 \), \( G_f = 200 \text{N/m} \), stiffness parameter of damping of the Rayleigh type \( \beta = 0.00323 \)^{[12]}\). Anti-seepage curtain material parameter reference case, the value is the same as the dam concrete. The initial geostress field is determined according to the engineering rock mass grading standard for the initial stress field, the vertical geostress is the rock mass self-weight \( \gamma h \), and the horizontal geostress is 1.2 \( \gamma h \).

3.2 Influence of thickness of sediment on dynamic damage of dam foundation

This paper considers the dam body and foundation as the plastic damage model. In order to improve the computational efficiency, parallel algorithms are used in the calculation process, after considering the seismic energy dissipation effect of the system to the distant domain\(^{[11]}\), the seismic response damage analysis of the dam body-water-sediment-foundation system is carried out. In the calculation, assuming that the thickness \( h \) of the bottom sedimentation layer is 0, 10m, 20m, 30m, corresponding to the four operating conditions a, b, c, d, the corresponding \( h / H \) values are 0.109, 0.219, 0.329. By comparing the damage areas of the model, the displacement of the key points of the dam body along the river and the energy dissipation index, the influence of different thicknesses of the sediment is quantified on the damage of the multi-coupling system of the gravity dam.

3.2.1 Effect on plastic damage areas

The analytical results show that the crack does not appear along the dam foundation interface (Figure 4), and the anti-seepage curtain has not been damaged, and the damage of the dam body is mainly concentrated near the abrupt change of downstream slope, at this elevation, the dam concrete appears through the damage zone. At the beginning of the earthquake, the damage zone of the bedrock at the dam is first extended vertically downward by 14m, with the ground motion time increases, the dam foundation damage zone shifts downstream and continues to expand deep, finally, the vertical expansion depth of the bedrock damage zone is about 35.5m. It turns out that as the thickness of the sediment at the bottom of the reservoir increases, the degree of damage to the dam is gradually decreases, this is due to the fact that the thick sediment absorbs part of the energy transmitted from the dam foundation to the upper structure.
When the thickness of the sediment at the bottom of the reservoir is \( h=0 \) (Figure 4(a)), there are two penetrating damage zones on the upstream surface of the dam body. The downstream of the dam body has a penetrating damage zone at the slope, and the thickness of the sediment at the bottom of the reservoir increases to \( h=30 \text{m} \) (Figure 4(d)), the concrete damage area of the dam body is reduced, and one upstream of the dam body runs through the damage zone, and the other damage zone is close to the through. Comparing Figure 4(a)–4(d), it is found that the influence of the thickness variation of the sediment on the damage of the dam foundation is not very significant.

Figure 4. Damage with proposed model.

According to the actual investigation after the earthquake, the location of the crack in the Koyna gravity dam caused by the earthquake was mainly concentrated near the 629m elevation (Figure 5)[12]. Sampling of the interface of the dam foundation revealed that the concrete and the bedrock were well cemented, and no signs of cracking at the interface of the dam foundation were found. The simulation results are in good agreement with the actual seismic damage.

3.2.2 Impact on energy dissipation indicators

In this paper, four kinds of working conditions are compared and analyzed from damage energy consumption and plastic strain energy consumption[13][14]. Figure 6 shows that in terms of damage energy consumption, when there is no sediment at the bottom of the reservoir, the system damage energy is the largest, the thickness of the sediment at the bottom of the reservoir is inversely related to the energy consumption of the system damage. Refer to the damage energy consumption with zero thickness of the sediment as the benchmark, when the thickness \( h \) of the sediment is increased to 10m, 20m and 30m, the damage energy consumption of the system is reduced by 5.3%, 13.2% and 23.7% (Figure 6). In terms of plastic strain energy consumption, similar to the damage energy consumption, when the thickness of the sediment at the bottom of the reservoir is zero, the thickness of the sediment at the bottom of the reservoir is inversely proportional to the plastic strain energy consumption of the system, Refer to the plastic energy consumption with zero thickness of the sediment as the benchmark,
when the thickness $h$ of the sediment is increased to 10m, 20m and 30m, the plastic strain energy consumption of the system is reduced by 7.8%, 15.2% and 25.4% (Figure 7).

3.2.3 Influence on dam deformation

Figure 8 shows that the displacement of the key points of the dam body along the river with different thickness of the sediment at different times. With the increase of the thickness of the reservoir bottom sediment, the displacement of the upstream dam and the downstream slope of the observation point gradually decrease. Refer to the displacement with zero thickness of the sediment as the benchmark, when the thickness $h$ of the sediment is increased to 10m, 20m and 30m, the displacement of the upstream apex of the dam body along the river is reduced by 2.4%, 7.1% and 10.25% (Figure 8(a)). The displacement of the downstream inflection point of the dam body along the river is reduced by 4.4%, 8.9% and 12.1% (Figure 8(b)).

4. Conclusion

In this paper, the materials of the dam body and the foundation are simulated as plastic damage materials, and the sediment at the bottom of the reservoir is simulated as viscous, high-density and compressible fluid. Considering the sediment absorption and the interaction of the dam body-water-foundation system, a multi-coupling simulation model is established. Based on this, the dynamic damage response of the Koyna gravity dam under seismic load is analyzed.

The materials of the dam body and the dam foundation are simulated with the establishment of the damage model, and it turns out that the crack does not appear along the interface between the dam and its foundation, the anti-seepage curtain is not damaged, and the damage of the dam body mainly distributes around the abrupt change point of the downstream slope. Through comparison, the simulation results are in good agreement with the actual seismic damage of the engineering project.

The seismic damage of the gravity dam can be consistently reduced with the increase of the thickness of the reservoir bottom sediment. Through the comprehensive comparison of the damage areas of the model, the displacements of the key points of the dam body along the river and the energy consumption of the system are reduced by 7.8%, 15.2% and 25.4% (Figure 7).

Figure 6. Damage energy consumption.

Figure 7. Plastic strain energy dissipation.

Figure 8. The displacement of the key points of the dam body along the river.

(a) 

(b)
dissipation index, the following conclusions are drawn: When the thickness of the sediment is at a low level (for example, h/H<0.1), the influence of the sediment at the bottom of the reservoir may be disregarded. Whereas when the sediment at the bottom of the reservoir is thick (for example, h/H>0.1), the absorption effect of the sediment on the seismic waves is obvious, for which the role of the sediment should be considered.

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