CHEMICAL ENGINEERING TRANSACTIONS
VOL. 66, 2018
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Songying Zhao, Yougang Sun, Ye Zhou

ISBN 978-88-95608-63-1; **ISSN** 2283-9216
DOI: 10.3303/CET1866183

Influence of Material Nonlinearity of Foundation on Seismic Damage of Koyna Gravity Dam

Xiaodong Zheng, Jing Ma*, Feng Li

Hebei University of Engineering, Handan 056038, China
373048972@qq.com

Based on the theory of damage mechanics, continuum mechanics and thermodynamics, this paper gives the concrete tension constitutive equation, then, the selection principle of the relevant parameters of the foundation rock is given. Finally, considering the damage evolution of rock foundation in the calculation process, this paper describes the real seismic damage characteristics of dam foundation system. The main conclusions are as follows: when the foundation rock mass and the dam use damage model, the earthquake damage area and damage degree of the dam are reduced, which makes the dam more partial safety. The result will be closer to the actual, which has certain reference significance to the guiding project.

1. Introduction

80% of China's hydropower resources are mainly concentrated in the southwest strong earthquake region, so the major water conservancy projects cannot ignore the issue of earthquake safety. Once the earthquake disaster happens to the major water conservancy project, it will cause unbearable secondary disasters to the downstream areas, so to make sure that dam break does not occur in the maximum credible earthquake to the major water conservancy projects (Chen and Guo, 2012). But so far, "no dam break" is only an uncertain fuzzy concept, and there is no quantitative analysis criterion of operability. The key problem lies in the further research on the process and mechanism of the seismic damage evolution of major water conservancy projects. Under the action of earthquake load, when the dam concrete stress exceeds the yield strength, (Zhang and Wang, 2013) the dam is bound to generate local cracks, and the stress in the dam will be redistributed, so the stress criterion based on the linear elastic material model cannot meet the requirements of the seismic damage analysis of the dam, that is, the introduction of the nonlinear material of the dam will be more close to the actual situation (Guo et al., 2013). Taking Koyna gravity dam as an example. Many scholars have used many methods to simulate and analyse the earthquake disaster. The results show that the extended Koyna dam heel and downstream slope crack evolution process, and near the dam heel appeared obvious stress concentration, and the grid division is more intensive, the stress concentration degree is higher (Yu et al., 2009). But when the Koyna dam was subjected to seismic load, the core-drilling was found to have a good cementation between the dam and the foundation, and the seepage flow rate at the dam foundation was not significantly increased, which shows that the interface between the dam and the foundation did not produce damage cracks, and it is contradict the research results of many scholars (Li et al., 2011). It puts forward new ideas for researchers in the existing model of stress analysis that the high stress of the dam heel area may not exist. Therefore, it is considered that the dam foundation cannot be considered as an elastic foundation or a rigid foundation, which cannot reflect the actual situation of the dam.
Based on the existing research of Koyna dam seismic damage, this paper discusses the influence to seismic damage characteristics of Koyna dam caused by the nonlinear foundation rock material and comparing the dam damage results between different foundation models.

2. The damage mechanical of concrete

2.1 Damage constitutive model

In general, the free energy is divided into the plastic part and the elastic part. Under the condition of isothermal

Please cite this article as: Zheng X., Ma J., Li F., 2018, Influence of material nonlinearity of foundation on seismic damage of koyna gravity dam, Chemical Engineering Transactions, 66, 1093-1098 DOI:10.3303/CET1866183

adiabatic (Wang et al., 2016), the damage variable D stands for internal variableV_k, and Eq. (1) can be rewritten as

$$\psi(\delta^e,\delta^p,D)=\psi^e(\delta^e,D)+\psi^p(\delta^p,D) \tag{1}$$

Where, $\varphi^e(\delta^e,D)$ represents the elastic free energy, and $\varphi^p(\delta^p,D)$ is the plastic free energy.
The damage of concrete can be expressed in a damage variable of the elastic free energy $\varphi^e(\delta^e,D)$.

$$\psi^e(\delta^e,D)=(1-D)\psi_0^e(\delta^e) \tag{2}$$

The material constitutive equation based on free energy can be deduced as

$$\sigma=\rho\frac{\partial\psi}{\partial\delta^e}=\rho\frac{\partial\psi^e(\delta^e,D)}{\partial\delta^e} \tag{3}$$

In the process of uniaxial tension, the relationship between the tensile elastic and plastic deformation of concrete should be satisfied

$$\delta_t=\delta_t^e+\delta_t^p \tag{4}$$

In which, δ_t represent under the seismic load (Li et al., 2012), δ_t^e is the tensile elastic deformation, and δ_t^p denotes the tensile plastic deformation.
The uniaxial tensile damage variable D_t is introduced into Eq. (1), and thus the scalars form of elastic free energy is acquired

$$\psi^e(\delta_t^e,D_t)=(1-D_t)\psi_0^e(\delta_t^e)=\frac{1}{2\rho}(1-D_t)K_0(\delta_t^e)^2 \tag{5}$$

In which, K_0 indicates the initial slope of concrete under uniaxial tension stress and deformation.
Replacing Eq. (5) and (4) into Eq. (3) can obtain the concrete damage constitutive relation under uniaxial tension cases as

$$\sigma_t=(1-D_t)K_0(\delta_t-\delta_t^p) \tag{6}$$

2.2 Damage evolution equation of concrete

In order to derive the damage evolution law of concrete material, it is necessary firstly to determine the plastic free energy expression as

$$\psi^p(\delta^p,D)=\int_0^{\delta^p}\sigma:d\delta^p \tag{7}$$

For a specific material, the total free energy is determined (Ren et al., 2015); hence the deformation variables can be used to describe relation function between the elastic free energy and the plastic the free energy, which is formulated as follows

$$\psi^p(\delta^p,D)=F(\delta^e,\delta^p)\psi^e(\delta^e,D) \tag{8}$$

Assume that after peak stress, concrete start to occur plastic deformation, peak deformation is $\delta_{pk}=\delta_{t0}^e$. The expression of the energy release rate of the tensile damage is written as

$$Y_t=\frac{1}{2}\left(1+k_t\frac{\delta_t^p}{\delta_t^e}\right)K_0(\delta_t^e)^2 \tag{9}$$

In which, k_t is material parameters.
The damage energy release rate and damage variable of the material can also be expressed as follows

$$D_t=1-\exp\left(-\frac{(Y_t-Y_{t0})^{a_t}}{b_t}\right) \tag{10}$$

In which, a_t and b_t are material parameters. Y_{t0} denotes initial energy release rate of tensile concrete.

3. Mechanical parameters of dam foundation

In the high dam engineering, we put forward the rock mass shear resistance parameter friction angle and the proposed value of adhesion (Pal et al., 2017). Finally, the uniaxial tension and compressive strength were obtained by Mohr-Coulomb criterion.

$$f_t = \frac{2c \cdot \cos\varphi}{1+\sin\varphi}, \quad f_c = \frac{2c \cdot \cos\varphi}{1-\sin\varphi} \tag{11}$$

The tensile damage model of foundation rock is analysed by the concrete damage model, and the damage curve of foundation rock mass is determined by the method of discount of concrete damage curve.

4. General situations of Koyna gravity dam

In December 11, 1967, the earthquake with magnitude as 6.5 attacked the India Koyna gravity dam, and caused many horizontal cracks in the dam, mainly focused on the slope of 629 m elevation, as shown in Figure 1.

The height of Koyna dam is 103 m, the length is 850 m. When the earthquake occurred the water level in the front of the dam is 91.75 m. The focal depth of earthquake is 27 km, and the epicentre distance is 13 km. The epicentre intensity is VIII-IX degrees. When the design reference period is 100 years, and the probability of exceeding the probability is 2%, the peak ground acceleration (PGA) is 3.99 m/s^2. When the vertical and horizontal earthquake ground motions are inputted to the finite element analysis model, the peak of vertical acceleration time histories is the 2/3 of that of the horizontal acceleration time histories, as shown in Figure 2.

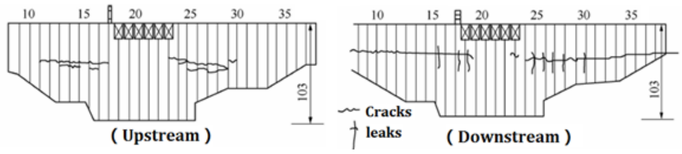


Figure 1: Seismic damage of Koyna dam (size unit: m)

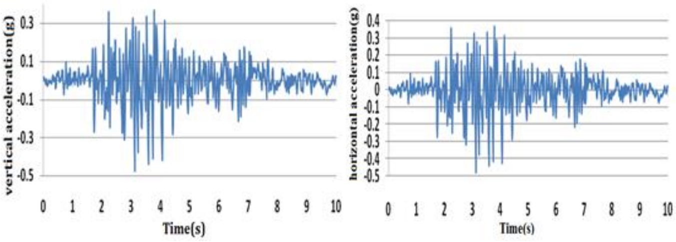


Figure 2: Acceleration time histories of vertical and horizontal earthquake ground motions

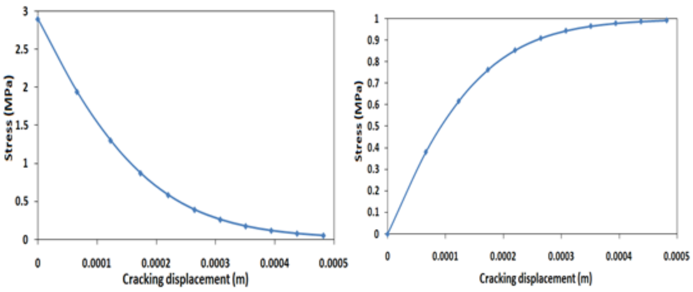


Figure 3: The concrete damage evolution curve

When the dam model is calculated and analysed, the water level of the dam is normal. The hydrodynamic pressure of reservoir water is simulated by Westergaard additive mass method, which ignores the compressibility of reservoir water (Alam et al., 2016). The Raleigh damping ratio *C* is taken as $C = \alpha M + \beta K$, *M* is the mass matrix, and K is the stiffness matrix. Because the damping force is changed with the closing and opening of the crack, thus α=0 s-1, β=0.0032 s. The dam material parameters are listed as follows, the elastic modulus is 3.1×104 MPa, the density is 2643 kg/m³, the Poisson ratio is 0.15, the tensile strength is 1.90MPa, the compressive strength is 24.1MPa, the fracture energy is 200 N/m, the compressive yield stress is 13 MPa. The damage evolution curve of concrete is shown in Figure 3.

The material parameters of the foundation rock are as follows, the elastic modulus is 20 GPa, the density is 2400 kg/m³, the Poisson ratio is 0.2, the fracture energy is 88.4 N/m, the cohesion is 2 MPa, the friction angle is 54.46°, the dilation angle is 36.31°. In the absence of tests on the foundation, the cohesive force and the friction angle of the foundation rock are substituted into the formula (11), and the tensile strength of the foundation rock is 1.28 MPa (Zhang et al., 2015). Finally, the damage curves of the foundation rock are determined by the method of discounting the strength of concrete damage curve, as shown in Figure 4.

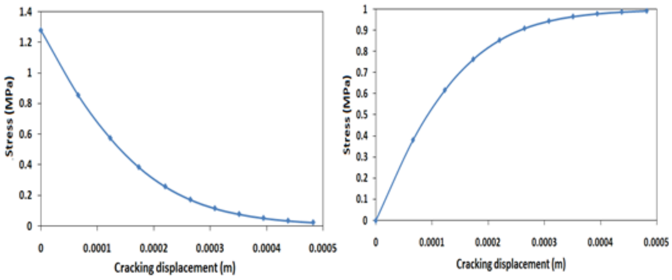


Figure 4: The foundation damage evolution curve

5. The analysis results

Figure 5 is the maximum principal stress distribution of dam-foundation system under earthquake action. As can be seen from Figure 6, for the dam body, the maximum principal stress at the dam heel is 6.44 MPa, the maximum principal stress at the dam toe is 4.23 MPa, the maximum principal stress at the downstream slope is 3.16 MPa, and the maximum principal stress at the upper and middle reaches is 6.36 MPa. For the foundation rock mass, the maximum principal stress of the foundation connected with the dam toe is 1.92 MPa, and the maximum principal stress of foundation connected with dam heel is 2.56 MPa. The stress values in these areas are much greater than the tensile strength of concrete and foundation rock mass, therefore, the seismic performance of these areas is relatively weak, and there may be damage.

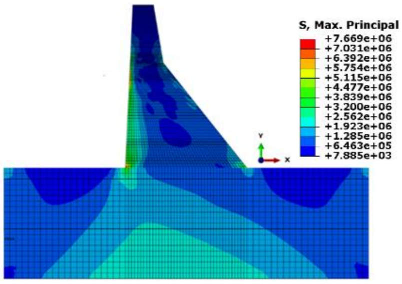
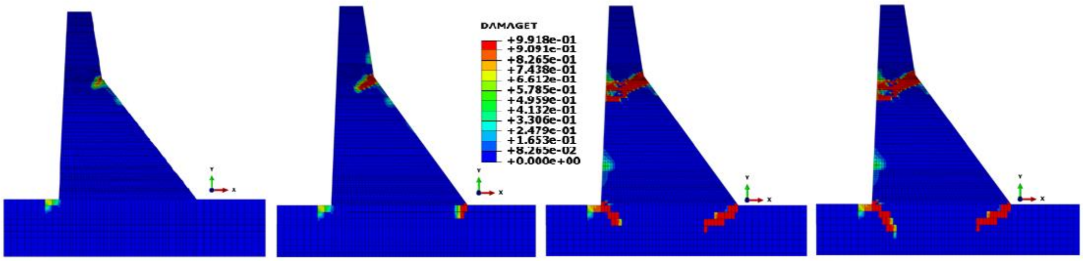


Figure 5: The maximum principal stress distribution of dam-foundation system

Figure 6 shows the damage area of the foundation-dam system at different times when the damage model is adopted, Figure 7 shows the damage area of dam-foundation system with different calculation models, Figure 8 shows the damage dissipation curve when foundation using different models. It can be seen from Figure 6 that the damage of the foundation-dam system starts from the junction of the dam's heel and the foundation, and the downstream slope of the dam. Along with the continuous seismic load, the damage at the dam heel and foundation junction extends along the depth of foundation; the damage length is about 13 m, damage depth of about 15 m. The damage at dam site extends along the depth of foundation, the damage depth is about 14 m, and the damage length in the upstream direction is about 17.5 m. In the downstream, the damage is developed along the dam to the upstream direction, and finally the penetrating damage is formed. There is no damage in the dam heel. The above analysis results are closer to the actual earthquake disaster.

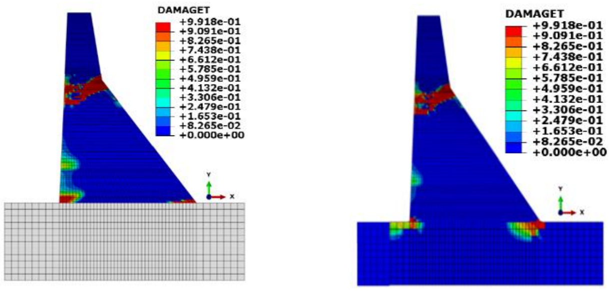
In Figure 7a, the damage at the downstream slope of the dam develops from downstream to upstream and runs through the dam; the damage occurs at the upstream dam heel, approximately 7 m; the damage occurs in the middle and lower reaches of the upstream, approximately 4 m; and the damage occurs at the downstream dam site, approximately 12 m. Compared with Figure 6d, it is found that there is damage

penetration at the dam slope, and the dam heel is damaged due to the stress concentration at the dam heel. The analysis result is in contradiction with the actual earthquake disaster.
As can be seen from Figure 7b, the damage at the dam site extends up to about 14 m along the upstream of the dam foundation interface, and the damage at the dam heel extends up to about 12 m along the downstream of the dam foundation interface, which makes the bond between the dam and the foundation damage. The analysis results are not consistent with the actual earthquake disaster of the dam.



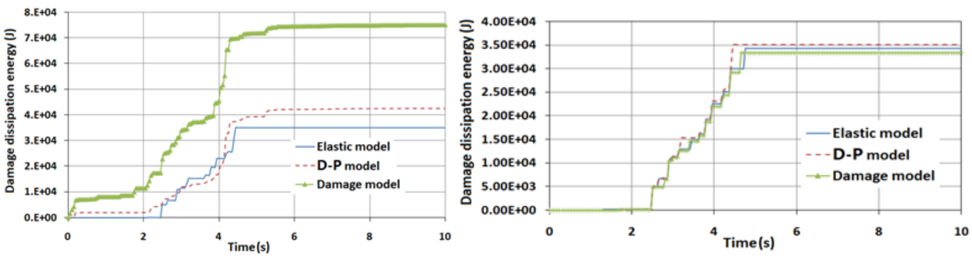
a. 0.5 s b. 2.5 s c. 4.5 s d.10 s

Figure 6: Damage area of foundation-dam system at different time of foundation using damage model



a. Elastic model of foundation b. D-P model of foundation

Figure 7: The damage area of the dam-foundation system with different models



a. the dam-foundation system b. the dam

Figure 8: The damage dissipation energy curve when foundation using different models

It can be seen from Figure 8a that when the damage model is adopted in the foundation, the dam-foundation system will be damaged when the earthquake occurs; when the D-P plastic model is used for the foundation, the system will be damaged only 0.5 s after the earthquake; when the elastic model is used for the foundation, the system will be damaged only 2.5 s after the earthquake. The damage dissipation energy calculated by the damage model is much larger than that of the D-P model and the elastic model, which is caused by the foundation and the dam at the same time produce damage. The foundation adopts the elasticity model, the foundation does not have the damage, only the dam body produces the damage; the D-P model is based on the plastic microscopic phenomenon, D-P model is based on the plastic micro-phenomenon, cannot reflect the rock material due to crack opening and closing caused by changes in intensity, therefore, the damage dissipation due to foundation damage is smaller than that of the ground nonlinear model.
It can be seen from Figure 8b that the damage dissipation energy of the dam is less than that of the other two cases when the damage model is adopted on the foundation, which shows that the damage scope of the dam body is relatively small and the dam is safer.

From the above analysis, it can be seen that the elastic model and D-P plastic model of the foundation cannot truly reflect the damage failure mode of the dam-foundation system during the dynamic response analysis of the dam-foundation system during the earthquake. Therefore, it is necessary to consider the damage nonlinearity of foundation and dam at the same time, so as to describe the damage failure process of dam-foundation system more truly.

6. Conclusions

Based on damage mechanics, continuum mechanics theory and thermodynamics, the constitutive equation of concrete is established. Then the principle of selection of relevant parameters of foundation rock mass is given. Finally, a more complete nonlinear dynamic model of dam-foundation system is established. So that the seismic damage characteristics of the system are described more realistically. The main conclusions are as follows, when the damage model is adopted for foundation rock mass and dam body, the damage area and the damage degree of the dam are reduced, which makes the dam body safer, the analysis result is closer to the actual earthquake disaster.

Acknowledgements

This work is supported by the Hebei Youth Natural Science Fund (Grant Nos. E2018402131), Handan Science and Technology Research and Development Plan Project (Grant Nos. 1721211050-4), Hebei Provincial College of Science and Technology Research Project (Grant Nos. BJ2018049), the Doctor Special Fund (Grant Nos. 17129033054) and the Open Foundation from Key Laboratory of Ministry of Education for Efficient Mining and Safety of Metal Mines (Grant Nos. ustbmslab201706).

References

Alam M.S., Rahman M.M., Parvin S., Vajravelu K., 2016, Finite element simulation for heatline visualization of natural convective flow and heat transfer inside a prismatic enclosure, International Journal of Heat and Technology, 34(3), 391-400, DOI: 10.18280/ijht.340307

Chen H.Q., Guo S.S., 2012, Seismic damage analysis of high concrete dam-foundation system, Shuilixuebao, 43(1), 2-7, DOI: 10.13243/j.cnki.slxb.2012.s1.023

Guo S.S., Chen H.Q., De-Yu L.I., Xiong K., 2013, Seismic damage and failure analysis of gravity dam and foundation system, ShuiLiXueBao, 44(11), 1352-1358, DOI: 10.13243/j.cnki.slxb.2013.11.016

Li X.Y., Zhong H., Lin G., 2011, Numerical simulation of damage process and failure modes of concrete gravity dams due to earthquakes, Journal of Hydraulic Engineering, 42(10), 1209-1217, DOI: 10.13243/j.cnki.slxb.2011.10.013

Li Z., Li A., Teng J., 2012, A plastic-damage uniaxial compression constitutive of concrete, China civil engineering journal, 45(S2), 182-186.

Pal M., Sarkar G., Barai R.K., Roy T., 2017, Design of different reference model based model reference adaptive controller for inversed model non-minimum phase system, Mathematical Modelling of Engineering Problems, 4(2), 75-79, DOI: 10.18280/mmep.040204

Ren X., Zeng S., Li J., 2015, A rate-dependent stochastic damage-plasticity model for quasi-brittle materials, Computational Mechanics, 55(2), 267-285, DOI: 10.1007/s00466-014-1100-7

Ren X.H., Liu Q., Zhang Y.M., 2015, The proportion of energy consumption structure prediction based on Markov Chain, Mathematical Modelling of Engineering Problems, 2(1), 1-4, DOI: 10.18280/mmep.020101

Wang X.P., 2016, Effect analysis of industrial structure of the border trade development in Inner Mongolia, Mathematical Modelling of Engineering Problems, 3(2), 101-107, DOI: 10.18280/mmep.030211

Yu S., Chen Z.Y., Wang Y.J., Duan Q.W., Jia Z.X., 2009, Analysis on the deep anti-sliding stability of concrete gravity dam foundation by FLAC strength reduction method, Hydrogeology and Engineering Geology, 36(3), 64-70.

Zhang S., Wang G., 2013, Effects of near-fault and far-fault ground motions on nonlinear dynamic response and seismic damage of concrete gravity dams, Soil Dynamics & Earthquake Engineering, 53(5), 217-229, DOI: 10.1016/j.soildyn.2013.07.014

Zhang X.Q. 2015. Hydraulic characteristics of rotational flow shaft spillway, International Journal of Heat and Technology, 33(1), 167-174, DOI: 10.18280/ijht.330123