Seismic analysis of concrete dam based on a simple damage model

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Abstract. The present improved simple damage model is capable of capturing the unilateral effect and the more realistic softening curve of concrete by adopting different compressive and tensile evolution equations for concrete. And a user subroutine UMAT has been developed. Using the commercial code Abaqus, the analysis of seismic damage and response of the Koyna dam is performed. The results show the importance of considering the concrete damage in the seismic analysis of concrete dam.

1. Introduction

At present, the linear elastic model combined with the allowable tensile stress criterion to evaluate the seismic safety of dams is still employed in some countries [1, 2]. However, concrete is a quasi-brittle material whose tensile strength is far less than the compressive strength, although it approximately maintains linear elastic behavior under small load. With the increase of load, especially under strong earthquake, tensile cracking and stress redistribution of concrete will happen, which makes the seismic response and bearing capacity of the dam change significantly. In order to properly evaluate the seismic safety of dam under strong earthquake, researchers have put forward several methods, including discrete crack approach, smeared crack approach and continuous damage mechanics approach. The discrete crack approach uses the concept of fracture mechanics to simulate the discrete cracks. This method can accurately give the geometry of each crack. However, with the change of fracture surface, re-meshing technique is needed, which leads to the calculation cost of structural dynamic response under earthquake becomes very large. The smeared crack approach is a continuous model, which is easy to be implemented by the standard finite element method, and become a built-in model in many finite element codes, such as Ansys, Abaqus, Adina, Diana, Marc, Midas. In recent years, the continuous damage mechanics method has been paid more attention by many researchers. This method describes the damage state of concrete by introducing damage variables. Especially, by introducing tensor damage variables, the anisotropic effect of damage can be considered. Furthermore, the inelastic deformation effect can also be considered by coupling with plastic process. Therefore, it is considered to be an effective method to describe the behavior of concrete and has been applied to seismic response analysis of concrete dams in many studies [3-9]. However, the damage constitutive models proposed in the past usually contained many parameters which were difficult to calibrate. Moreover, if the tensor damage variable is applied, the calculation cost becomes larger. That limits the application in the practical engineering.

Based on a simple damage constitutive model proposed by Faria, Oliver et al. [5,6], further improvement is proposed to make it more reasonable to describe the compression stiffness recovery effect of concrete under seismic cyclic load. Scalar damage variables are used and the heterogeneity
between tensile and compressive damage are considered. Meanwhile, some advantages of the model are still kept, such as less parameters, simple calibration, easy numerical implementation and high calculation efficiency. Based on the improved damage constitutive model, the user material subroutine UMAT was developed in Abaqus. And then the seismic response and damage analysis of Koyna concrete gravity dam are carried out. The analysis results show that the seismic damage has an important influence on the seismic response of concrete dam, and the applicability of this model is also verified.

2. Formulation of the damage model for concrete

2.1. Relationship of the stress and strain

According to the principle of continuum damage mechanics, the damage degree is described by damage variable \( d \). The relationship between Cauchy stress \( \sigma \) and effective stress \( \bar{\sigma} \) can be expressed as follows:

\[
\sigma = (1 - d) \bar{\sigma}
\]

(1)

Where the damage variable \( d \) is a scalar and its value ranges from 0 (no damage) to 1 (complete failure). The effective stress \( \bar{\sigma} \) represents the net stress actually borne by the concrete between the micro cracks. For the sake of simplification, the effect of plastic strain is not considered, so the effective stress is defined as:

\[
\bar{\sigma} = D_0 \varepsilon
\]

(2)

Where \( D_0 \) is the initial (undamaged) elastic stiffness of the material. \( \varepsilon \) is the total strain. By substituting (2) into (1), the stress-strain relationship can be obtained

\[
\sigma = (1 - d)D_0 \varepsilon = D \varepsilon
\]

(3)

Where \( D = (1 - d)D_0 \) denotes the degraded (damaged) elastic stiffness of the material.

2.2. Decomposition of the effective stress

In order to describe the behavior of concrete in tension and compression, the effective stress \( \bar{\sigma} \) is decomposed into tension and compression components. The tensile and compressive components are as follows:

\[
\bar{\sigma}^i = \sum \langle \bar{\sigma}^i \rangle p_i \varepsilon_i \text{, } \bar{\sigma} = \bar{\sigma}^t + \bar{\sigma}^c
\]

(4)

Where \( \langle \cdot \rangle \) is the Macaulay bracket \( (\langle x \rangle = (x + |x|)/2) \), \( p_i \) is the unit vector of the principal direction of the effective stress.

2.3. Evolution equations of the damage variables

The definition of tensile and compressive stress norm is introduced for describing the stress state [6]:

\[
\bar{\tau}^i = \sqrt{\langle \bar{\sigma}^i \rangle} D_0 \langle \bar{\sigma}^i \rangle \text{, } \bar{\tau} = \sqrt{3}(K\bar{\sigma}_8 + \bar{\tau}_8)
\]

(5)

Where \( \bar{\sigma}_8 \) is octahedral normal stress, \( \bar{\tau}_8 \) is octahedral shear stress, and \( K \) is a material parameter, which is defined as:

\[
K = \sqrt{2} \frac{1 - R_0}{1 - 2R_0}
\]

(6)

\( R_0 \) is the ratio of biaxial strength to uniaxial strength of concrete under biaxial equal pressure, whose value is usually in the range [1.16, 1.20].

The experiment of concrete shows that there is a stress threshold, before which the concrete maintains linear elasticity, and then it appears damage and goes into nonlinear stage. The definition of damage threshold in tension and compression is introduced as follows [5,6]:
\[ r_0^+ = \frac{f_t}{\sqrt{E}}, \quad r_0^- = \sqrt{\frac{2}{3}} \frac{R_u}{1-2R_0} f_0 \]  

(7)

Where \( f_t \) is the tensile strength, \( f_0 \) is the initial yield strength under compression, and \( E \) is the elastic modulus.

According to the typical shape of uniaxial tension curve, the evolution equation of concrete tensile damage is defined [6], as shown in equation (8); considering the shape characteristics of uniaxial compression curve, equation (9) is proposed as the evolution equation of concrete compressive damage.

\[ d^+ = 1 - \frac{r_0^+}{\bar{r}^+} \exp\left(A^+ \left(1 - \frac{\bar{r}^+}{r_0^+}\right)\right), \bar{r}^+ \geq r_0^+ \]  

\[ d^- = \frac{1}{1 + A^- \left(\frac{r^-}{r_0^-} - 1\right)}, \bar{r}^- \geq r_0^- \]  

(8)  

(9)

In equation (8), \( A^+ \) the model parameters of tensile damage evolution equation are introduced. In order to avoid mesh dependence of the results, the concept of fracture energy is introduced.

\[ A^+ = \left(\frac{G_f E}{l_c t_c^2} - 0.5\right)^{\frac{1}{2}} \geq 0 \]  

(10)

Where \( G_f \) is the tensile fracture energy of concrete, \( l_c \) is the characteristic width of the crack zone, and is related to the mesh. And \( A^- \), \( B^- \) are the model parameters of the damage evolution equation under compression.

2.4. Degradation variable of stiffness

In view of that the expression of stiffness degradation variable proposed [5] cannot consider the stiffness degradation of concrete from compression to tension, according to the study [8], the definition of stiffness degradation variable is as follows:

\[ d = 1 - (1 - d_0) (1 - s d_0) \]  

(11)

In equation (11), \( s \) is the stiffness recovery factor, and the value range is \([0,1]\), which is defined as:

\[ s = \begin{cases} 0, \hat{\sigma} = 0 \\ \frac{\sum \langle \hat{\sigma}_i t_i \rangle}{\sum \hat{\sigma}_i}, \text{other} \end{cases} \]  

(12)

Where \( \hat{\sigma}_i \) is the \( i \)th eigenvalue of effective stress \( \bar{\sigma} \).

3. Seismic analysis of the Koyna concrete dam

3.1. Finite element model and parameters

In the present study, the Koyna concrete gravity dam in India is taken as the analysis object. The geometry of the whole dam is shown in figure 1, and the finite element mesh is shown in figure 2.
Assuming that the dam body is fixed on the foundation, the seismic hydrodynamic pressure of the reservoir water is simulated by the added mass method, and the self-weight of the dam and the hydrostatic pressure of the reservoir water are applied in advance as two analysis steps in Abaqus. The model is the plane stress model. The 4-node plane stress element CPS4 in Abaqus is adopted, and the concrete model is implemented as user material subroutine UMAT. The recorded ground acceleration of Koyna earthquake is used as the input excitation, and the horizontal and vertical seismic waveforms are shown in figure 3 and 4. Rayleigh model is used as the damping model, and the damping ratio is 0.03. The material parameters of the model are shown in table 1. The tensile strength is increased considering the strain rate effect.

Table 1. Concrete material parameters of the Koyna dam

| $E$ (MPa) | $\rho$ (Kg/m$^3$) | $f_s$ (MPa) | $f_c$ (MPa) | $f_t$ (MPa) | $G_f$ (N/m) |
|-----------|------------------|--------------|------------|-------------|-------------|
| 31027     | 0.2              | 15           | 24.1       | 2.9         | 410         |
3.2. Result and discussion

The analysis results show that the tensile damage of Koyna dam mainly occurs under earthquake, and the evolution process of tensile damage of the dam under earthquake action is clearly shown in figure 5-7.

In figure 5, it can be found that due to the stress concentration, the cracks first occur at the slope change of the downstream face and the bottom of the upstream face of the dam body under the earthquake action; then the cracks gradually expand to the interior of the dam body, in which the cracks at the slope change of the downstream face at 4.29s expand downward obliquely; the two cracks fully develop at the maximum displacement response, i.e. 4.68s (as shown in figure 6), after that the cracks almost no longer spread. The cracking development at the end of the earthquake is shown in figure 7. The above crack propagation process and crack shape are consistent with the previous research conclusions, and are also similar to the actual earthquake damage of the dam [2-4].

The displacement time history of dam crest under earthquake action is shown in figure 8. It can be seen that the linear and nonlinear displacement responses of the dam crest are basically the same...
before 4s, but the difference is obvious due to the influence of crack propagation. At the peak, the crack causes the upper part of the dam to make an approximate rigid body swing, which leads to the larger nonlinear displacement response. Then, with the decrease of the earthquake action, the energy dissipation caused by the cracking makes the amplitude of the nonlinear displacement response of the dam smaller and the period longer.

Figure 8. Linear and nonlinear displacement responses of the crest

Figure 9 shows the displacement time history of dam crest under horizontal and vertical ground motions. The difference between the two curves is small. However, as shown in figure 10, there are some differences in the distribution of cracks in the dam.

Figure 9. Crest displacements under the horizontal only and bi-directional ground motions

Figure 10. Damage field of the dam under the horizontal ground motion at 10s
4. Conclusions
A simple damage constitutive model of concrete is developed. Taking Abaqus as the research platform, the seismic response and damage process of Koyna concrete gravity dam in India are analyzed. Through the analysis, it can be found that, the nonlinear damage effect of concrete under seismic action has an important impact on the seismic response, the damage can significantly change the seismic dynamic behavior of the dam.

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