SEISMIC SAFETY EVALUATION OF CONCRETE DAMS USING DAMAGE MECHANICS APPROACH

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ABSTRACT:

Concerns on the seismic safety of concrete dams have been growing in recent years, This is partly because the population at risk in locations downstream of major dams continues to expand. Also it has increasingly become evident that the seismic design concepts in use at the time when most existing dams were build are inadequate. In this article, an anisotropic damage mechanics approach in Gaussian point level is introduced which models the static and dynamic behavior of mass concrete in 3D space. The proposed numerical model is able to consider non-uniform cracking within the cracked element in Gaussian points. The validity of the proposed model is considered using available experimental and theoretical results. The Morrow Point dam is analyzed including dam-reservoir interaction effects to consider the nonlinear seismic behavior of the dam. It is found that the resulting crack profiles are more localized than those resulting from the smeared crack approach. It can be concluded that the proposed damage mechanics model can be readily used in nonlinear static and dynamic analysis of complex structures and enables engineers to define the damage level of structures.

KEYWORD: Concrete dams, Dam-reservoir interaction, Damage mechanics, Dynamic analysis, Non-uniform cracking

1. INTRODUCTION

Seismic failure of concrete dams can be disastrous due to sudden release of reservoir water. Although there is no report indicating such failure, safety evaluation of dams using various linear and nonlinear models is an important issue for owners, designers and executors. The safety evaluation procedure generally contains the following steps:

- Evaluating the maximum credible earthquake, MCE
- Selecting an appropriate numerical environment for solving the system
- Selecting an appropriate model to simulate the linear and the nonlinear behavior of the system under the static and dynamic loads

In the study represented by Ghrib and Tinawi (1995a, b), the damage mechanics theory was developed to model the static and dynamic behavior of mass concrete in 2D space. Gunn (2001a, b) used the damage mechanics theory in 3D space for analyzing concrete structures under the static loads. Several investigators such as Hall (1998), Malla and Wieland (1999), Espandar and Lotfi (2003), Lotfi and Espandar (2004) and Mirzabozorg and Ghaemian (2004) have represented models based on the smeared crack approach to study the nonlinear behavior of mass concrete in 3D space.

In the present study, an approach based on the damage mechanics model is presented so that the cracking within an element is non-uniform. This means that cracks in the candidate element propagate within the Gaussian points. The major efficiency of the proposed numerical model is the ability of more accurate tracing crack paths within the dam body and therefore, reducing time and saving analysis requirements.

The main aspect of the damage mechanics theory is to define the damage level of the cracked elements which can be used as an index for safety assessment of concrete dams. By obtaining the damage indices of the cracked

Gaussian points using the damage mechanics approach, the designer can identify the performance level of the structure using given quantitative criteria (USACE (2005)).

2. CONSTITUTIVE LAW

The stress-strain relationship within the pre-softening phase and also, the softening initiation criterion are given in Mirzabozorg and Ghaemian (2005). The softening initiation criterion is based on the elastic uni-axial energy of the considered Gaussian point.
During the softening phase, when a Gaussian Point initiates softening, its elastic stress-strain relationship is replaced using the modulus matrix which is formulated based on the damage level in each of the three principal directions. Based on the energy equivalence principle and neglecting the coupling between the three principal fracture modes, the modulus matrix is given as (Gunn (2001a)):

$$[D]_d = \begin{bmatrix} [D]_d^t & 0 \\ 0 & [D]_d^r \end{bmatrix} \tag{1}$$

where,

$$[D]_d^t = \frac{E}{(1+\upsilon)(1-2\upsilon)} \begin{bmatrix} (1-\upsilon)(1-d_1)^2 & \upsilon(1-d_1)(1-d_2) & \upsilon(1-d_1)(1-d_3) \\ \upsilon(1-d_1)(1-d_2) & (1-\upsilon)(1-d_2)^2 & \upsilon(1-d_2)(1-d_3) \\ \upsilon(1-d_1)(1-d_3) & \upsilon(1-d_2)(1-d_3) & (1-\upsilon)(1-d_3)^2 \end{bmatrix} \tag{2}$$

$$[D]_d^r = \begin{bmatrix} \gamma_{12}G & 0 & 0 \\ 0 & \gamma_{23}G & 0 \\ 0 & 0 & \gamma_{13}G \end{bmatrix} \tag{3}$$

in which,

$$\begin{aligned} \gamma_{12} &= \frac{2(1-d_1)^2(1-d_2)^2}{(1-d_1)^2+(1-d_2)^2} \\ \gamma_{23} &= \frac{2(1-d_2)^2(1-d_3)^2}{(1-d_2)^2+(1-d_3)^2} \\ \gamma_{13} &= \frac{2(1-d_1)^2(1-d_3)^2}{(1-d_1)^2+(1-d_3)^2} \end{aligned} \tag{4}$$

where d_1, d_2 and d_3 are the damage variables corresponding to the principal strains in the local directions. Satisfying the principle of energy equivalence and assuming linear stress-strain curve in the post-peak phase, d_i is given as:

$$d_i = 1 - \sqrt{\frac{\varepsilon_0}{\varepsilon_i} - \left(\frac{\varepsilon_i - \varepsilon_0}{\varepsilon_f - \varepsilon_0}\right) \cdot \frac{\varepsilon_0}{\varepsilon_i}} \tag{5}$$

where ε_o and ε_f are the stains corresponding to the crack initiation and no resistance strain, respectively and ε_i is the principal strain of the element in the considered direction.

The proposed modulus matrix given in Eqn. (1) is in local coordinate which is corresponding to the direction of the principal strains. This matrix should be transformed to the global coordinate as follows:

$$[D]_S = [T]^T [D]_d [T] \tag{6}$$

where, $[T]$ is the strain transformation matrix. Clearly, increasing of the strain of the considered Gaussian point leads to increasing the corresponding damage variable and finally, when the strain reaches to the fracture strain, the Gaussian point is fully cracked in the corresponding direction and the related damage variable sets to be unit. Satisfying the fracture energy conservation principle in the static and dynamic loading conditions, the no resistance strain is given as:

$$\varepsilon_f = \frac{2G_f}{\sigma_0 h_c} \quad \text{and} \quad \varepsilon'_f = \frac{2G'_f}{\sigma'_0 h_c} \tag{7}$$

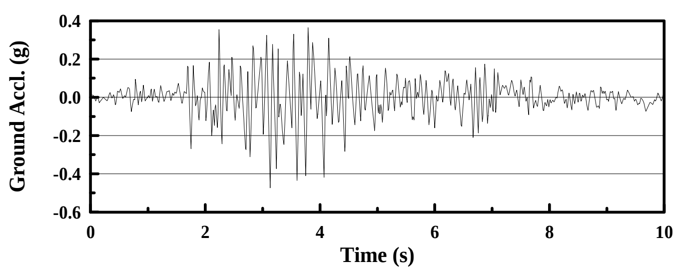
where, h_c is the characteristic dimension of the cracked Gaussian point and is assumed equal to the third root of the Gaussian point's contribution volume within the cracked element. The primed quantities show the dynamic constitutive parameters. The strain-rate sensitivity of the specific fracture energy is taken into account through the dynamic magnification factor DMF_f as follows:

$$G'_f = DMF_f \, G_f \tag{8}$$

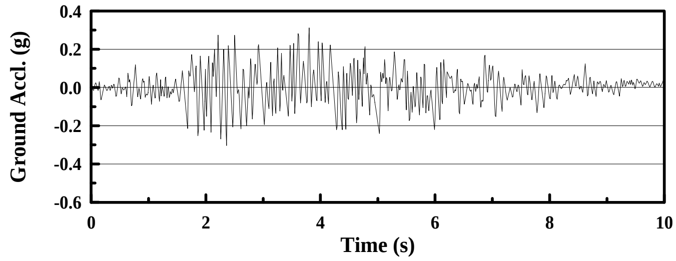
In the proposed formulation, **C**o-axial **R**otating **C**rack **M**odel (CRCM) is used to model the behavior of the cracked Gaussian points within the cracked elements and the crack opening and closing criterion is based on the principal strains.

3. SEISMIC ANALYSIS OF KOYNA DAM

Koyna dam in India is a classic example which has been used by several investigators as a benchmark for seismic analysis of gravity dams (Ghrib and Tinawi (1995), Mirzabozorg and Ghaemian (2005)). The 3D unit-thickness finite element model of the tallest block includes 520 20-node iso-parametric elements and 3858 nodes. The upstream face is assumed vertical which has a negligible difference with the actual dam body. The modulus of elasticity, Poisson's ratio, the unit weight, the tensile strength and the specific fracture energy are taken as 31.027GPa, 0.2, 25.920KN/m^3, 1.5MPa and 150N/m, respectively. The dynamic magnification factor applied on the tensile strength and the specific fracture energy is 1.2. The two components of Koyna earthquake in 1967 are used to excite the system in the upstream-down stream and the vertical directions. These components are shown in Figure 1.



(a)



(b)

Figure 1: Ground motion recorded at Koyna dam, Koyna earthquake 1967;
(a) Stream component; (b) Vertical component

The time integration step is 0.001s. At the first step, the self weight and the hydrostatic loads are applied on the model. There is not any cracked element at the end of this stage. In the second step, dynamic analysis is conducted. The **Q**uasi **L**inear **D**amping mechanism (QDM) is used in dynamic equations.
In Figure 2, the time history of the crest displacement in the upstream-downstream direction is compared with that resulted from the smeared crack approach (Mirzabozorg et al. (2007)) and the linear response of the system. There is not any numerical instability during the conducted dynamic analysis. The resulted crack profiles within the three parallel planes through the thickness of the model are shown in Figure 3. There is excellent agreement between the resulted crack profiles with that obtained from the experimental work and the other available reported theoretical results (Mirzabozorg et al. (2007)).

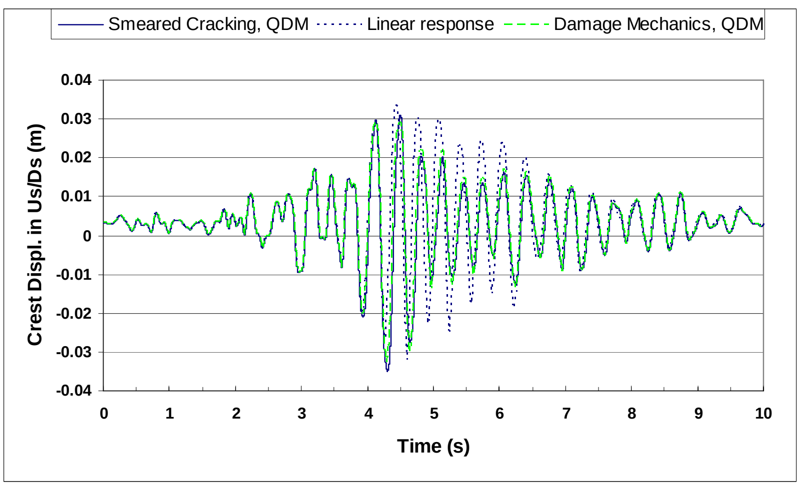
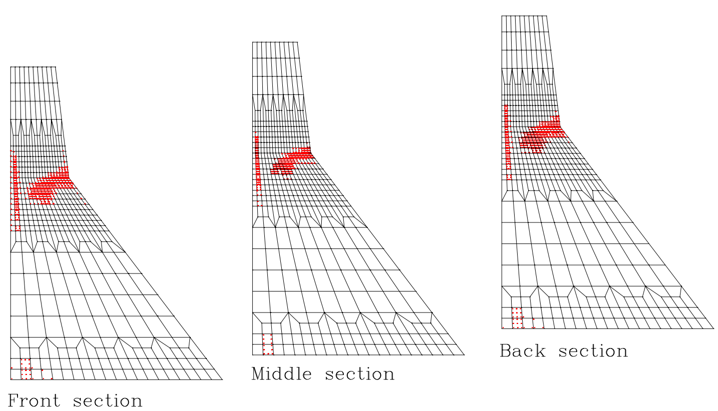
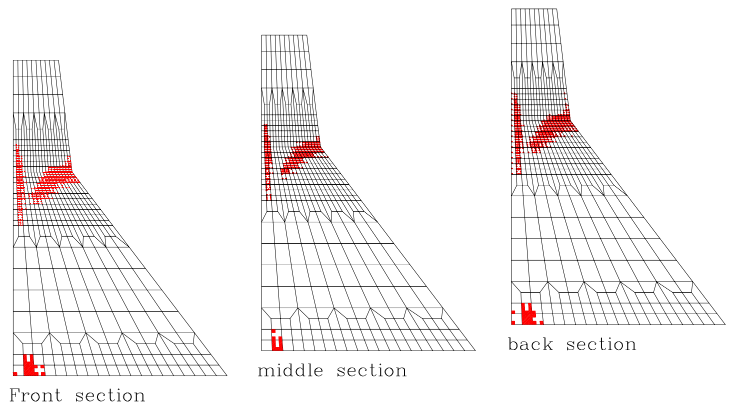


Figure 2: Crest displacement time history of Koyna dam



(a)

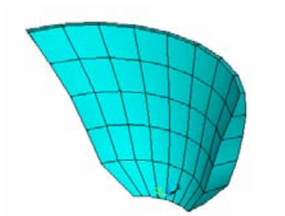


(b)

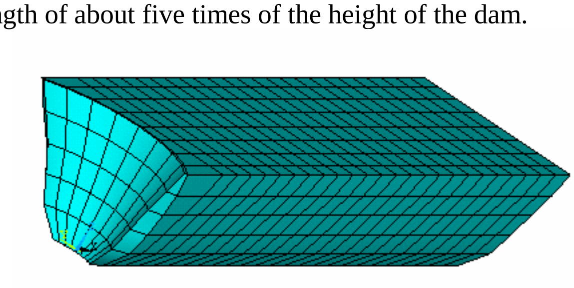
Figure 3: Crack profiles within the dam body;
(a) Damage mechanics approach; (b) Smeared crack approach (Mirzabozorg et al. (2007))

4. NONLINEAR SEISMIC ANALYSIS OF MORROW POINT DAM

The considered dam has been constructed on Gunnison River in Colorado in a U-shape valley during 1963 to 1968. The height of the dam, the radius of curvature at the crest level and the crest length of the dam are 145.74m, 114.3m and 220.67m, respectively. The thickness of the central block is 3.66m at the crest level and 15.85m at the foundation level. Figure 4 shows the considered system which includes the finite element model of the dam body and the reservoir with the length of about five times of the height of the dam.



(a)



(b)

Figure 4: FEM of the dam-reservoir system with rigid foundation;
(a) Dam body; (b) Coupled dam-reservoir system

The dam body is modeled using 40 20-node iso-parametric solid elements and the reservoir model includes 1000 8-node fluid elements. The modulus of elasticity, Poisson's ratio, the unit weight, the true tensile strength and the ratio of the apparent to the true tensile strength, the specific fracture energy and the dynamic magnification factor are 27.604MPa, 0.2, 24027.15N/m^3, 2.5MPa, 1.25, 200N/m and 1.30, respectively. The pressure wave propagation speed within the reservoir and the unit weight of the water are 1436m/s and 9807 N/m^3, respectively. The wave reflection coefficient is taken as a conversational value of 0.8. The system is excited using the three components of the Taft earthquake on July 21, 1952 recorded at the Lincoln Tunnel School, shown in Figure 5.

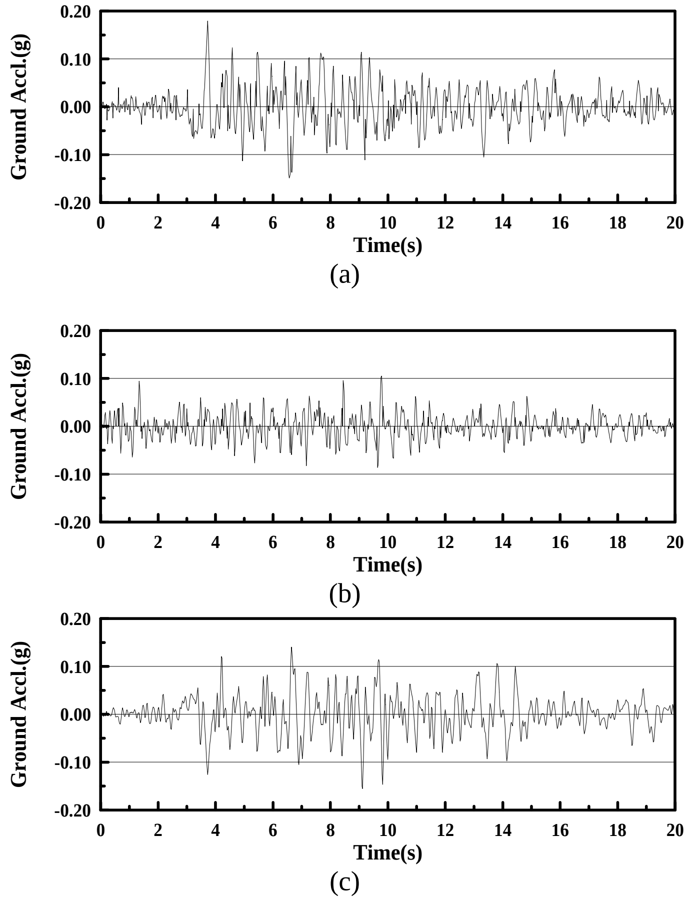
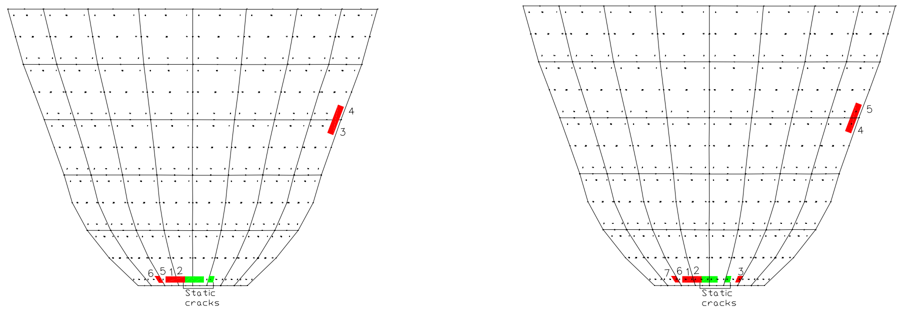


Figure 5: Ground motion recorded at Taft Lincoln School Tunnel, California earthquake 1952;
(a) Stream component; (b) Cross stream component; and (c) Vertical component

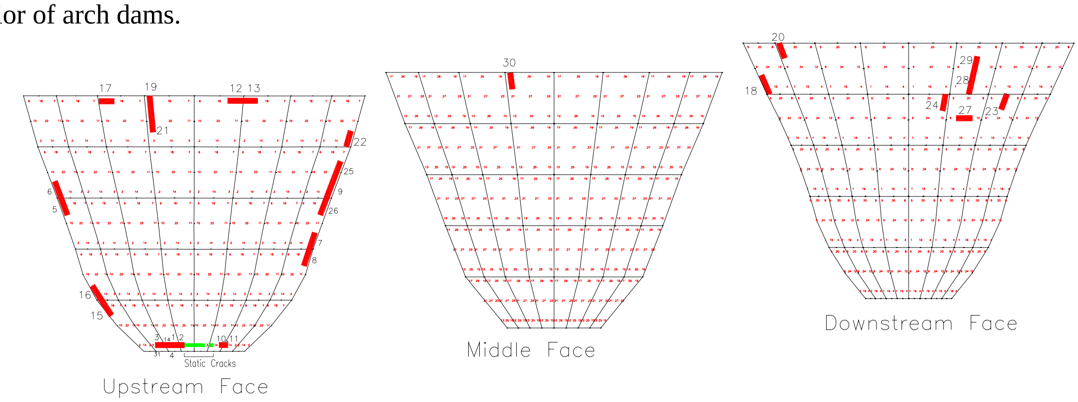
Applied loads on the system are the self weight, the hydrostatic pressure and the seismic load. The system is analyzed using the staggered displacement method (Mirzabozorg et al. (2003)). The time integration step is 0.001s and the quasi linear damping mechanism is used to model the energy dissipation due to the damping.
At the first step, the dam body cracked at the heel due to the self-weight and the hydrostatic load as shown in Figure 6. The initial crack profile, resulted from applying the static loads, propagates on the upstream face when the system excited using the three components of the earthquake record. At the end of the analysis, there are just two positions on the upstream face in which cracks propagate. Other sections through the thickness of the dam body experience no cracks. Clearly, because of few cracked Gaussian points within the dam body, the cracked elements do not affect the crest response of the dam body and the crest displacement time history is the same as that resulted from the linear analysis. In addition, as shown in Figure 6, there are just negligible differences between the results obtained from the damage mechanics approach and the smeared crack approach proposed by the authors (Mirzabozorg et al. (2007)).



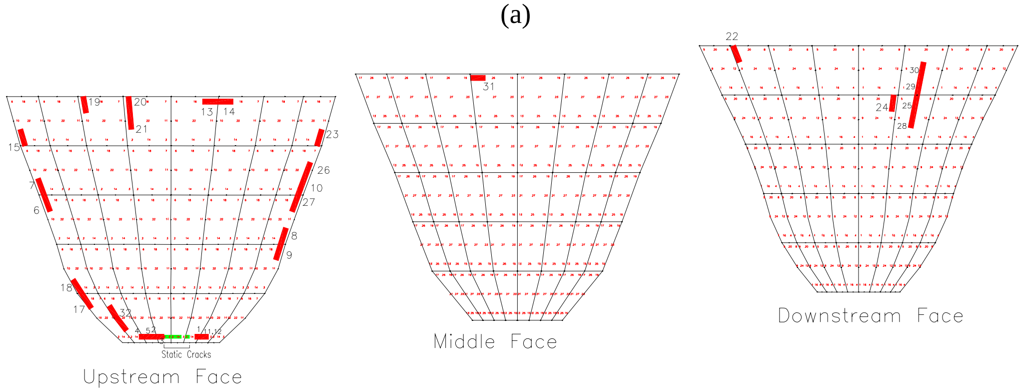
(a) (b)

Figure 6: Cracked elements on the upstream face of dam body including cracking sequence; (a) Damage mechanics approach; (b) Smeared crack approach (Mirzabozorg et al. (2007))

At the last step, the system is excited using the earthquake components scaled by a factor of 1.7 after applying the static loads, to compare with the same analysis reported in Mirzabozorg et al. (2007). Figure 7(a) shows the resulted crack profiles in detail within the dam body. Figure 7(b) shows the crack profiles reported in Mirzabozorg et al. (2007) in which the smeared crack approach is used. As shown, the resulted crack profiles for both models are in excellent agreement and both of them are in good agreement with the common seismic behavior of arch dams.



(a)



(b)

Figure 7: Cracked Gaussian points within the dam body including cracking sequence, due to applying the static and the scaled seismic loads by 1.7; (a) Damage mechanics approach; (b) Smeared crack approach (Mirzabozorg et al. (2007))

Similar to the gravity dams, there are acceptable criteria for safety evaluation of arch dams which are based on the **D**emand-**C**apacity **R**atios (DCRs) and cumulative inelastic duration within the dam body (USACE (2005)) using the damage mechanics approach, the overstresses regions can be estimated more accurately and therefore, judgment about the safety of the considered system can be more realistic.

5. CONCLUSIONS

A 3D damage mechanics model was presented which is able to simulate cracking in the Gaussian point level. Dynamic analysis of Koyna dam using the proposed method shows that the pertinent numerical algorithms and the proposed model is stable in the dynamic conditions and gives excellent results when compared with the experimental and the other numerical results.

The Morrow Point dam was analyzed under the static and dynamic loads. The conducted analysis includes the dam-reservoir interaction. It was found that the resulted profiles within the dam body can be studied in detail and the crack propagation can be traced within the three layers of each element. Clearly, crack tracing through the thickness of the dam body in arch dams is a significant task in terms of both the dam safety evaluation and the dam design stage. In addition, the stability of the proposed method is excellent because of gradual change in the stiffness matrix of the finite element model due to Gaussian point cracking instead of element cracking. The other aspect of the proposed damage mechanics approach is its ability to identify a damage index to the cracked dam body which is a significant factor in dam safety assessment based on the recent safety criteria.

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