Seismic Performance Evaluation of Concrete Gravity Dams by Using Pseudo Dynamic Testing and Simulations

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Abstract

Dams are one of the most important infrastructure components serving for water storage and energy production. Experimental studies on the seismic response of concrete gravity dams are scarce due to the complications regarding the large scale of dams and their interaction with the reservoir. This study presents the results of recent novel pseudo-dynamic dam tests (PSD) along with the nonlinear finite element simulations of the specimens. The test specimens were 1/75 scaled version of the highest monolith of a 124 m high concrete gravity dam in Turkey. Specimens were constructed with conventional concrete (CVC) and roller compacted concrete with different compressive strength values. They were subjected to three subsequent ground motions followed by static pushover tests. It was found that the dam was expected to sustain significant base cracking, while retaining its integrity under the most credible earthquake scenario. The specimen with the lowest compressive strength failed through the formation of an inclined crack showing the importance of concrete tensile strength on the seismic response of concrete gravity dams. Numerical simulations were able to estimate the global demand parameters (i.e. base shear force and crest displacement), however crack estimations were significantly dispersed compared to the actual crack patterns.

Keywords: numerical simulation, gravity dam, cracking, demand

1. INTRODUCTION

From the beginning of 1930's, many studies have been carried out to understand the seismic behaviour of gravity dams especially under the effect of ground excitations (see for example Westergaard 1933, Hatanaka 1955, Kuo 1982, Fenves and Chopra 1984, Tinawi et. .al. 2000, Wang and Chopra 2010). Important challenges in this process of design and analysis of dams have been: i- simulating an extremely complex interaction problem of dam-reservoir-foundation, ii- establishing design performance criteria to maintain the functionality of dams for sustainability and iii- reducing the risk associated with complete or partial collapse. In literature, the first attempts on dam research dates back to Westergaard (1933) who were to estimate the earthquake forces on dams, which is still in use by some dam engineers. This concept was later updated by Kuo (1982) to eliminate the upstream geometry restrictions. Chopra and his colleagues (Fenves and Chopra 1984, Wang and Chopra 2010) contributed significantly to the dam-reservoir-foundation interaction problem by developing both two and three dimensional computational models, mostly being in the frequency domain, to solve the seismic response of the dam-reservoir foundation systems under the influence of multi-directional ground motions.
In the literature, there were some studies to observe the seismic behaviour of gravity dams experimentally (Hatanaka 1955, Niwa and Clough 1980, Donlon and Hall 1991 and Harris et al 2000, Uchita et al 2005, Mridha and Maity 2014). Most of the experiments were conducted by using a shake table on scaled gravity dam sections. The evidence from these tests are usually used as benchmark to calibrate the numerical models that can be employed for design. The use of appropriate numerical tools for the seismic performance estimation of dams is extremely important due to the fact that i- there is a very limited number of concrete dams subjected to strong ground motions to quantify actual performance and make a judgement based solely on observed behaviour and ii- the number of experimental studies on dams is quite limited to reach a decisive conclusion on their performance by using an experimental database. Consequently, numerical simulations play a crucial role in seismic design of dams. Design engineers, when employing nonlinear models for dam analysis are usually unaware of the accuracy of their models in predicting displacements, strains, crack lengths, etc.

In this study, numerical analyses of a recently performed innovative experiment on three scaled gravity dam specimens (Aldemir et. al. 2015) were conducted. The scaled dam specimens were tested by a novel using pseudo-dynamic loading system under the effect of three consecutive ground excitations. The first specimen was made from conventional concrete (CVC) and the other two specimens were made up of roller compacted concrete (RCC) with different compressive strengths. For brevity, the details on the experiments are summarized followed by the explanation of the computational approach and comparisons of results in terms of load – deformation and cracking response.

2. SPECIMENS AND GROUND MOTIONS

A 1/75 scaled version of 120 meter-high Melen Dam, being built for water supply and energy generation purposes in the North West of Turkey, is utilized for this study. This prototype dam is composed of monoliths of 15m width. The geometrical properties of the tallest section of the dam along with the scaled specimen are shown in Fig. 1. The spectrum compatible ground motions were developed based on the site-specific design response spectrum used in the actual design of the dam body (Akkar 2010) for three different seismic hazard levels, namely the Operational Based Earthquake (OBE), the Maximum Design Earthquake (MDE) and the Maximum Characteristic Earthquake

(MCE) levels. The peak ground acceleration of the ground motions OBE, MDE and MCE were 0.11g, 0.16g and 0.33g, respectively. The original time histories were compressed in time by a factor of $1/\sqrt{75}$ to account for the effects of scaling with respect to similitude law (Bertero et al. 1984 and Elkhoraibi and Mosalam 2007). The response spectra of both the unscaled and scaled ground motions are presented in Fig 2. The compressive strengths of CVC, RCC1 and RCC2 specimens were 24.95MPa, 15.6MPa and 23.1MPa, respectively. The complete details of the employed continuous pseudo-dynamic dam testing scheme can be found in Aldemir et. al. (2015). The idea was inspired from the equivalent single degree of freedom approach of Fenves and Chopra (1984). The dam model was converted into an equivalent single degree of freedom and the displacement was imposed from an effective height such that both hydrostatic and dynamic effects could be represented. Significant calibration efforts were placed prior to the pseudo dynamic testing as discussed by Aldemir et. al. (2016). After the successful completion of the pseudo dynamic tests, a static pushover test was conducted in order to determine the reserve capacity after motions. The results of the tests are presented in Section 4 and 5 along with the numerical results.

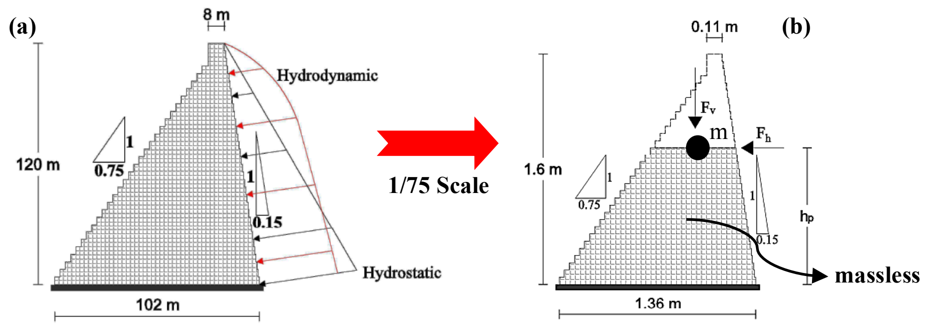

Fig. 1 Models used in Tests : (a) Prototype Dam and (b) Scaled Dam Specimen

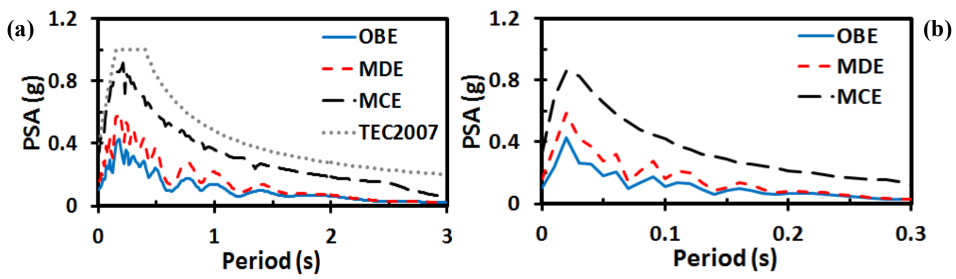

Fig. 2 (a) Unscaled and (b) Scaled Spectra for OBE, MDE and MCE

3. DETAILS OF THE NUMERICAL MODELS

The specimens were modelled by using polynomial based 8 node 3D solid elements with cracking capability up to three directions within a fixed crack framework. ANSYS (2010) platform was used to model and analyze the test specimens dynamically by using an implicit time integration scheme. Softening function in ANSYS was adjusted to approximately match the fracture energy of concrete in tension. The tests showed that the base flexibility must be modelled appropriately in order to match the wave form of the measured response as discussed by Tinawi et al (2000). For this purpose, the dam base was assumed to be fixed while the increased flexibility due to base and foundation rotations was incorporated by reducing the modulus of elasticities of each specimen. In this way, the first fundamental period of the numerical model was matched with the experimentally determined period at the beginning of OBE test. The utilized reduced modulus of elasticity values were 10,500MPa, 8,750MPa and 13,500MPa, which corresponded to a reduction of about 60% for specimens 1, 2 and 3, respectively. In addition, the uniaxial tensile strength of all specimens was used as 80% of their determined split tensile strength suggested by Raphael (1984) along with the measured cylindrical compressive strengths. First, the vertical loads to simulate the axial stresses on the prototype dam were applied on the specimens in the numerical models and then the OBE, MDE and MCE EQ's were applied with an implicit integration scheme subsequently. Then, each specimen was pushed over by conducting an incremental static analysis to obtain the full capacity curves similar to the procedure employed during experiments.

4. COMPARISON OF RESULTS

The comparisons of the base shear-tip displacement histories of specimens are presented in Fig. 3-5. The comparisons of pushover curves are given in Figure 6.

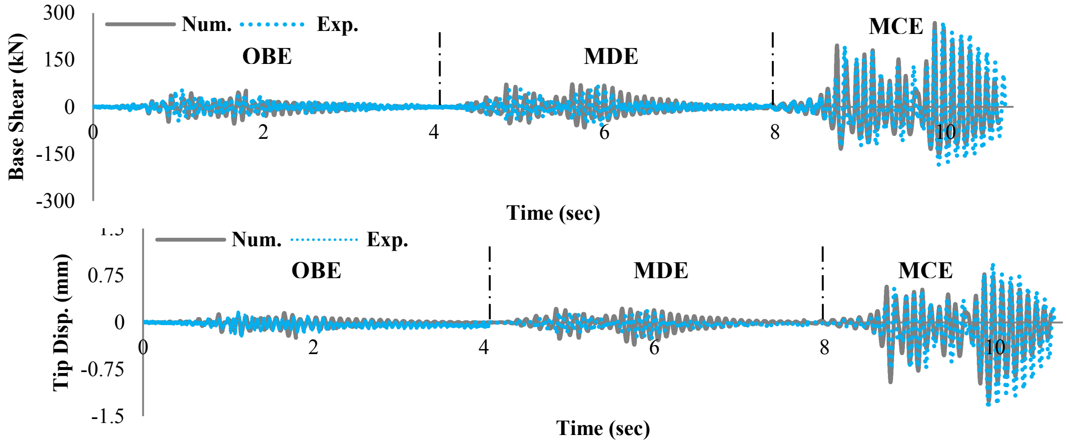

Fig. 3 CVC Specimen : Comparison of (a) Base Shear and (b) Tip Displacement Histories for OBE, MDE and MCE

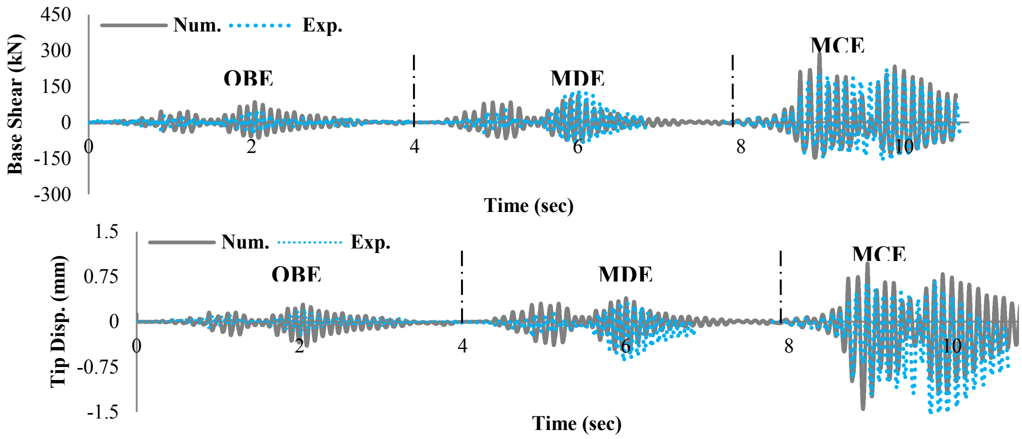

Fig. 4 RCC1 Specimen : Comparison of (a) Base Shear and (b) Tip Displacement Histories for OBE, MDE and MCE

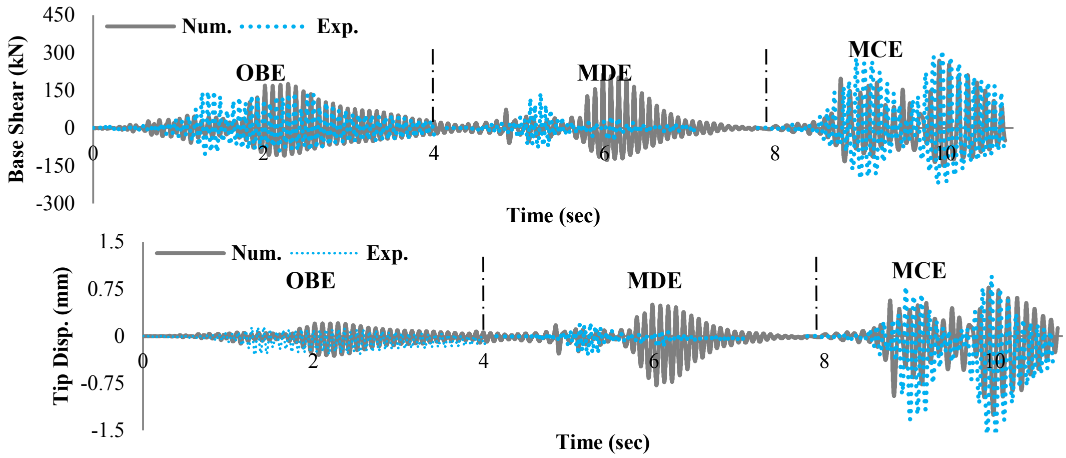

Fig. 5 RCC2 Specimen : Comparison of (a) Base Shear and (b) Tip Displacement Histories for OBE, MDE and MCE

The performance of the numerical model in estimating the maximum and minimum base shear demands was observed to be acceptable, with less than 10% error (Fig. 3-5) for specimens CVC and RCC1. For specimen RCC2, the error in the base shear demand was underestimated for the MDE motion, while estimations for OBE and the MCE were reasonably accurate as can be seen from the base shear-time response curves. On the other hand, the crack lengths were mostly overestimated by the numerical model (Fig. 7-9) for motions OBE and MDE, whereas the crack length estimations were acceptable for the most demanding earthquake scenario MCE. For MCE, the estimated maximum base crack length was similar to that observed from the test.

The pushover analysis results presented in Figure 6 demonstrate that the stiffness, ultimate capacity and deformation capacity of the specimens were estimated with a good accuracy. For specimen RCC1, sudden brittle shear failure due to inclined cracking was also captured by the numerical model.

In the numerical model, it was observed that the cracks started to spread more around the previously opened cracks, which resulted in considerably more smeared cracking than the actual cracks at the final stages especially during pushover tests (Fig. 7-9). The analysis case with the most crack dispersion was that of specimen RCC1 (Figure 8). The severe inclined crack observed in the test was simulated as dispersed cracking of the full dam body. This phenomenon was due to the deficiency of the smeared crack models. In the smeared crack models, the nature of crack could not be modeled correctly due to the lack of physical opening and separation. Furthermore, the continuous polynomial based shape functions cannot represent the stresses around the actual crack regions. This shortcoming forced the neighbor elements to easily crack due to the unavoidable redistribution of the stresses from the readily damaged (cracked) ones. Instead, in the tests, the behavior around the cracks were in the form of an opening and closing of a single discontinuity.

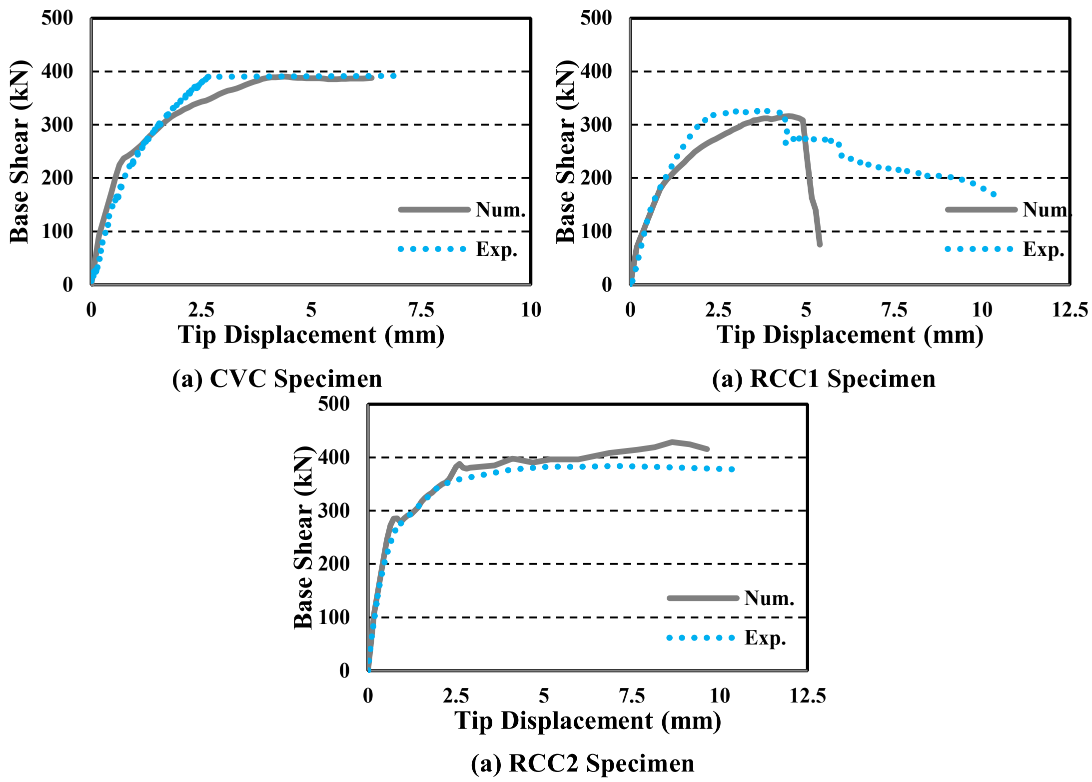

Fig. 6 RCC2 Specimen : Comparison of (a) Base Shear and (b) Tip Displacement Histories for OBE, MDE and MCE

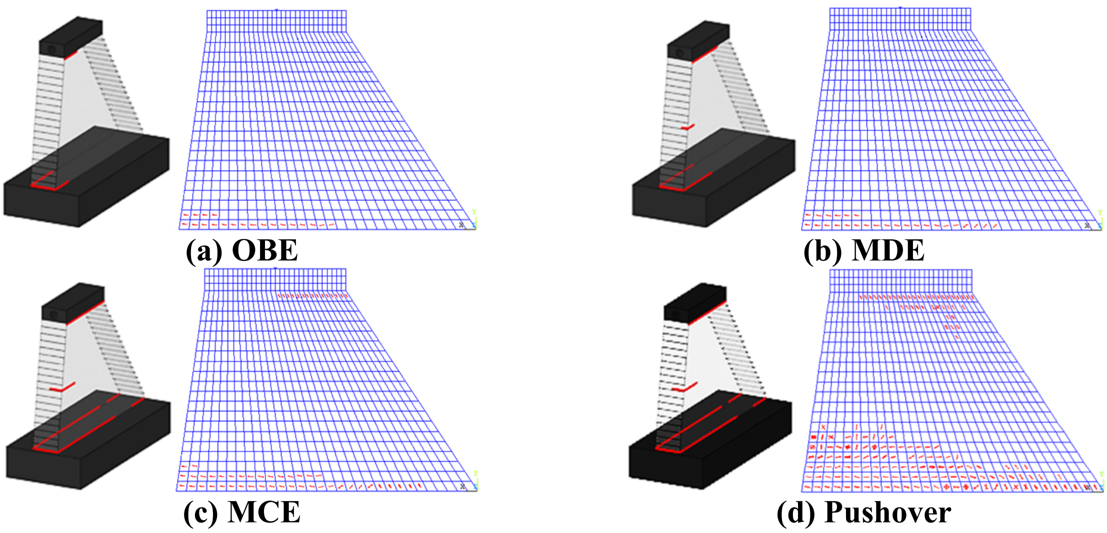

Fig. 7 CVC Specimen : Comparison of Crack Patterns (a) OBE, (b) MDE, (c) MCE and (d) Pushover experiment

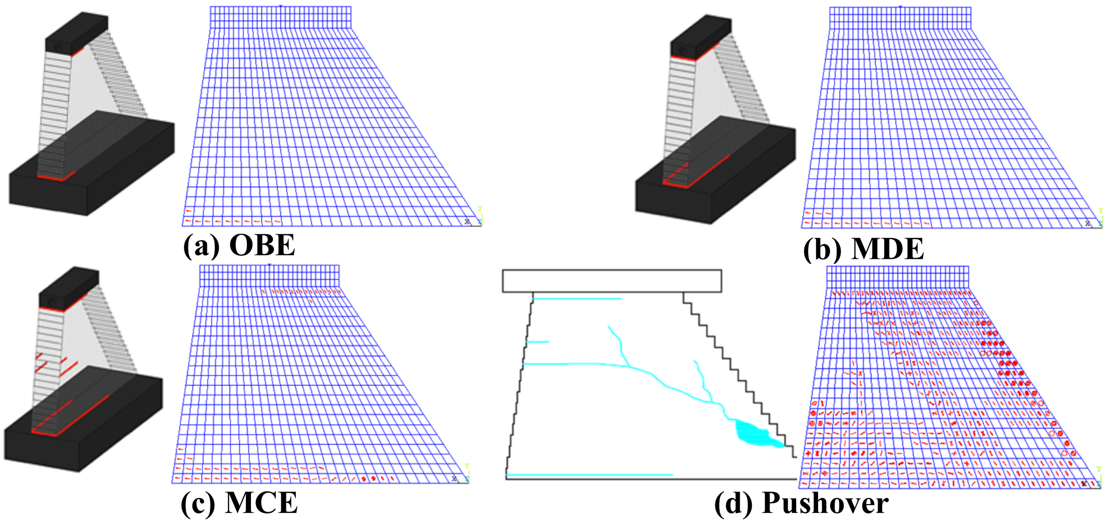

Fig. 8 RCC1 Specimen : Comparison of Crack Patterns (a) OBE, (b) MDE, (c) MCE and (d) Pushover experiment

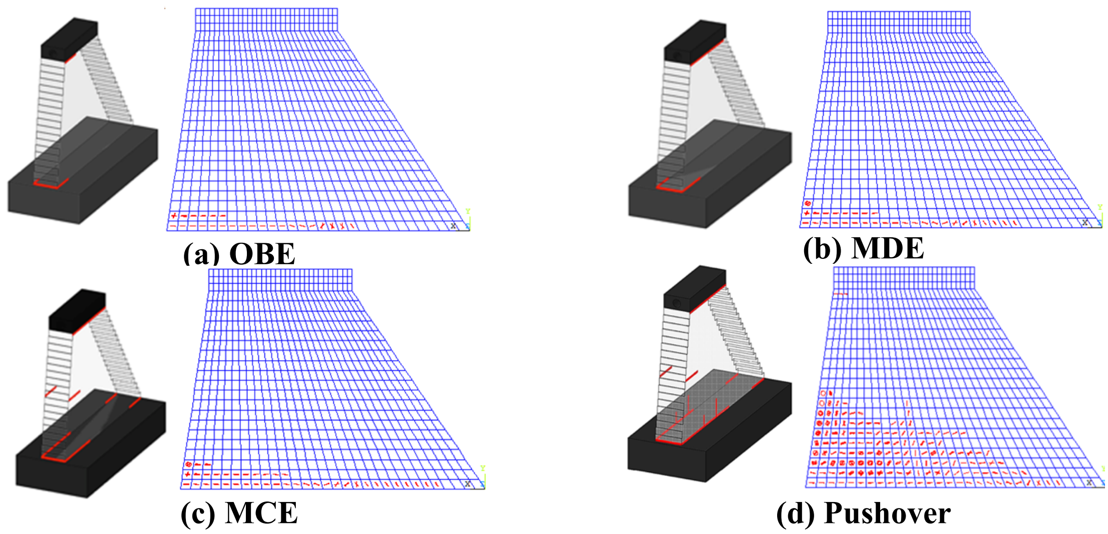

Fig. 9 RCC2 Specimen : Comparison of Crack Patterns (a) OBE, (b) MDE, (c) MCE and (d) Pushover experiment

5. CONCLUSION

In this study, the results of a numerical modeling strategy are presented and compared with the monitored base shear response, tip displacement histories, the static capacity curves and the observed crack patterns. The numerical method was successful in estimating the global seismic demand parameters such as the base shear force, the tip displacement, the static capacity curve and the dam failure displacements. This result shows that classical smeared crack based finite element analysis can be used with confidence for such evaluations. However, the crack lengths were mostly overestimated by the numerical model except the most demanding earthquake scenario, MCE. Numerical model estimated a more dispersed crack pattern and a larger damage zone compared to the observed singular ones. This phenomenon was due to the deficiency of the smeared crack models along with the use of classical finite element approach. The key outcomes from this research are: i- Standard nonlinear finite element approaches to model dam seismic response appear to be useful tools in estimating global response parameters, ii- the numerical model results on the crack lengths widths and damage zones should be evaluated carefully without placing too much confidence at the design and evaluation stages. Other approaches such as the discrete element methods, extended finite elements or discrete cracking models could be preferred for a better evaluation of crack related parameters.

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