Seismic Design and Performance of an High RCC Dam

A. Aldemir, U. Akpınar, Y. Arıcı & B. Binici
Middle East Technical University, Ankara, Inonu Bulvari, 06531, TR.

SUMMARY:
In this paper, a three-stage analysis-design approach is presented for a 141-m-high RCC dam, (Andıraz Dam) planned to be constructed in Turkey. First, 2D nonlinear time history analyses (THA) were conducted to estimate the locations of possible cracking based on a smeared rotating crack approach within the framework of the finite element method. In the second stage, 3D finite element analyses were conducted considering the dam-foundation interaction under the application of bi-directional earthquake motions. The earthquake performance was checked based on the available time-stress criterion given by USACE-EM-1110-2-6051. Finally, 3D nonlinear THA's were conducted under the action of three-directional earthquake effects and the required zones of high tensile strength were determined to obtain an acceptable pattern of base cracking. The results show that the use of 2D model may not necessarily result in safe designs and 3D effects need to be considered for accurate performance estimation for RCC dams built without transverse joints in relatively long valleys.

Keywords: Stability, 2D Analysis, 3D Analysis and RCC Dam

1. INTRODUCTION

1.1 General

The ease and speed of construction, the reduction in the quantity of cement used, and the corresponding decrease in the heat of hydration are the primary advantages that led to an increased use of RCC in dam construction. When fly ash or pozzolans are available nearby the construction site, the use of RCC results in a much more economical solution for a dam compared to the placement of conventionally vibrated concrete (CVC).

The behaviour of dams, especially under the effect of seismic actions, is one of the most complicated problems in earthquake engineering. Dams usually rest on flexible foundations, which necessitates taking the soil – structure interaction into account. Complex geometry of the valley and the dam necessitate considering higher mode effects along with the dam reservoir interaction. A number of different linear elastic boundary element and finite element procedures were proposed in the literature to analyze the three dimensional dam-foundation-reservoir interaction problem rigorously (see for example Chopra Wang (2008), Medina and Dominguez (1999) among others)

Gravity dams are usually analyzed as two dimensional plane stress problem owing to the use of transverse joints or as plane strain for dams lying on long valleys. However for dams on relatively short valleys and/or RCC dams built without any transverse joints may require special care as the applicability of two dimensional analyses may not be realistic. It is apparent that the aforementioned remedies are difficult to apply in 3D models. This study compares the different analysis methodologies and their results, by mainly focusing on a case study dam. This RCC dam is planned to be built in Kastamonu, Turkey, which is nearly 10-km far from the seismically very active fault, North Anatolian Fault. Therefore, it is in a very high seismic risk and the design is governed by the seismic actions. In this work, we discuss the seismic analyses conducted within the framework of Andıraz Dam design. First, seismicity of the region is briefed followed by the nonlinear two and three dimensional finite elemet analyses results. Then, the expected cracking of the dam is discussed and a design alternative with zones of grout enriched higher strength RCC is proposed. Results presented in this work provide an opportunity to compare the two dimensional and three dimensional nonlinear analyses results. We uncover the importance of 3D nonlinear modeling for the damage estimation of gravity dams built in relatively narrow valleys without transverse joints, and support the conclusions of Rashed and Iwan (1984), who first stated the importance of 3D modeling for short gravity dams.

2. ANALYSIS PARAMETERS

2.1 Local Seismic Risk Results

Andıraz Dam is located in a seismically very active region (the first seismic zone defined by Turkish Earthquake Code 2007 (TEC2007)). Therefore, the earthquake – induced effects are very critical in the design process. The spectrum compatible ground motions were developed after determining the site specific design response spectrum (Akkar, 2011). For this purpose, three different design earthquake levels were selected: Operational Based Earthquake (OBE), Maximum Design Earthquake (MDE) and Maximum Characteristic Earthquake (MCE). The site specific design spectrums of these earthquake scenarios are shown in Figure 1. Three synthetic ground motions for each three level of hazards are generated and shown in **Error! Reference source not found.**.

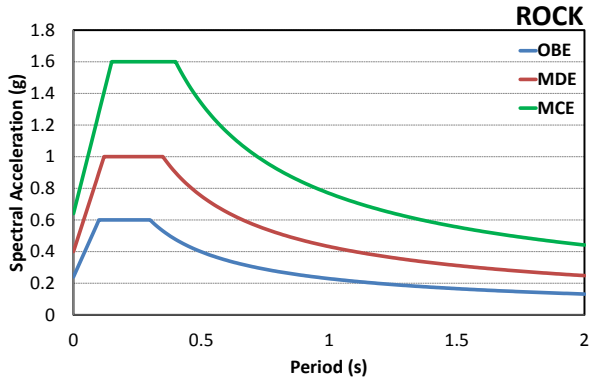


Figure 1. Site Specific Design Spectrums for OBE, MDE and MCE

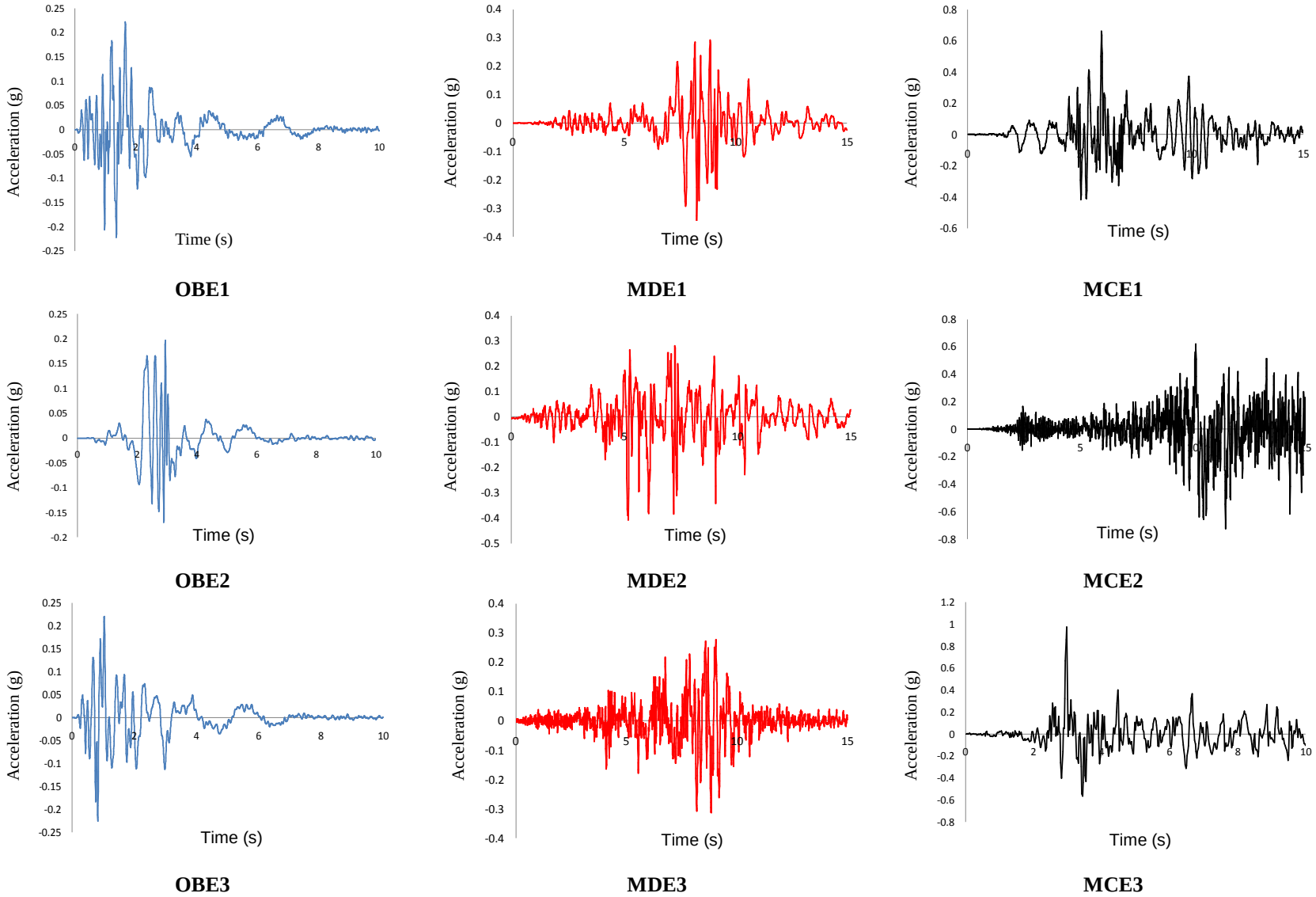


Figure 2. Site Specific Design Spectrum compatible Synthetic Ground Motions

2.2 Material Properties

Average modulus of elasticity and Poisson ratio values for the foundation rock obtained from material tests carried out at the site were 10800 MPa and 0.2, respectively. Concrete uniaxial compressibe strength was decided as 20 MPa based on preliminary stability analysis performed by CADAM (2003). The allowable dynamic tensile strength was selected as 2.5 MPa in light of several references on the subject (USACE-EM-1110-2-2200, USACE-EP-1110-2-12 and Harris et al. 2000). The modulus of elasticity values for concrete was calculated from USACE-EP-1110-2-12 and ACI-318 (2005) resulting 23.75 GPa. The unit weight of concrete was taken as 24 kN/m^3. Although the dam rests on rock, modulus of elasticity of the foundation is only half of the dam body. Therefore, the foundation flexibility may result in period elongation and radiation damping as noted by Fenves and Chopra (1984).

In USACE-EP-1110-2-12 document, which is mainly based on the studies carried out by Chopra and Fenves (1985), the damping ratio for FEM analysis with massless foundation is recommended to be computed from three factors affected by the structure, foundation and reservoir. From this study, the damping ratio is calculated as 15%. For the time history analyses, the Rayleigh damping is adjusted to produce15% damping ratio at the first mode of vibration and 20Hz, which is the maximum frequency contained in the synthetic ground motions.

3. ANALYSES MODELS

Andıraz Dam was investigated by utilizing the following three analyses types:

AT 1 : Nonlinear time history analysis by employing the Westergaard added mass approach for the hydrodynamic forces and the flexible massless foundation.

AT 2 : Linear time history analysis for the 3D model employing the Westergaard added mass approach for the hydrodynamic forces and the flexible massless foundation.

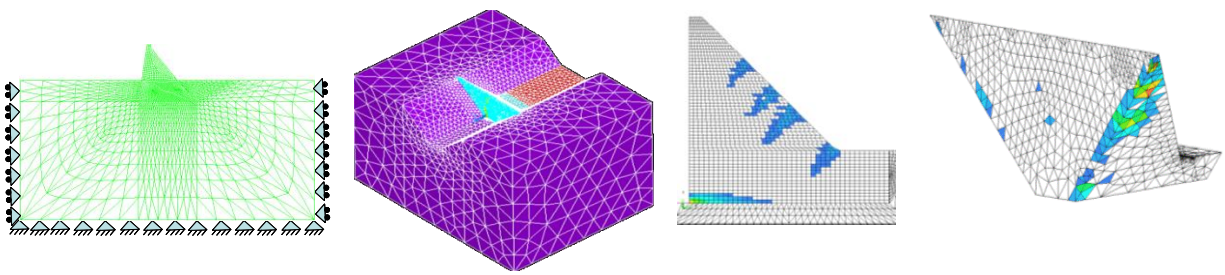
AT 3 : Nonlinear time history analysis for the 3D model employing the added mass approach for the hydrodynamic forces with the flexible massless foundation.

The modeling details and assumptions are summarized in Table 1. The employed finite element mesh and schematic damage patterns are given in Figure 3. From Table 1, it can easily be inferred that the nonlinear time history analysis promises the most comprehensive results. In order to simulate nonlinear concrete behavior, a total strain rotating crack model as explained in detail by Vecchio and Collins (1986), Selby and Vecchio (1993) was employed. Compressive behavior is defined by a parabolic stress-strain relationship, which is prone to strength reduction due to transverse tensile strains. The crushing behavior and ultimate strain is governed by the compressive fracture energy so that the ultimate crushing strain in the models is mesh independent. The tensile behavior is modeled by using a linear softening function beyond the tensile strength. Regularization by using the tensile fracture energy is employed to remove mesh dependency. The interface behavior of dam body on foundation rock (slip, crack opening and overturning) was modeled by employing interface elements between dam's body and foundation. For the interface elements, the Mohr-Coulomb constitutive model was employed to model the sliding behavior and crack formation. Further details of the constitutive models can be found in TNO (2008).

Table 1. Comparison of Modeling Methods

ANALYSIS TYPE	DAM'S DEFORMATION	GROUND DEFORMATION	EARTHQUAKE EFFECT	SIZE EFFECT	CONCRETE CRACKING EFFECT	SILT EFFECT	HYDRODYNAMIC EFFECT
AT 1	√	√	√	X	√	√	~
AT 2	√	√	√	√	X	X	~
AT 3	√	√	√	√	√	X	~

First, the largest cross-section of Andıraz dam was analyzed by utilizing a two-dimensional plane strain model as no transverse joints were planned. Evaluation of seismic behavior of the different sections was conducted for based on the results of crack locations, widths and the fact that post earthquake stability could be ensured. Analyses results showed that maximum damage was observed for the MCE2 ground motion record. For brevity, analysis results are presented only for this synthetic ground motion in the next sections.



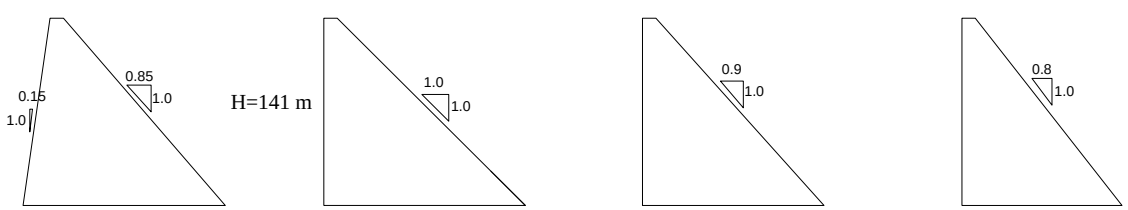
(a) 2D Model (b) 3D Model (c) Dam Cracking in 2D Model (d) Dam Cracking in 3D Model

Figure 3. Illustration of Models

4. ANALYSIS RESULTS

4.1.1 2D Nonlinear Analyses Results

Four different sections shown in
Figure *4* were investigated by employing 2D nonlinear finite element analysis.



(a) Section I (b) Section II (c) Section III (d) Section IV

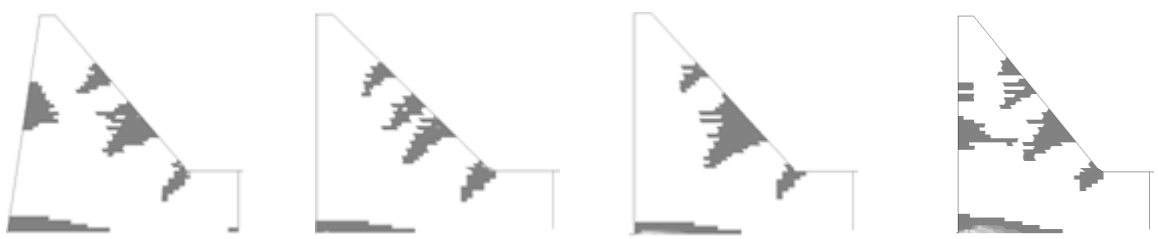
Figure 4. Investigated Dam Sections in 2D Analyses

According to results, Section I exhibited the stiffest response resulting in maximum crest acceleration and minimum crest displacements (Table 2). Conversely, Section IV was the most flexible one with the maximum crest dispalcement under MCE2 earthquake.

Table 2. MCE2 event comparison of different parameters

Parameter	Section I	Section II	Section III	Section IV
Crest Acceleration (g)	**2.1**	1.76	1.69	1.73
Crest Deflection (cm)	15	15	16	**18**
Max. Crack Length (m)	66	63	67	**67**
Max. Soil Pressure (MPa)	12.0	10.8	11.6	**12.8**

Figure 5 shows the envelope of expected cracking for the sections examined. It can be observed that there is one dominant crack and three separate cracks in upstream and downstream faces of Dam Section I, respectively. If upstream face was vertical, no crack would occur in this face. However, this adjustment led to the formation of additional cracks in the downstream face of the dam. For Section II, there were four separate crack paths observed in downstream face of the dam. In Section III, two of the cracks in the middle combined and propagated deeper into dam's body. For Section IV, there were also cracks observed in upstream face of the dam due to lowered slope of downstream face. According to these results, Section II and Section III were not subjected to cracking on the upstream faces, and so they could be considered as more acceptable sections prone to minimal leakage. Between these two sections, Section II can be claimed to have the better performance based on the distribution of cracking.



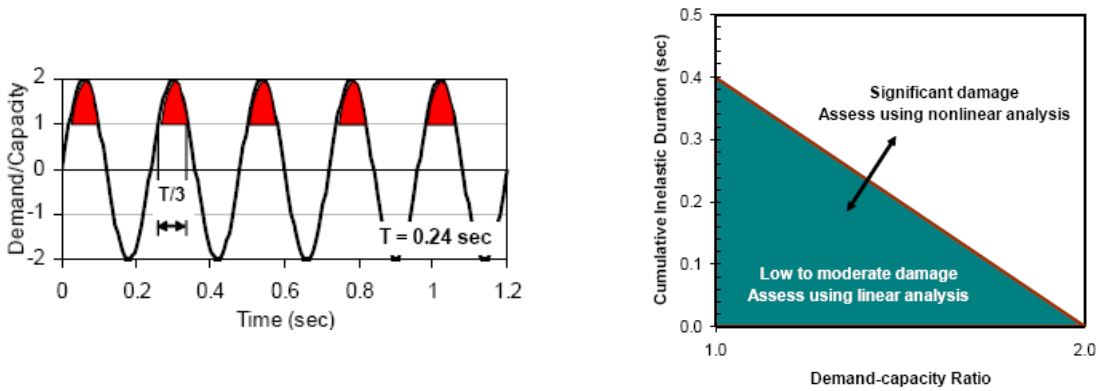
(a) Section I (b) Section II (c) Section III (d) Section IV

Figure 5. Investigated Dam Sections in 2D Analyses

4.2 3D Linear Time History Analyses Results

In this part, multi-directional earthquake effects were investigated and time-stress criterion of USACE-EM-1110-2-6051 was employed to estimate the seismic performance of Andıraz Dam based on linear elastic analysis. In the analyses, the load factor of 1 was applied to the earthquake motion perpendicular to the dam axis whereas this factor was assumed to be 0.3 for the motion along the dam axis. From the analyses, the principal stress envelopes were obtained and the dam body was assessed.

USACE-EM-1110-2-6051 method requires the calculation of the demand-capacity ratio (DCR) from the linear time history analyses along with the cumulative duration of stress excursions. After that, cumulative duration versus DCR curve is ploted for every analyses and then this plot is compared with the limits given in USACE-EM-1110-2-6051 (Figure 6). If the curve is below the limits and no DCR values higher than 2 exists, then the linear analysis is sufficient to assess the dam body. Otherwise, more detailed nonlinear analyses are needed.



(a) Cumulative inelastic duration of Stress excursion (b) Evaluation Criteria

Figure 6. DCR Evalution Method given in USACE-EM-1110-2-6051

The most critical DCR curves from OBE, MDE and MCE earthquakes are given in Figure 7.

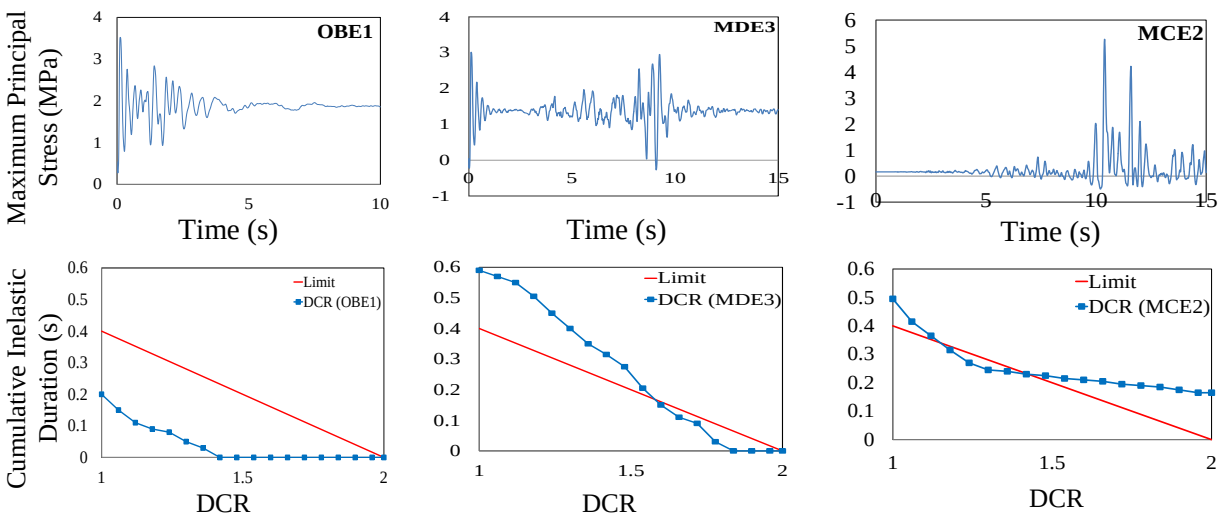


Figure 7. Most Critical DCR Time History Diagrams from OBE, MDE and MCE Earthquakes

It can be easily inferred from Figure 7 that the dam section is not adequate for being assessed by linear time history analysis as far as MDE and MCE are concerned. However, this dam section is sufficient for OBE earthquakes. Therefore, the nonlinear analyses are required for MDE and MCE earthquakes.

4.3 3D Nonlinear Time History Analyses Results

The cracking pattern of the dam section (Section II from 2D Analyses) under 3-directional application of the most critical MCE earthquake, MCE2, is shown in Figure 8. From this figure, it can be concluded that the base resistance to sliding has nearly been diminished and the cracks at the upstream face has reached the downstream face, indicating that the dam section does not have enough post earthquake resistance against sliding. Furthermore, 3D analyses results significantly depart from the 2D nonlinear time history analyses results, which by itself produce a safe design decision.

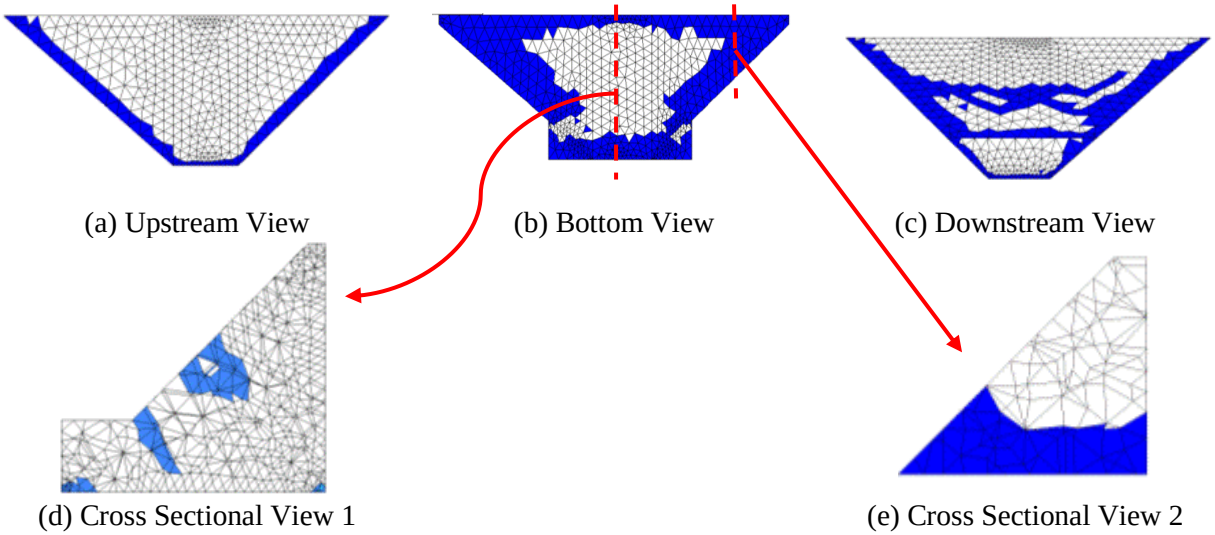


Figure 8. Crack Pattern after MCE2 Earthquake

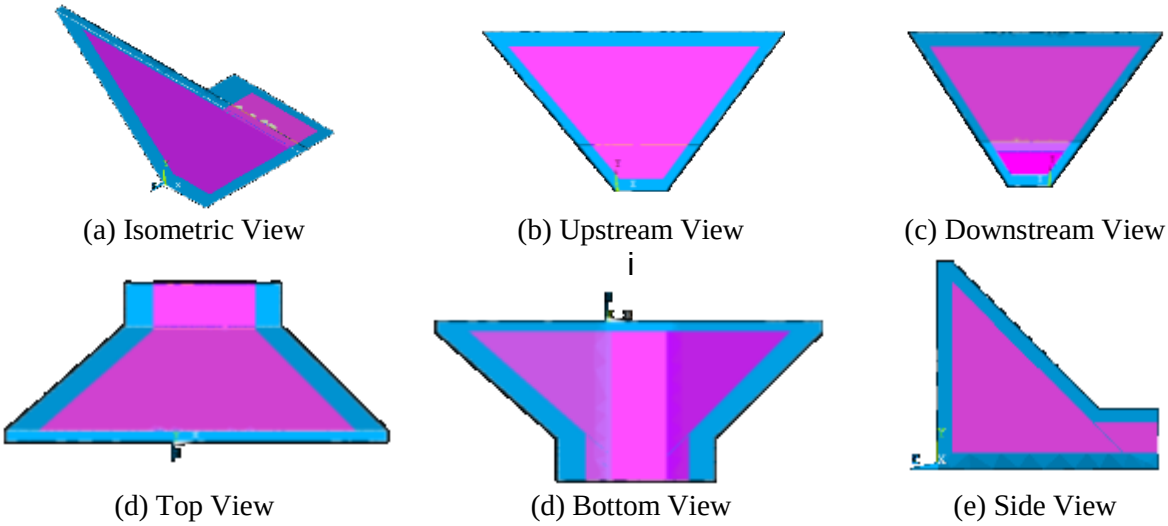


Figure 9. Shell and Core Concretes in Dam Body (Blue: Enriched Concrete and Pink: C20 Concrete)

It is a common design approach to increase locally the concrete strength in regions of distress (USACE-EM-1110-2-2200). The effect of such an approach was investigated next. Consequently, a 10-meter thick strong shell whose dynamic tensile strength was taken as 4.5 MPa was proposed. The inner region was kept with the aforementioned propoerties of concrete (Figure 9). In this way, it was aimed to limit base cracking response.

The most critical crack pattern for this kind of dam construction is shown in Figure 10. From Figure 10, it is clear that the shell protects the dam core from severe base cracking and provides post earthquake stability due to the presence of a large uncracked base region.

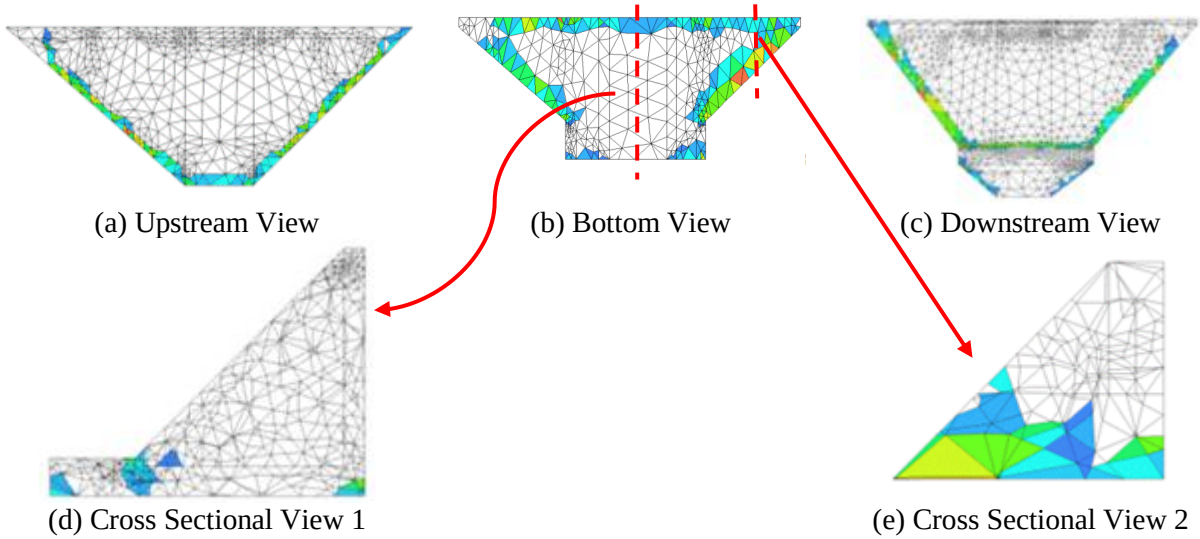


Figure 10. Crack Pattern after MCE2 Earthquake

5. CONCLUSIONS

The most important conclusion drawn from this study is that the different analysis methodologies namely 2D nonlinear, 3D linear and 3D nonlinear time history analyses, estimate quite different damage patterns for the same dam. From 2D analyses, a dam body made from an RCC with 2.5 MPa dynamic tensile strength with a vertical upstream slope and 1:1 downstream slope was sufficient for the earthquake scenarios generated for Andıraz Dam. However, 3D analyses (both linear and nonlinear) predict that this section was not adequate due to the excessive base cracks at sides as well as bottom of the dam. In fact, this result is due mainly to the nature of the 2D analysis method, i.e. the topological information is lost in 2D analyses, making it impossible to forecast the cracking potential at the dam sides. Therefore, it is vital to conduct 3D analyses when the dam is in a narrow canyon and built without any or long transverse joints. The use of enriched concrete for the regions of possible distress was found to render the damage in an acceptable pattern of cracking. In this way, post earthquake stability could be ensured.

REFERENCES

Akkar, S., (2011), Andıraz Barajı için Tasarım Spektrumunun Olasılık Hesaplarına Dayalı Sismik Tehlike Analizi (in Turkish).

American Concrete Institute, (2005), Building Code Requirements for Structural Concrete. *ACI 318.*

CADAM, (2003), CADAM User's Manual.

Chopra, A.K. and Wang, J. (2008), Analysis and Response of Concrete Arch Dams Including Dam-Water-Foundation Rock Interaction to Spatially-Varying Ground Motions, *Report No.* UCB/EERC-2008-03.

Chopra, A. K. and Fenves, G., (1985), Simplified Analysis for Earthquake Resistant Design of Concrete Gravity Dams. *Report No. UCB/EERC-85/10*.

Fenves, G. And Chopra, A.K., (1984), EAGD84: A Computer Program for Analysis of Concrete Gravity Dams, *Report No. UCB-EERC/84-11*.

Harris, D.W., Mohorovic, C.E. and Dolen, T., (2000), Dynamic Properties of Mass Concrete Obtained from Dam Cores. *ACI Materials Journal*, **97:3**, 290-296.

Medina F. and Dominguez, J., (1989), Boundary Elements for the Analysis of the Seismic Response of Dams including Dam-water-foundation Interaction Effects, *Engineering Analysis with Boundary Elements*, **6:3**, 152:157.

Rashed A.A., and Iwan, W.D., (1984), Earthquake Response of Short-length Gravity Dams, Procedings of 8th World Conference on Earthquake Engineering, San Francisco, California, VII, 343-350.

Selby, R.G., and Vecchio, F.J., (1997), A Constitutive Model for Analysis of Reinforced Concrete Solids, *Canadian Journal of Civil Engineering*, **24:3**, 460-470.

TNO Diana, (2008), Diana User´s Manual.

Turkish Earthquake Code, (2007), Specification for Structures to be Built in Disaster Areas, TEC2007, *Ankara, Turkey*.

United States Army Corps of Engineers, (1995), Seismic Design Provisions for Roller Compacted Concrete Dams. *Engineering Procedure EP 1110-2-12*.

United States Army Corps of Engineers (1995), Gravity Dam Design, *Engineering Procedure EM 1110-2-2200.*

United States Army Corps of Engineers, (2003), Time-History Dynamic Analysis of Concrete Hydraulic Structures. *Engineering Procedure EM 1110-2-6051*.

Vecchio , F.J. and Collins, M.P., (1986), The Modified Compression Field Theory for Reinforced Concrete Elements subjected to Shear. *ACI Journal*, **83:2**, 219-231.

Westergaard, H.M., (1933), Water Pressures on Dams During Earthquakes, *Transactions of the American Society of Civil Engineers*, Vol:98, 418–433.