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Seismic Performance Verification of Arch Dam by Nonlinear 3D-FEM Analysis

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ABSTRACT:

In this research, we have studied the seismic performance of an arch type concrete dam. Maintenance of water holding capacity is a big problem at the soundness of the dam. In a strong earthquake case, there is a possibility that gap may occur between dam and bedrock, or at dam body. Water holding capacity may also fall by a broad cracks occurring on concrete part. We consider the nonlinear behavior of separation of joint and concrete. We discuss the difference of behavior by comparing to the result of linear dynamic and non-linear dynamic analysis of finite element method. We show the importance of nonlinear dynamic analysis in a strong earthquake case.

KEYWORDS: arch dam, FEM, non-linear analysis, 3D analysis

1. Introduction

In recent years, several arch dams have been constructed in Turkey, including Deriner Dam, which began operations in 2012, and more are expected in the future. It has been pointed out that, when evaluating the seismic performance of an arch dam, while it is necessary to consider earthquake damage to the body of the dam, from the perspective of maintenance of water holding capacity, it is also necessary, to consider separation in the joints between the dam and the bedrock or between sections of the dam body. Recently, many researches have been carried out on this topic. In this research, we evaluated the seismic soundness of an arch dam by means of three-dimensional finite element analysis. There are a number of approaches to seismic performance evaluation, including stress evaluation using linear static analysis or linear dynamic analysis, as well as non-linear dynamic analysis, which takes into account the non-linearity of the concrete and joints in the dam body. In this study, we focused on dynamic analysis, and examined differences in seismic performance evaluation by comparing the results from linear and nonlinear analyses.

2. Analysis Models

ADINA was used for the finite element analysis code. The target dam was an arch dam with a crest length of about 300 m and a dam height of about 100 m. The analysis area including the surrounding ground has been defined as an area about 800 m by 900 m. The finite element model used in this study is shown in Figure 1. Two analysis models have been created as linear and non-linear. We have introduced solid elements to simulate the dam body and surrounding bedrock, and gasket elements to simulate separation between the dam body and bedrock. In the linear model, there is a rigid connection between the dam body and bedrock. The physical properties which have been used in the model are shown in Table 1. The materials are configured to be able to simulate the non-linear behavior of cracking and compression in the concrete in the dam body (See Figure 2). Note that we have not model joints within the dam body in this study.
For seismic motion, the record which was obtained during the M7.4 Kocaeli Earthquake on August 17, 1999 at IZMIT station have been used. The station site was located on the bedrock and the EW component of the record with a maximum horizontal acceleration of 224.9 Gal has been used. The acceleration time history and acceleration response spectrum are shown in Figure 3. In this study, we have used the record until 20 sec, where peak acceleration noted.

The analysis was divided into two major parts. After calculated the initial stress due to gravity loads, dynamic analysis is performed for the seismic motion input.

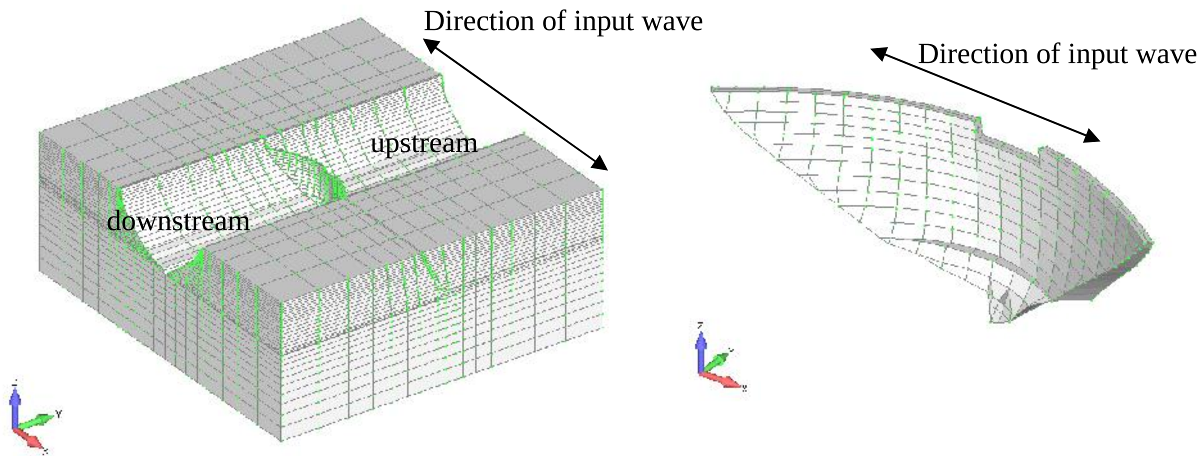


Figure 1 Analysis model

Table 1 Physical properties

	Young Modulus E	poisson ratio ν	mass density ρ	tensile strength F_t	compressive strength F_c
	kN/m^2	-	t/m^3	kN/m^2	kN/m^2
Bedrock	4.00×10^6	0.2	2	-	-
Concrete	2.80×10^7	0.2	2.4	2200	30000

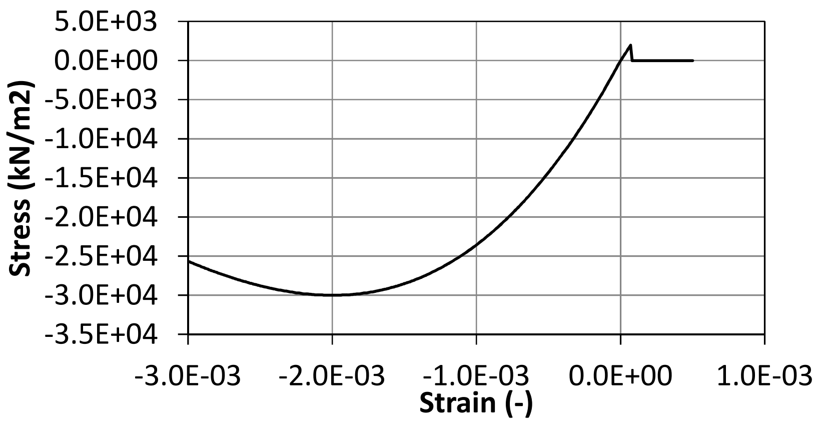


Figure 2 Stress-Strain curve of concrete material

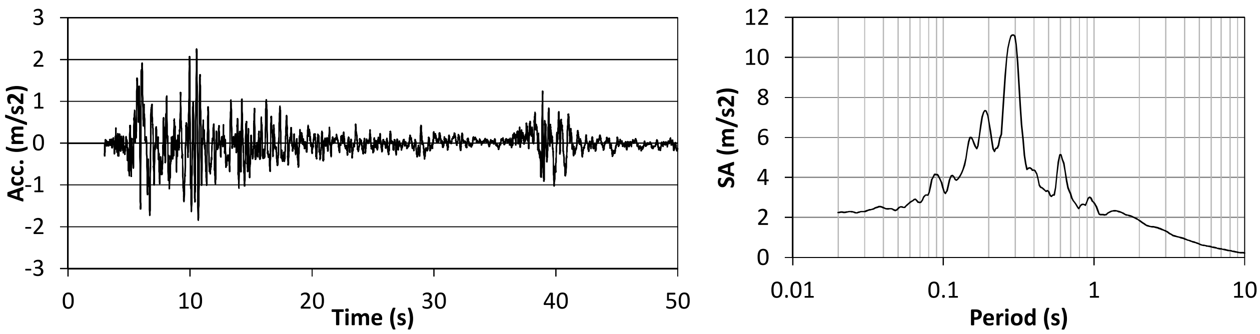


Figure 3 Input seismic motion

2.1. Initial stress

For initial stress due to gravity load, we used a static analysis in which a body force of 1G was applied vertically downward. In this case, we carried out staged construction analysis, which takes into account the building of the arch dam. In the first step, the load was added to a model of the bedrock only, and then the arch dam was built. In this case, the boundary conditions were set to a fixed bottom and vertical roller for the side surface.

2.2. Dynamic analysis

In the dynamic analysis, the model's bottom has been considered as a viscous boundary using a dashpot, and then the seismic motion was input at the bottom of the dashpot. This allowed the radiation damping of reflected waves to be taken into account. For the sides of the model, the boundary conditions of the roller in the vibration direction were set. Damping was set to Rayleigh damping with parameters $\alpha = 0.3142$ and $\beta = 0.001592$ for 3% damping at the target frequencies 1 Hz and 5 Hz. The target frequencies were set based on eigenvalue analysis of the model including the ground, which found the main modes of the dam body distributed around 1 Hz to 3Hz. The main eigenmodes are shown in Figure 4.

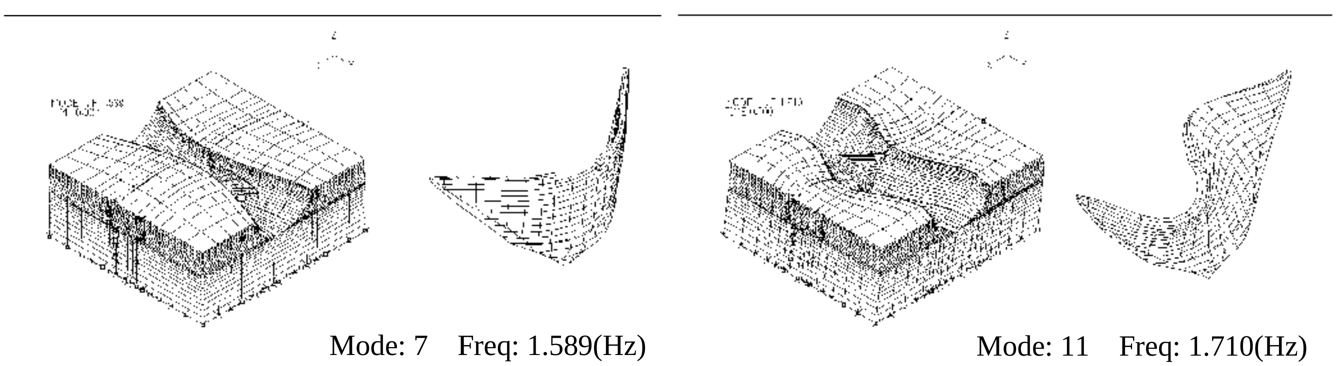


Figure 4 Natural modes of the analysis model

2.3. Analysis cases

The two analysis cases were dynamic time history analyses, one based on a linear model and the other one a non-linear model.

3. Analysis results

We compared the acceleration time history, the deformation level, and the stress in the dam body obtained from the two analysis cases. In the non-linear analysis case, we also checked the state of cracking in the concrete and the state of separation between the dam body and bedrock.

3.1. Response acceleration time history

Figure 5 shows a comparison of the response acceleration time history at the top of the dam for the two cases in which dynamic time history analysis have been performed. In the initial stage of the analysis, the linear and non-linear response accelerations are almost the same, but they diverge significantly as time progresses, and a large difference in horizontal acceleration can be seen around 7-8 seconds, with the non-linear analysis having the greater acceleration. Looking at maximum acceleration, whereas the linear analysis has a maximum acceleration of 2.61 m/s^2, the non-linear analysis has a maximum acceleration of 4.05 m/s^2. This is an effect of reduced stiffness due to cracks in the dam body and the separation of the joint surfaces, demonstrating the importance of taking into account non-linearity when evaluating acceleration.

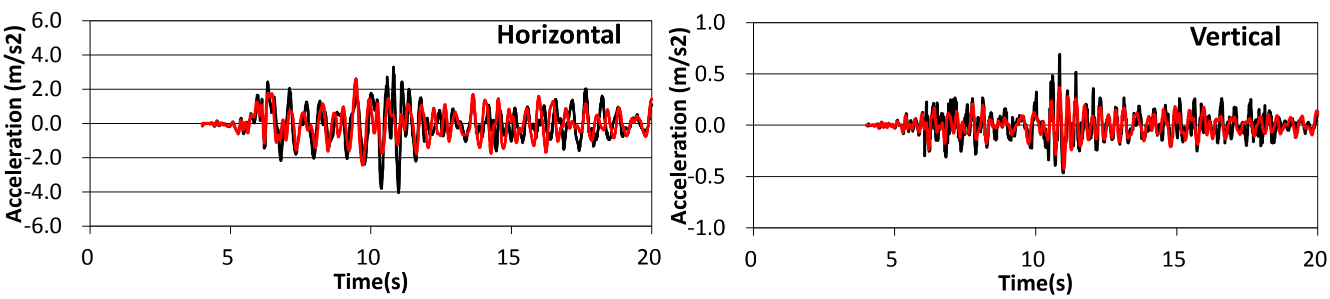


Figure 5 Response acceleration time history (red: linear; black: non-linear)

3.2. Amount of deformation

We compared the relative amount of deformation of the top versus the bottom of the dam in the two analysis cases. The results are shown in Figure 6.

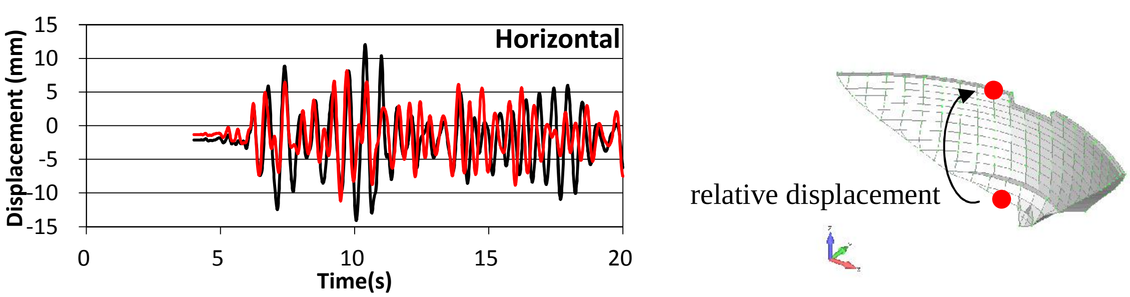
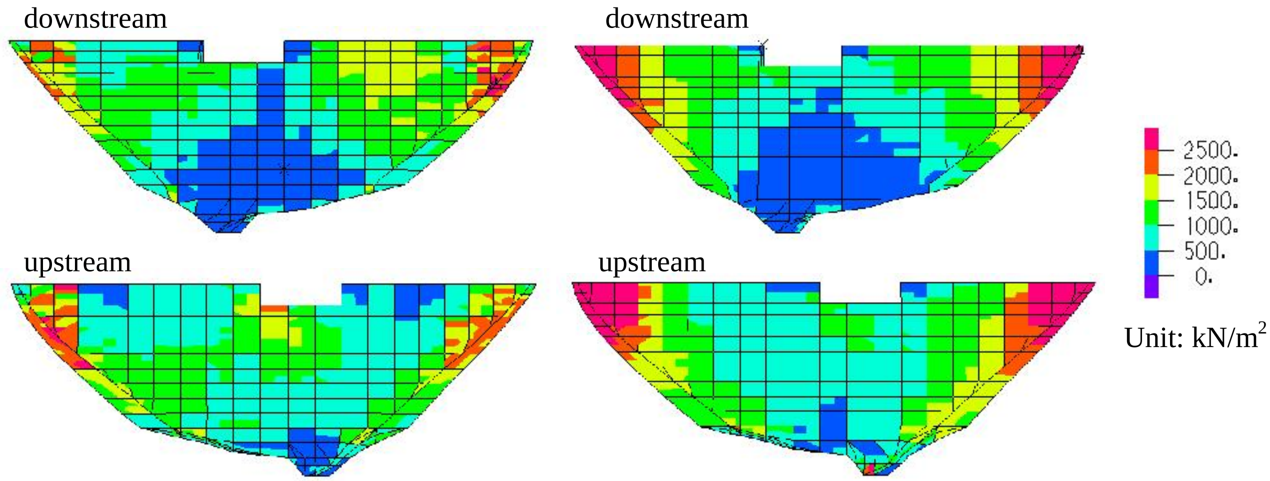


Figure 6 Relative displacement time history (red: linear; black: non-linear)

3.3. Tensile principal Stress

Figure 7 shows a contour plot of the tensile principal stress occurring in the dam body. Note that the results show the maximum values of the time history. The stress is relatively high at the edges of the bedrock foundation of the dam. Here, the stress peaks at the tensile strength is lower in the non-linear analysis, due to its use of a constitutive law that takes into account tensile strength, compared to the linear analysis. On the other hand, near the center of the dam, in some places the stress can be seen to be higher in the non-linear analysis. It is believed that the stress near the center becomes higher due to the relaxation of the stress at the edges of the bedrock foundation.



(a) Non-Linear (b) Linear

Figure 7 Contour plot of the tensile principal stress

3.4. Cracking

With respect to the case using non-linear dynamic analysis, Figure 8 shows the post-analysis state of the cracking that occurred in the dam body. The discs shown in the figure represent cracks on the surface.

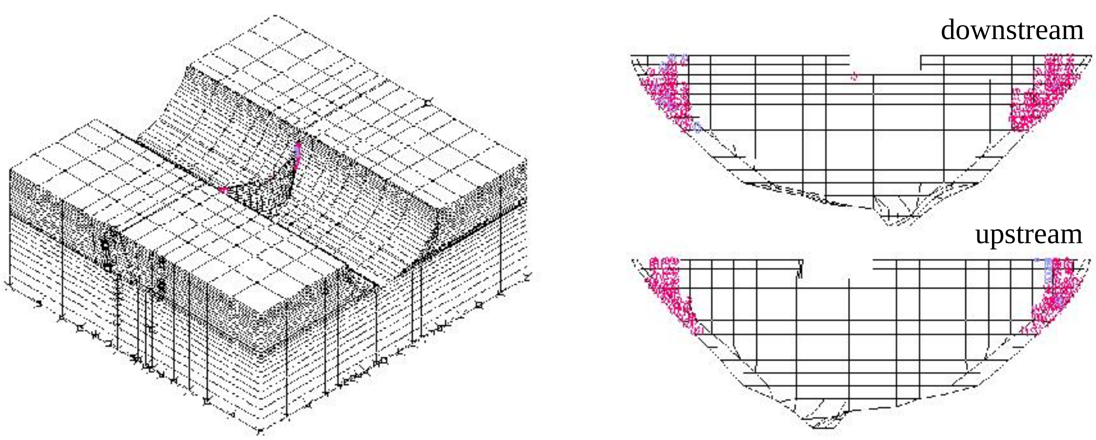


Figure 8 Cracking

3.5. Separation

With respect to the case using non-linear dynamic analysis, Figure 9 shows the maximum values for the openings that occurred at the joint surface throughout the entire analysis time. The results indicate that the maximum openings exceeded 5 mm at the foundation ground sides, where the large size of the openings are cause for concern, even allowing for the shear key blocks and water shut plates. We believe this result and the large difference in response acceleration between linear analysis and non-linear analysis noted in Section 3.1 are due to the fact that the openings are subject to large non-linear effects.

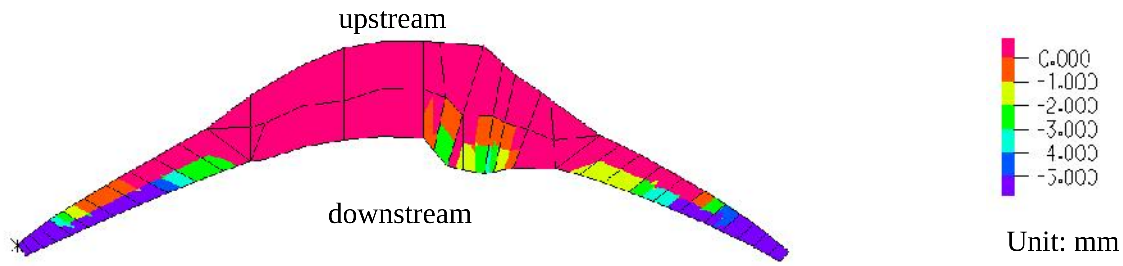


Figure 9 Contour plot of maximum separation

4. Summary

We examined differences in seismic performance evaluation of arch dams by carrying out analyses using linear and non-linear models. The results show that implementing a non-linear model not only allows evaluation of cracking of the dam body and separation of the joint surface, but also reveals differences in acceleration time history and main stress distribution caused by the influence of non-linearity. It is therefore important to apply non-linear analysis when evaluating the seismic performance of arch dams.
This analysis considered separation between the dam body and the foundation ground, but in an actual dam, the dam body itself is divided into multiple blocks. Furthermore, when evaluating the performance of dams exposed to extremes of cold and heat, consideration of temperature load is also an important issue. In the future we hope to perform analyses that take into account these conditions.

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