SEISMIC RELIABILITY ANALYSIS OF HIGH CONCRETE ARCH DAMS UNDER NEAR-FAULT EFFECT

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ABSTRACT:

In this study, seismic reliability analysis of a high concrete arch dam under near-fault effect is performed to determine the probability of exceeding the limit values. Firstly, 3D finite element model of Deriner concrete arch dam considering dam-reservoir-foundation coupling system and appropriate boundary conditions is modeled. The Eulerian approach is used to model the reservoir, and the foundation is considered as massless and linear-elastic. Nonlinear behavior of concrete is modeled utilizing the Drucker-Prager material model. Secondly, deterministic time-history analyses are performed under operating basis earthquake (OBE) and maximum credible earthquake (MCE) with near-fault and far-field strong ground motions to define the limit states. After selecting the input variables from the material properties of dam body and foundation rock, reliability analyses of the dam-reservoir-foundation system are conducted. The probability of exceeding the limit values and the reliability indices at the critical regions of the dam body is determined according to the Monte Carlo Simulation results obtained through the Response Surface Method. Lastly, the probability of exceedance and the reliability indices obtained from the reliability analyses for near-fault and far-field earthquakes are compared by taking account both earthquake levels.

KEYWORDS: Arch Dam, Drucker-Prager Material Model, Near-Fault Ground Motion, Reliability Analysis, Response Surface Method, Monte Carlo Simulation

1. INTRODUCTION

High concrete arch dams are complex and critical infrastructures whose failure would cause catastrophic destruction. Therefore, their response under seismic events should be estimated deterministically and probabilistically.

Some researchers have shown the effects of near-fault earthquakes on the response of concrete dams. Quimei et al. [1] performed seismic analyses on concrete gravity dams subjected to near-field, pulse-like ground motions using a massless foundation. They found that the principle stress and displacement of all the specific points with a pulse-like ground motion were greater than those obtained without using any such motion. Bayraktar et al. [2] and Akköse [3] compared near-fault and far-field ground motion effects on the nonlinear response of concrete arch and gravity dams. They found a greater seismic demand on stresses and displacements when the dam is subjected to near-fault ground motions. Hariri-Ardebili and Saouma [4] investigated the impact of input ground motion characteristics on the seismic response of a typical concrete arch dam with rigid, massless and massed foundation. In all these foundation types, they found that near-fault ground motions have led to higher response than far-field motions.

Reliability analysis methods have been used to estimate the seismic safety of dams regarding certain failure modes in the literature. Araujo & Awruch [5] performed a probabilistic finite element analysis of concrete
gravity dams subjected to seismic excitation, which concrete properties and seismic excitation are considered as random variables. Horyna [6] investigated the safety of existing concrete gravity dams against sliding considering nonlinear effects in the dam-foundation interface. Leclerc et al. [7] implemented a computer program, called CADAM, to evaluate the static and seismic stability of dams using deterministic and probabilistic analyses. MCS method is used to perform the probabilistic analysis in CADAM. Tekei and Ellingwood [8] constituted a seismic fragility assessment of a concrete dam using a commercial FE code ABAQUS for the nonlinear analyses. In the analyses, material failure of foundation/concrete at the toe, sliding failure at the dam-foundation interface, material failure at the neck of the dam and deflection of the top of dam relative to heel were considered as limit states. Lupoi and Callari [9] proposed a procedure to obtain the system fragility curves of an existing concrete gravity dam using MCS method. In probabilistic analyses, excessive deformation of the dam body, cracking or sliding at dam base, cracking at the dam neck and cracking at the upstream face were considered as limit states. Xu et al. [10] used the Pseudo Excitation Method and the Response Surface Method (RSM) based on weighted regression to analyze the functional reliability of gravity dam. Functional reliability is denoted as the displacement at the head of the dam. Chen et al. [11] investigated the reliability of an arch dam subjected to seismic load using RSM. The reliability index of each element of the dam is calculated by gradient optimization method.

The aim of this paper is to determine the near-fault effect on the seismic reliability of high concrete arch dams. For this purpose, Deriner arch dam is selected as an application. The reliability analyses of the dam-reservoir-foundation systems are performed according to the Monte Carlo Simulation (MCS) results obtained through the Response Surface Method (RSM) for operating basis earthquake (OBE) and maximum credible earthquake (MCE).

2. FORMULATION

2.1. Dam-Reservoir-Foundation Coupled System

The dam-reservoir-foundation coupling system is modeled based on Eulerian approach. In the Eulerian approach, the analysis of a fluid-structure system is based on the substructure concept in which fluid and structure are treated as two substructures. The coupled dam-reservoir-foundation equation can be written as the following in the matrix notation;

\[
\begin{bmatrix}
[M] & [0] \\
[\rho[B][G]] & [C]
\end{bmatrix}
\begin{bmatrix}
\{\dot{r}\} \\
\{\dot{\bar{P}}\}
\end{bmatrix}
+ \begin{bmatrix}
[0] & [L]
\end{bmatrix}
\begin{bmatrix}
\{\dot{r}\} \\
\{\bar{P}\}
\end{bmatrix}
+ \begin{bmatrix}
[K] & -[B]
\end{bmatrix}
\begin{bmatrix}
\{r\} \\
\{P\}
\end{bmatrix}
= \begin{bmatrix}
-M[J]\{a_s\} \\
-\rho[B][J]\{a_s\}
\end{bmatrix}
\]

(1)

where [M], [C] and [K] symbolize the mass, damping, and stiffness of the dam and foundation body; \{r\}, \{\dot{r}\} and \{\ddot{r}\} are the vectors of the nodal displacement, velocity, and acceleration relative to the ground; \{a_s\} is the vector of ground acceleration. [G], [L] and [H] symbolize the mass, damping, and stiffness of the reservoir domain; \{P\} is the nodal pressure. [J] is the identity matrix and [B] is the coupling matrix.

2.2. Drucker-Prager Material Model

Drucker-Prager material model is widely used for frictional and pressure-dependent inelastic behavior of materials such as rock and concrete. Drucker and Prager [12] obtained a convenient yield surface to determine the elasto-plastic behavior of concrete by smoothing Mohr-Coulomb criterion. This function is defined as

\[
f = \alpha I_1 + \sqrt{J_2} - k
\]

(2)
where $I_1$ is the first invariant of stress tensor $(\sigma_{ij})$ and $J_2$ is the second invariant of deviatoric stress tensor $(S_{ij})$. 

$\alpha$ and $k$ are constants that depend on cohesion $(c)$ and angle of internal friction $(\phi)$ of the material given by:

$$\alpha = \frac{2 \sin \phi}{\sqrt{3} (3 - \sin \phi)} \quad \text{and} \quad k = \frac{6c \cos \phi}{\sqrt{3} (3 - \sin \phi)}$$

### 2.3. Reliability Analysis

The reliability analysis of structures deals with the calculation of the failure probability under a defined limit state conditions. The probability of failure of a structural component on a single failure mode can be formally calculated as [13-16]

$$P_f = \int_{g(x) < 0} f_X(x) dx$$

where $X$ is the vector of basic random variables and $g(x)$ is the limit state function for the failure mode considered, $f_X(x)$ is the joint probability density function of the vector $X$. If $g(x) < 0$, then the failure domain, if $g(x) > 0$, then the safe domain and if $g(x) = 0$, then the failure surface is defined. The basic random variables comprise physical variables describing uncertainties in loads, material properties, geometrical data and calculation modelling [17]. There are different reliability methods to calculate the probability of failure. In this study, to estimate the $P_f$, Monte Carlo Simulation (MCS) results obtained through the Response Surface Method (RSM) is used. The probability of failure can be expressed in terms of a reliability index, $\beta$, also called safety index. The reliability index can be computed as;

$$\beta = -\Phi^{-1}(P_f)$$

where $\Phi$ is the standard normal cumulative distribution function.

#### 2.3.1. Response Surface Method

Response surface method is based on the fundamental assumption that the influence of the random input variables on the random output parameters can be approximated by a mathematical function [18]. In this way, the actual limit state function $g(X)$ is replaced by a polynomial type function $\hat{g}(X)$, as an example, a quadratic polynomial;

$$\hat{g}(X) = a + \sum_{i=1}^{n} b_i X_i + \sum_{i=1}^{n} \sum_{j=1}^{n} c_{ij} X_i X_j$$

where $a$, $b_i$, and $c_{ij}$ are the coefficients of the polynomial, $n$ is the number of the variable $X$. To obtain unknown coefficients, the experimental points should be chosen. There are many sampling methods to obtain the experimental points. In this study, Box-Behnken design is used, which consists of a central point plus the midpoints of each edge of an $N$-dimensional hypercube. The location of the sampling points for a problem with three random input variables is illustrated in Figure 1.
2.3.2. Monte Carlo Simulation

In this study, MCS is used with RSM to obtain the probabilistic response of the dam. For this purpose, firstly, the approximate functions are obtained from the RSM for stress indicated by $g(\cdot)$. Then, MCS is applied by using this function. The stress for each iteration in the simulation are obtained as,

$$\sigma_i = g(X^i)$$  \hspace{1cm} (7)

where $\{X^i\}$ is the vector of sample values for random parameters. The mean values of the stress is calculated by;

$$\sigma_{\text{mean}} = \frac{1}{N} \sum_{i=1}^{N} \sigma_i$$  \hspace{1cm} (8)

3. EARTHQUAKE GROUND MOTIONS

Two ground motion records that represent the near-fault and far-field effects have been selected from PEER Ground Motion Database [19] to investigate seismic performance of the dam. PGA and PGV, surface projection distances from the site to the fault and PGV/PBA values are depicted in Table 1, which only shows the major horizontal components of ground motion applied in the stream direction. These selected ground motions are matched to OBE and MCE level response spectrum [20]. Acceleration and velocity time-histories of all scaled ground motions are depicted in Figure 2. Also, Figure 3 shows the horizontal acceleration response spectrum of the Deriner Dam site (as target spectrum) with OBE and MCE level obtained by conducting a hazard analysis of the dam site.

<table>
<thead>
<tr>
<th>Event</th>
<th>Near-Fault</th>
<th>Far-Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station</td>
<td>Corralitos</td>
<td>Belmont-Envirotech</td>
</tr>
<tr>
<td>Component</td>
<td>CLS090</td>
<td>BES075</td>
</tr>
<tr>
<td>PGA (g)</td>
<td>0.483</td>
<td>0.111</td>
</tr>
<tr>
<td>PGV (cm/s)</td>
<td>47.58</td>
<td>16.58</td>
</tr>
<tr>
<td>PGV/PBA (s)</td>
<td>0.100</td>
<td>0.152</td>
</tr>
<tr>
<td>Mw</td>
<td>6.93</td>
<td>6.93</td>
</tr>
<tr>
<td>R (km)</td>
<td>0.16</td>
<td>44.1</td>
</tr>
</tbody>
</table>
Figure 2. a) Scaled acceleration time-histories; b) scaled velocity time-histories for near-fault and far-field ground motions

Figure 3. Scaled acceleration response spectra of selected records based on the target spectrum
4. FINITE ELEMENT MODEL OF DERİNER CONCRETE ARCH DAM

The Deriner dam and hydroelectric power plant located on the Çoruh River in north-eastern Turkey is a high concrete arch dam and completed in 2012. The views are given in Figure 4. The dam was constructed at an altitude of 397m above sea level. The 249m high special double-curvature arch dam has a crest length of 721m and a concrete volume of 3.5Mm\(^3\). The maximum thickness of the dam at the base is 60m, and the crest width of the crown cantilever is 12m.

The 3D structural model of the dam is provided based on the as-built drawings, and the finite element model of dam-reservoir-foundation coupled system is shown in Figure 5a. The ANSYS commercial finite element software [21] is used as the main platform for the modeling and analysis. Fluid-structure interaction (FSI) is modeled based on Eulerian approach, and the foundation is considered as massless and linear-elastic. Nonlinear behavior of concrete is modeled utilizing the Drucker-Prager material model. The material properties of the concrete and the foundation rock are given in Table 2. To consider the interaction effects of the rock and the water in the dam during seismic analysis, the length of the reservoir and the foundation in the upstream direction is taken three times that of the dam height. Also, the foundation model is to be extended one dam height in downstream and right and left bank side directions. The dam and foundation are modeled with eight-node solid-structural elements which have three translational degrees of freedom at each node. To model the reservoir medium, eight-node Eulerian-fluid elements with three translational degrees of freedom and one pressure degree of freedom are used. It should be noted that translational DOFs are applicable only at nodes on the interface with solid elements.

<table>
<thead>
<tr>
<th>Material</th>
<th>Properties</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulus of Elasticity</td>
<td>33 GPa</td>
<td></td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>Mass Density</td>
<td>2400 kg/m(^3)</td>
<td></td>
</tr>
<tr>
<td>Cohesion</td>
<td>4.5 MPa</td>
<td></td>
</tr>
<tr>
<td>Friction Angle</td>
<td>40º</td>
<td></td>
</tr>
<tr>
<td>Modulus of Elasticity</td>
<td>11.25 GPa</td>
<td></td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>0.2</td>
<td></td>
</tr>
</tbody>
</table>
The water level is 7m below the crest. Water is assumed to be linear compressible with a density of 1000 kg/m³. The wave velocity in water is 1440m/s and the wave reflection coefficient with the abutments is taken to be 0.75. Boundary conditions on the reservoir water and their mathematical equations are shown in Figure 5b where $n$, $\alpha_{n}^{\text{struc}}$, and $\alpha_{0}$ are outwardly normal direction to the dam body, the normal acceleration on the dam, and the wave reflection coefficient at the foundation-reservoir interface respectively [22].

Figure 5. (a) Finite element model of the dam-foundation-reservoir system; (b) Mathematical representation of the reservoir boundary conditions

5. DETERMINISTIC ANALYSES OF DERİNER DAM

Nonlinear time-history analyses were first conducted to determine the most critical regions where the highest tension stresses occur on the dam body under operating basis earthquake (OBE) and maximum credible earthquake (MCE) [23]. It is noteworthy that time interval 1-10 sec of the ground motions is taken into account.
for the analyses. Structural damping is assumed to be 5% of critical damping, and mass and stiffness proportional damping coefficients $\alpha M$ and $\beta K$ are obtained using Rayleigh damping method. The maximum principle stress distribution on the dam body and the values are given in Table 3 and Figure 6.

<table>
<thead>
<tr>
<th></th>
<th>NEAR</th>
<th>FAR</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCE</td>
<td>6.01</td>
<td>6.07</td>
</tr>
<tr>
<td>OBE</td>
<td>4.15</td>
<td>3.35</td>
</tr>
</tbody>
</table>

Table 3. Maximum first principle stress values obtained from deterministic analyses (MPa)

Figure 6. Maximum first principle stress contours obtained from deterministic analyses (Pa)

6. SEISMIC RELIABILITY ANALYSES OF DERINER DAM

In the scope of this study, reliability analyses of Deriner arch dam are performed in the selected critical nodes according to principle stress components. The ANSYS Probabilistic Design System (PDS) is used to analyze the components involving uncertain input variables. Also, the critical nodal points are defined as random output parameters. The RSM is used to replace the actual limit state function $g(X)$ by a polynomial type function $\hat{g}(X)$. Then, MCS is used to obtain the probabilistic response of the dam.

6.1. Limit State Function and Variables

The deterministic model has four parameters that are regarded as random input variables. It is assumed that the variables have a lognormal distribution. The mean and COV (standard deviation/mean) values of the variables used in the reliability analyses of Deriner concrete arch dam are given in Table 4.
Table 4. Input variables and COVs used in the reliability analyses

<table>
<thead>
<tr>
<th>Variables</th>
<th>Mean</th>
<th>COV (%)</th>
<th>Distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable-1 Modulus of elasticity of concrete (GPA)</td>
<td>33</td>
<td>10</td>
<td>Lognormal</td>
</tr>
<tr>
<td>Variable-2 Cohesion of concrete (MPa)</td>
<td>4.5</td>
<td>10</td>
<td>Lognormal</td>
</tr>
<tr>
<td>Variable-3 Friction angle of concrete</td>
<td>40</td>
<td>10</td>
<td>Lognormal</td>
</tr>
<tr>
<td>Variable-4 Modulus of elasticity of foundation rock (GPA)</td>
<td>11.25</td>
<td>10</td>
<td>Lognormal</td>
</tr>
</tbody>
</table>

The limit state function considers the principle tensile stress, $\sigma_t$, of the concrete as given in equation (9). In equation (9), the dynamic tensile strength of 6.10 MPa of the concrete is used as criteria. Only one critical nodal point is selected in the dam body considering the maximum principle stress components obtained from the deterministic analysis.

$$g(X) = 6.10 - \sigma_t$$  \hspace{0.5cm} (9)

6.2. Reliability Analyses Results

This section of paper gives seismic reliability analyses results of Deriner arch dam subjected to OBE and MCE level earthquakes. A set of 25-sample probabilistic analyses were performed to fit the response surface for each earthquake level. The random output parameters were fitted with quadratic regression model including cross-terms. The Forward-Stepwise-Regression filtering technique was used to fit the random output parameters. The fitted response surfaces were simulated by MCS with 5000 random samples. MCS results of the dam under MCE and OBE level earthquakes are given in Table 5.

Table 5. Seismic reliability analysis results of Deriner dam for MCE and OBE level earthquakes

<table>
<thead>
<tr>
<th>Earthquake</th>
<th>Mean Tensile Stress (MPa)</th>
<th>$P_t \times 10^{-4}$</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near</td>
<td>5.491</td>
<td>0.0</td>
<td>-</td>
</tr>
<tr>
<td>Far</td>
<td>5.211</td>
<td>8.596</td>
<td>3.135</td>
</tr>
<tr>
<td>Near</td>
<td>3.915</td>
<td>0.0</td>
<td>-</td>
</tr>
<tr>
<td>Far</td>
<td>3.216</td>
<td>0.0</td>
<td>-</td>
</tr>
</tbody>
</table>

7. CONCLUSIONS

After conducting deterministic and probabilistic analyses of Deriner concrete arch dam, the following conclusions can be drawn:

- The maximum first principle stress values obtained from deterministic analyses with MCE are close for near-fault and far-field earthquakes. However, maximum first principle stress occurred on the upstream face of the dam body under near-fault earthquake while it occurred at the crest of the downstream face under far-field earthquake.
From deterministic analyses under OBE, the near-fault earthquake has led higher stress than the far-field motion. Also, maximum principle stresses occur at the crest.

Probabilistic analyses have led less mean tensile stress results than deterministic analyses have.

From all four probabilistic analyses, only far-field earthquake under MCE level has exceeded the limit tensile stress, 6.10 MPa.

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