# Seismic Fragility and uncertainty Analysis of Concrete Gravity Dams under Near-Fault Ground Motions

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**Abstract.** Throughout the world there are numerous concrete gravity dam has been made in areas of very high seismicity with least attention to seismic actions. Dam safety during and after an earthquake, is the objective of the present study. The failure of a dam in a seismic excitation has dramatic consequences in terms of loss of human lives and financial losses. In the present work, an analytical fragility analysis was performed in order to characterize the seismic vulnerability of concrete gravity dams by using a numerical simulation procedure to model sources of uncertainty that could impact dam performance, with combination with non-linear dynamic response analysis. The seismic fragility of concrete gravity dams under near-fault ground motions was performed and compared to assess their performance against seismic hazards. An uncertainty analysis is also carried out to evaluate the effectiveness of the Latin Hypercube Sampling method using different combinations of performance thresholds through fragility analysis. A case study was considered, it is about the dam of Oued el Fodda on the Oued Chelif River, West Algeria. This dam was designed in the early 1930s.

## 1 Introduction

Many damaging earthquakes have been recorded in Northern Algeria (Chelif 1980, Mw=7.3; Ain Temouchent 1999, M=5.7; Beni ourtilane 2000, M=5.6 and the one in Boumerdes 2003, Mw=6.8), indicating the importance of the seismic hazard assessment for this region [1-3]. The seismic fragility that describe the probability of a structure being damaged beyond a specific damage state for various levels of ground motions. In the literature, several studies for generating seismic fragility curves have been developed [4-13]. Fragility curves are plots of system fragilities versus a scalar measure of seismic intensity. Traditionally, peak ground acceleration (PGA) has been used as an intensity measure. Recent studies show that pseudo-spectral acceleration provides a superior measure of seismic intensity than PGA [14].

In recent years, many efforts have been devoted to the characterization of effect of near-fault ground motions on the structures. Near-fault ground motions have caused much damage in the vicinity of seismic sources during recent earthquakes (Northridge 1994, Kobe 1995 and Taiwan 1999). There is evidence indicating that ground shaking near a fault rupture may be characterized by a short-duration impulsive motion that exposes structures to high input energy at the beginning of the record [15]. There are two factors for classifying ground motions as near-fault. The spike in velocity should generally exceed (152 cm/s) or, the distance of the epicenter of the earthquake should be within approximately 15 km of a structure of interest [16]. A sensitivity analysis is also carried out to evaluate the effectiveness of the Latin Hypercube Sampling method.

The aim of this study is to develop the analytical seismic fragility curves of concrete dams subjected to near-fault ground motion excitations. The methodology is applied on the Oued el Fodda dam located west Algeria. It was built in the early of 1930s.

## 2 Structural modeling of dam behavior

The study is based on a concrete gravity dam with a vertical upstream face, which maintains a reservoir of water that extends to infinity in the upstream direction and is based on a semi-infinite foundation. The geometry of the dam-reservoir-foundation system is shown in figure.1.

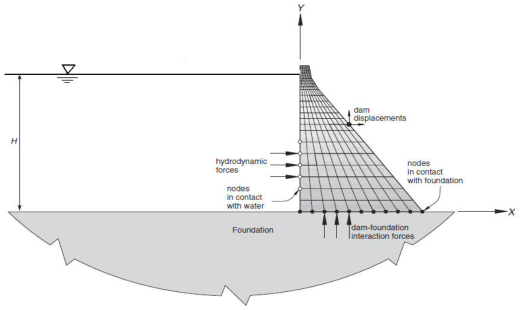


**Fig. 1.** Geometry of dam-reservoir-foundation system

### 2.1 Description of model

The model of the dam-foundation system is illustrated in figure.2, used 4-node, bilinear finite elements. The concrete-rock interface is assumed to be horizontal and to obey the Coulomb friction law. The foundation material was assumed to be a Mohr-Coulomb material, with its non-linear behavior assumed to be perfectly plastic. The concrete in the dam was modeled as an impervious material. The bottom horizontal boundary of the FE model is the application point of the de-convolved seismic ground motion. Different boundary conditions must be imposed on the nodes on the vertical boundaries of the FE model. Those nodes, representing the outlying nodes where the effect of dam–foundation interaction is presumed to have attenuated, are constrained to move together in the horizontal direction. While the spatial variation of the earthquake ground motion across the base of the model is neglected, those nodes in the vicinity of the base of the dam clearly are affected by the dam–foundation interaction. The above provisions provide an adequate model for the dam–foundation interaction.

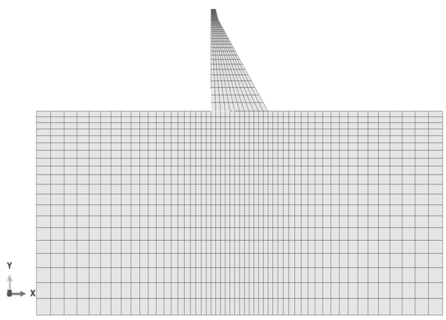


**Fig.2.** Finite element model of dam-foundation system

### 2.2 Material properties

In this study, the values of material properties used for dam model are: Unit weight of the concrete is 2500 kg/m3, 0.2 Poisson's ratio, and the modulus of elasticity is taken as 31000 MPa. Compressive strength of the concrete has been assumed as 25 MPa. The concrete tensile strength is assumed to be 15% of compressive strength (3.75 MPa). The water has the unit weight, 1000 kg/m3, pressure wave velocity 1440 m/s. In the analysis, the damping ratio is assumed to be 5% of the fundamental frequency of system.

Table 1 lists the near-fault earthquake records selected to create an ensemble for the seismic fragility of the Oued el Fodda Dam. All occurred between 1987 and 1999, and have epicentral distances of 4.77 to 10.36 km with magnitudes ranging from 6 to 7.1.

Figure. 3 show the spectral accelerations used for scaled the both near-fault earthquakes used in the time history analyses.

**Table 1**. Properties of selected Near-fault earthquakes records [17]

| N° | Earthquake | Year | Magnitude | E.D [km] | PGA [$m/s^2$] |
|---|---|---|---|---|---|
| S1 | Cap Mendocino | 1992 | 7.1 | 10.36 | 1.497 |
| S2 | Cap Mendocino | 1992 | 7.1 | 10.36 | 1.039 |
| S3 | Kocaeli Izmit Turkey | 1999 | 7.4 | 5.31 | 0.152 |
| S4 | Kocaeli Izmit Turkey | 1999 | 7.4 | 5.31 | 0.22 |
| S5 | Whittier Narrows | 1987 | 6 | 4.77 | 0.304 |
| S6 | Whittier Narrows | 1987 | 6 | 4.77 | 0.199 |

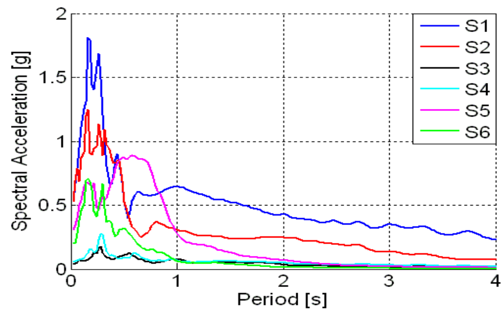


**Fig. 3.** Spectral acceleration of Near-fault earthquakes records

## 3 Structural fragility model

The fragility modeling process allows the combined effect of the uncertain variables to be propagated through the model by numerical means (e.g. simulation). The fragility is modelled commonly by a lognormal cumulative distribution function (CDF) [4,5].

$$F_R(y) = \Phi\left[\frac{\mathrm{Ln}(y/m_R)}{\beta_C}\right] \quad (1)$$

Where [ Φ ] = the standard normal probability integral, $m_R$=median capacity (expressed in units that are dimensionally consistent with the demand parameter, y, e.g. spectral acceleration) and $\beta_C$, the 'combined' uncertainty is:

$$\beta_C = \sqrt{\beta_R^2 + \beta_U^2} \quad (2)$$

Where, $\beta_R$ is the logarithmic standard deviation describing the inherent (aleatory) uncertainty and $\beta_U$ is the logarithmic standard deviation describing the epistemic uncertainty.

The steps for constructing the analytical fragility curves are as follows:

- Select the earthquake ground motion records;
- Scaling ground motion records to the same spectral acceleration at the fundamental frequency of structure;
- Make an analytical model of the structure;
- Modeling uncertainty with Latin Hypercube Sampling method;
- Select uncertainty parameters;
- Perform the non linear dynamic response analysis using selected records and uncertainty parameters;
- Construct the fragility curves using the obtained response and the ground motion indices for each limit state.

*Uncertainty modeling*

A number of sources of uncertainty are present in the modeling of fragility of the dam-foundation system and have been described statistically. Concrete compressive strength is assumed to be described by normal probability distributions [19]. For our study, the usefull statistical data are limited. Therefore, a uniform distribution was chosen to model the remaining variables. These parameters are taken as follows table 2:

**Table 2.** Uncertain parameters

| Variables | Random variables | Probability distribution |
|---|---|---|
| Var 1 | Angle of friction | U (34; 45) degrees |
| Var 2 | Cohesion | U (0.145; 0.435) MPa |
| Var 3 | Dilation angle of foundation | U (27; 33) degrees |
| Var 4 | Young modulus of concrete | U (31.2; 36) $10^3$ MPa |
| Var 5 | Young modulus of soil | U (40; 80) $10^3$ MPa |
| Var 6 | Compressive strength of concrete | N (35;4.8) MPa |

These values are based on an review of data summarized for various types of intact rock [20-23].

### 3.1 Treatment of uncertainty in fragility estimates

Seismic fragilities that incorporate sources of uncertainty considered above can be derived efficiently using Latin-hypercube sampling (LHS) [24] coupled to the finite element structural models. LHS is a stratified sampling procedure in which the PDF of each input variable, Xi, i=1,…,k, is divided into N disjoint intervals of equal probability. Latin Hypercube Sampling (LHS) provides a stratified sampling scheme rather than the purely random sampling, providing a more efficient means for covering the probability space than Monte Carlo simulation [25,26]. The sampling plan is given by

$$S = \frac{1}{N}(P - R) \quad (3)$$

where P is an N × K matrix, in which each of the K columns is a random permutation of 1, 2, . . . ,N; R is an N × K matrix of independent random numbers from the uniform distribution U(0, 1); and N and K are the numbers of hypercubes and uncertain parameters, respectively [25,26]. Each element of S, $s_{ij}$, is then mapped according to

$$x_{ij} = F_{x_j}^{-1}(S_{ij}) \quad (4)$$

Where ($F^{-1}$) is the inverse of cumulative distribution function (CDF) for parameter j. Each row of x contains different sets of sampled parameters, from which statistical samples were obtained.

### 4 Fragility analysis

The seismic fragilities for the Oued el Fodda Dam are developed from non linear dynamic analyses and to get a wider range of the variation of input ground motion, strong motion records were selected. This last are conducted with a set of earthquakes include six near-fault ground motions that are scaled to different spectral acceleration levels which varying between 0.2g and 2g with a step of 0.2g. However, every ground motion set has different spectral acceleration at the fundamental frequency of Dam. Six finite elements analyses were performed for each randomized group and the results were adequately treated. All results presented herein will be discussed for a scenario of a strong ground motion with a spectral acceleration of 2.0g. For each limit state, three performance measures and corresponds fragilities are presented.

For LS1 the fragility curves are shown in figure 4. The probability of exceedance indicating that for tensile stresses in the neck of the dam greater than 1.0 MPa , 1.5 MPa and 2.0 MPa are 100%, 76.01% and 32.57%, respectively.

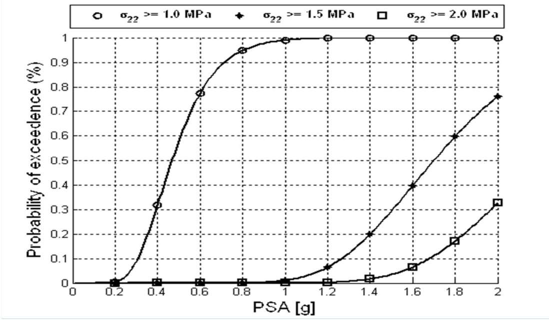


**Figure 4.** Seismic Fragility Curves for LS1 Tensile stress at the neck of dam

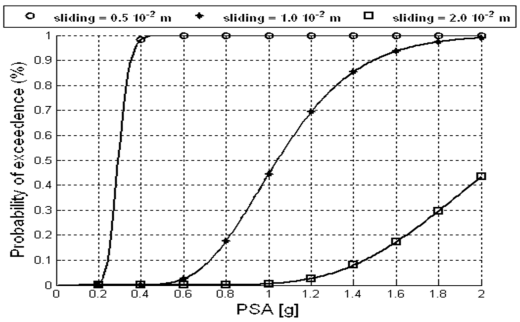


**Figure 5.** Seismic Fragility Curves for LS2 Sliding at Dam-Foundation interface

The fragility curves for sliding (LS2) at the dam–foundation interface in figure 5. Indicate that probabilities of sliding 5mm and 10 mm are very high, while the probability of sliding 20 mm is about 43.3 %. Thus, some damage to the drainage system, particularly at the dam–foundation interface, might be expected at this intensity of seismic excitation.

Relatively large sliding 20 mm or more could cause differential movements between adjacent monoliths in the dam and initiate monolith instability leading to eventual loss of pool control.

The fragilities for the displacement of the top of the dam (LS3) with respect to the heel are depicted in figure 6. A seismic excitation with spectral acceleration of 2.0g would cause relative deformations of 5 mm; 20 mm and 40 mm with probabilities of 100%; 91.32% and 82.45% respectively.

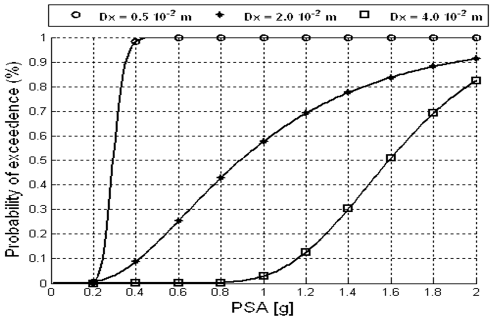


**Figure 6**. Seismic Fragility Curves for LS3 Displacement at the top of dam

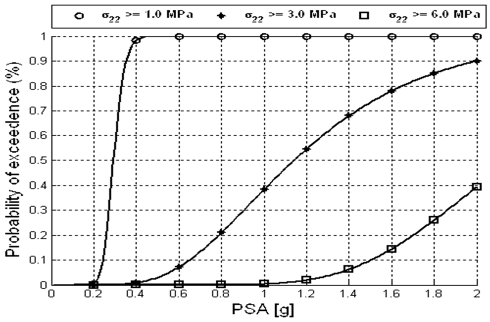


**Figure 7**. Seismic Fragility Curves for LS4 Compressive stresses at the heel of dam

These deformations are very small compared to the height of the dam and only minimal damage should be expected to gates and other appurtenant structures and operating equipment due to these deformations. Moreover, the fact that the overall deformations are on the order of 0.0004% of the height of the dam suggests that a rigid body model of the monolith might be an appropriate simplification to the problem, provided that one is not interested in the likelihood of tensile cracking at the neck of the dam.

Limit stat 4 is related to material failure and it was achieved if stresses at the heel of the dam exceeds the compressive strength of the concrete (25 MPa). It was found that the fragility illustrated in figure 7. Show that a compressive stresses of 1 MPa, 3 MPa and 6 MPa had a probability of failure of 100 %, 89.98 % and 39.28 % respectively.

## 5 Quantification of uncertainties

In order to identify the principal sources of uncertainties in the sensitivity analysis, regression analyses were performed for two cases in this study. In general, in these regression analyses, the dependent variable is risk expressed in terms of various uncertain parameters. These analyses are particularly useful in investigating how uncertainties in source term variables affect the responses of the structural system. Also determined were partial correlation coefficients that represent the importance of uncertain variables as a function of the magnitude of the environmental risk. To confirm the influence of each variables parameters as well as to remove the covariates on the correlation between a given input variable and the response variable, a sensitivity analysis based on the partial correlation has been performed. The partial correlation coefficient (*PCC*) between two random variables *Xi* and *Y* given a set of covariates $X_{/i} = \{X_1, ..., X_{i-1}, X_{i+1}, ..., X_p\}$ is defined as follows Equations 5 to 9 [27,28]:

$$PCC_i = \hat{\rho}\left(e_{X_i.X_{/i}}, e_{Y.X_{/i}}\right) \qquad 5$$

$$e_{X_i.X_{/i}} = X_i - \hat{X}i \qquad 6$$

$$\hat{X}i = \alpha_0 + \sum_{j \neq i} \alpha_j . X_j \qquad 7$$

$$e_{Y.X_{/i}} = Y - \hat{Y} \qquad 8$$

$$\hat{Y} = \beta_0 + \sum_{j \neq i} \beta_j . X_j \qquad 9$$

With:

$\beta$, $\alpha$ are the reliability index; $X_i$, $Y$ are the random variables and $X_{\backslash i}$ is the covariates; $\hat{\rho}$ is the partial correlation coefficients; $e_{X_i.X_{/i}}$ is the residual of prediction of *Xi* by *X\i* $e_{Y.X_{/i}}$ is the residual of prediction of *Y* by *X\i* ; $\hat{X}_i$ & $\hat{Y}$ are the regression variable.

The effect of the different input parameters on the displacement at the top of dam and the compressive stresses at the heel of dam under near faults earthquakes using the PCC are given on figures 8 and figure 9.

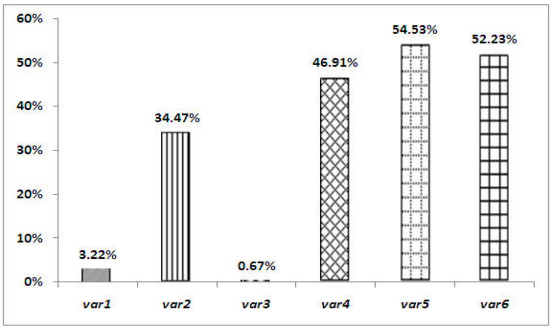


**Figure 8**. Effects on the displacement at the top of dam

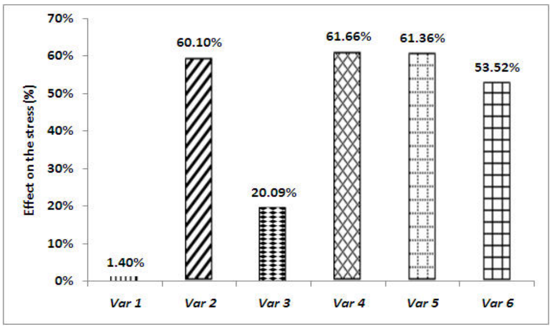


**Figure 9**. Effects on the Compressive stresses at the heel of dam

It can be shown that for both sensitivity cases studied the cohesion (Var2); the young modulus of concrete (Var4); the young modulus of soil (Var5) and the compressive strength of concrete (Var6) are the most influent when the dam is subjected to near fault earthquakes. As the displacement response and compressive stress are directly dependent on Var2; Var4; Var5 and Var6, the sensitivity should increase as shown in figure 8. And figure 9.

On the other hand, the Var1 and Var2 have a minimal sensitivity defined by the displacement at the top and stress at the heel of dam.

## Conclusions

The evaluation of seismic fragility curves of dams involving dam–reservoir–foundation interaction is studied in this paper. The seismic fragility curves were studied by means of numerical simulation procedure Latin Hypercube Sampling (LHS) in combination with nonlinear dynamic analysis. Concrete gravity dams subjected to near-fault earthquake scaled to different spectral acceleration were calculated; results for spectral acceleration of 2.0g have been considered and discussed. A series of potential sources of uncertainty associated with a seismic performance assessment of concrete gravity dam's structures are identified and also evaluated. The sensitivity study presented utilizes the uncertain parameters as inputs variables to identify which modeling parameters significantly impact the seismic response (output variable) of a number of different component responses in concrete gravity dams. The main conclusions from the presented comparison of seismic vulnerability curves of concrete gravity dams under near-fault ground motions could be summarized as follows.

It was found that, for all limits states LS1; LS2, LS3 and LS4, the probability of failures is important for low structural failure modes. However, this probability decreases with the increase of these structural failure modes. For limit state LS1, the probability of failure for tensile stress is about 2 MPa. Limit state LS2 presented a lower fragility for a sliding at dam-foundation interface of 20 mm this value is 43.3 %. For the fragility of the displacement at the top of the dam which is characterized by the limit state LS3, it was found that the likelihood of displacement is very important is about 82.45%. For limit state LS4, it was found that there is no great risk; the compressive stress is very small compared to the compressive stress of concrete, therefore, there is no significant risk at the heel of the dam. The results of sensitivity analysis, however, have been found that the variables parameters the cohesion (Var2); the young modulus of concrete (Var4); the young modulus of soil (Var5) and the compressive strength of concrete (Var6) for both faults earthquakes have a considerable sensitivity with high correlation on structure responses for displacement at the top of dam and stress at the heel of dam. However, a further study using various types of dams must be necessary to draw a solid conclusion for the fragility curves of dam's structures.

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