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Uncertainty Quantification and Sensitivity Analysis of Concrete Structure Using Multi-Linear Regression Technique

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Abstract

The dynamic analysis of structures with uncertain parameters presents an attractive field of structural health monitoring in many cases of technological interest. In the dynamic analysis of hydraulic structures, such as existing dams, modeling assumptions, resulting inaccuracies, and changes in seismic loading are typically the main sources of uncertainties. Many hydraulic structures of concrete can be subjected to seismic loads. However, it is necessary to take haphazard or random phenomena as crucial considerations when assessing the security of these structures or planning new ones. This paper shows computational analysis for the characterization of the behavior of a concrete gravity dam under seismic loads, which are considered sources of uncertainties. The multi-linear regression methodology was performed and applied to evaluate the dynamic response of the considered structure. Numerous nonlinear time history analyses based on Latin Hypercube Sampling were realized to investigate the effect of uncertain parameters on the dynamic response. These analyses were applied to two types of seismic actions, the near and far earthquakes, which act on a concrete gravity dam. Then, a sensitivity analysis was used for each random variable to quantify its risk and clarify its influence on the dynamic behavior of the dam. Results divulge that for near-fault cases, major variables affecting the global sensitivity across all limit states are the Young's modulus of soil and concrete. On the other hand, for far-fault cases, the important variables influencing the global sensitivity index include the compressive strength of concrete, Young's modulus of soil, and cohesion.

Keywords: *Damage Assessment, Multi-Linear Regression Technique, Probabilistic Model, Sensitivity Analysis, Concrete Structure.*

1. Introduction

Dynamic analysis of structures is achieved by assuming the behavior of different loads and parameters. In many fields of engineering, these loads and parameters have various origins (mechanical, thermal, environmental, etc.). They can be uncertain and relate to several excitations, such as the wind, seismic activity, and water motion. However, it is vital to find out how changes in certain loads and parameters affect the values of the dynamic response of the structure.

Hydraulic operational structures on concrete, such as dams, are structures that present important challenges in terms of public safety since their failure would have catastrophic consequences [1], [2]. Seismic activity is a particular loading that can induce the total or partial destruction of these structures (the case of the Shih-Kang dam, Taiwan). This load can present serious dangers and affect the lifespan of these structures.

The seismic activity (ground motion) has an important impact on the dam design and strongly affects

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its safety, reliability, and service quality. It is always considered a random phenomenon and can be taken as an uncertain parameter. Therefore, it is important to consider its effects on the structural responses of dams and to characterize the behavior of these structures under seismic loads. In this context, quantifying the impact of uncertainty effects is one of the most significant tasks related to the design and control of engineering constructions. Furthermore, application and development of numerical models became a major requirement to predict and analyze the dynamic response of structures. However, this suggestion is vital to limit seismic damage, quantify the impact of uncertainty attached to the model parameters and improve the analyses quality.

The importance of the impact of uncertainties might be directly related to the intensity of the seismic actions, which are usually classified as near-fault and far-fault [3], [4], [5]. Several studies have been conducted to characterize the seismic movement induced by these faults [6], [7], [8]. On the other hand, previous works investigated the effects of near/far fault ground motions. They showed that it was possible to understand the behavior of structures under seismic action [9], [10].

The sensitivity analysis reports that there are parameters which are more significant than others for the dynamic response of the dam. Parameters such as the elasticity modulus, Poisson's ratio, and the elasticity modulus of the concrete slab are frequently investigated. A sensitivity analysis on concrete rockfill dams (CFR) was carried out by Murat et al. [11]. This analysis is performed using the Monte Carlo Simulation (MCS). The effective parameters are defined by taking into account the vertical and horizontal components of displacement and principal stress.

In general, two principal models are available to predict, analyze, and estimate the behavior of structure through changes in parameters. These predictive mathematical models are the deterministic models and the statistical models. The Harmony Search algorithm (HS) is applied to optimize a Back Propagation Neural Network (BPNN). On the other hand, the HS-BPNN algorithm is trained and used for the inversion analysis of parameters of the rockfill material [12]. This study confirmed that certain parameters are sensitive to the deformation of the riprap dam. These parameters are the initial friction angle φ_0, loading modulus K, damage ratio R_f and bulk modulus number K_b. The orthogonal design method is also applied to evaluate the parameters sensitivity. Results related to this analysis show that the parameters (φ_0, K, R_f and K_b) are more sensitive to displacements. The E-ν model and the modified Burgers model are combined to define the deformation behavior of riprap materials [13]. The adapted Morris method was initially used to evaluate the parameter sensitivity in the modified E-ν model and Burgers couplers. Subsequently, a new approach has been proposed to analyze the above parameters. It is based on the grouping of the BPNN algorithm and the Cuckoo Search (CS) algorithm. This computational approach showed that the parameters K, R_f, φ_0 as well as G are more sensitive to the deformation of the body of the rockfill structure.

The model of multi-linear regression MLR may be used for the prediction and analysis of the behavior of various structures and infrastructures of concrete. As mentioned in reference [14], the authors performed MLR to predict the total estimated cost for the road construction analysis. In addition, results investigated in reference [15] focused on the application of the MLR algorithm to train machine learning concerning concrete strength prediction. On the other hand, references [16], [17] studied the behavior of concrete dams to ensure that the quality of concrete is adequate for usage conditions.

This work focuses on the study of the sensitivity of various random variables and their influence on the dynamic behavior of the concrete gravity dam. However, the admitted random variables in this study are the friction angle, cohesion, dilation angle, Young modulus of concrete, Young modulus of soil, and compressive strength of concrete. To investigate the applied analysis, the finite elements method FEM was coupled to the statistical model MLR for determining the sensitivity of parameters and quantifying their risk. Thus, the statistical MLR model brings out the correlation between the dynamic response of the concrete gravity dam and the above selected parameters. Several analyses are performed and investigated beforehand for two types of earthquakes: near-fault and far-fault earthquakes.

2. Problem Presentation

The required material characteristics and the structural model are specified in this section.

2.1. Dam description

Profiles of gravity dams have evolved with the progress of engineering and materials. Various profiles are available in practice, such as arched, symmetric, and trapezoidal profiles. Arched profiles are generally employed for masonry structures. Trapezoidal profiles with vertical areas upstream are the most traditional and better correspond to the concrete dam construction.

The studied structure is a concrete gravity dam of a trapezoidal shape completed in 1932 and can impound 225.10^6 m^3 of water. It is located in Chelf province (west Algeria) and founded on hard calcareous bedrock.

In order to obtain an appropriate dynamic analysis, the model sizes chosen for this study are as noted in [18], [19]. The model must horizontally extend the foundation length from the dam limits in the upstream and downward directions. This distance is almost the height of the dam which is 100 m. In the vertical direction (the downstream), the foundation thickness reaches a value of 200 m which is equal to twice the dam height. The thickness of the dam body increases from 5 m at the crest to 65 m at the base and the crest length is 182 m. Other dimensional details and more geometrical information are presented in Figure 1.

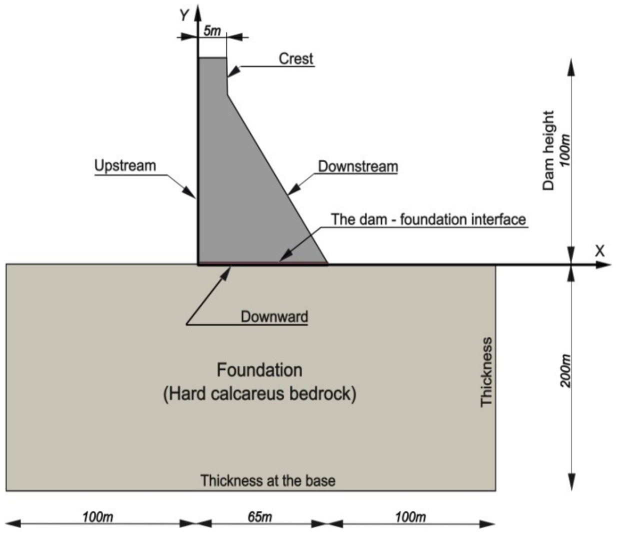


Figure 1. Dimensional details of the considered dam.

2.2. Material properties

The present section views the material properties for each one of the considered domains (massive concrete, foundation and reservoir). The mechanical properties of concrete are taken as follows: the Poisson's ratio is ν_c = 0.2, mass density is ρ_c=2500 kg/m^3, and the Young's modulus (modulus of elasticity) E_c = 31 GPa. According to previous studies [18], [19], the effects of strain rate increase the tensile strength in the case of nonlinear dynamic analyses. For this, the tensile strength of the concrete is taken as 3.75 MPa, which represents 15% of the compressive strength almost to 25 MPa. The Poisson's ratio and the Young's modulus of the foundation material are ν_f = 0.25 and E_c = 60 GPa, respectively. In addition, the water density ρ is 1000 kg/m^3 and the sound speed in water is C=1440 m/s. The value of the damping coefficient is 5%. It is taken as a ratio of the fundamental frequency of the system.

3. Problem Modeling

The complete system presented in the above section must be numerically modeled. This system consists of the dam, the reservoir, and the foundation region. It will be analyzed as a single structural system using the FEM procedures.

3.1. Mathematical and theoretical basis

The analysis of fluid-structure systems and the determination of their dynamic response have received considerable attention in the last few years. The coupled equation of motion for the solid-fluid system is given in the matrix form as follows:

$$[M]\{\ddot{X}\} + [C]\{\dot{X}\} + [K]\{X\} - [M]\{g\} = \{F_1\} + \{Q\} \quad (1)$$

$$[M_f]\{\ddot{P}\} + [C_f]\{\dot{P}\} + [K_f]\{P\} = \{F_2\} - \rho[Q]\{\ddot{X}\} \quad (2)$$

where [M], [C] and [K] are mass, damping and stiffness matrices of the solid, respectively. $[M_f]$, $[C_f]$ and $[K_f]$ denote mass, damping and stiffness matrices of the fluid, respectively. [Q] indicates the coupling matrix. {X} is the vector of displacements, {P} is the vector of pressure and the dot denotes the time derivative. $\{F_1\}$ and $\{F_2\}$ are the vectors of body force and hydrostatic force, respectively. ρ is the mass density of the fluid and {g} is the ground acceleration.

F_2 implicitly includes the force due to effects of acceleration at the boundaries of the solid-fluid (dam-reservoir and foundation- reservoir).

In order to determine the displacement and various load effects, the above system of equations must be solved in the time domain. Several integration schemes can be applied to obtain the desired solution.

3.2. Finite elements modeling and boundary conditions

The modeling of the dam–foundation dynamic interaction comprises principally three models: rigid, massed and massless. The foundation model in this study is treated as massless to facilitate the application of the ground motions input and avoid the complexities associated with large foundation models.

As noted in the above section, previous studies show that the model and size of the foundation affect the seismic response of the concrete dams. The massless foundation model requires the truncation boundary of the foundation (see Section 2: the foundation is almost twice the dam height in the upstream direction and equals the dam height in the downstream direction). Moreover, the installation of dampers at the dam–foundation boundary increases the simulation agreement, particularly for the case of the gravity dam. In addition, the consideration of the radiation damping effect of its infinite boundaries is very weak in this model and can be ignored.

The finite element model is applied for the analysis of dam–foundation interaction. This suggested model includes both dam and foundation to analyze the dam–foundation dynamic interaction.

At this level, the ABAQUS code is used to create the finite elements model. This software is computationally more useful and efficient for problems related to the evaluation of the dynamic response of structures, and it is inexpensive in terms of time cost [20]. The formulation through the finite elements model of the studied system includes 5532 isoparametric elements and 8817 nodes. Each mesh element consists of 4 nodes. In this case, it is assumed that the nodes at the bottom of the foundation are considered fixed. At the same time, only horizontal displacement is permitted to the nodes of the vertical limits of the foundation. The effect of dam-foundation interaction is considered attenuated at these nodes, but it is more significant at the horizontal surface designated for the dam-foundation interaction. Figure 2 illustrates the mesh model of the studied dam.

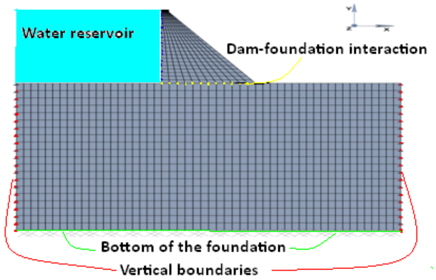


Figure 2. Domain mesh of the studied dam–foundation system.

The selected finite element model is developed to take into account the dam-foundation interaction. The relative mesh nodes to this perfect horizontal interface are able to model a two-dimensional translational problem with two degrees of freedom. The soil stratum of 200 m height is considered homogeneous and isotropic. It is placed on an infinitely rigid substratum.

The dam-reservoir interaction is represented using Darbre's model based on two parameters. This model suggests that water must be considered an incompressible mass associated in a series to dampers, which are affixed to the upstream face of the dam [21]. The idea of the Darbre's model is shown in Figure 3, and because it is discrete, it may be used immediately in time domain.

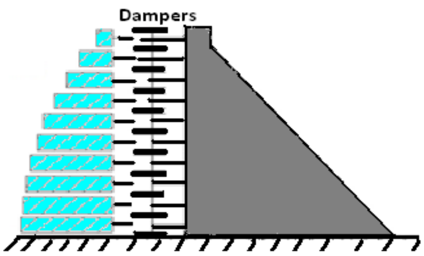


Figure 3. Description of the selected model.

3.3. Input ground motions

Selection of ground motion records is a significant topic in the dynamic analysis of structures under seismic loads. To establish the sensitivity analysis, a nonlinear analysis of the dynamic response must be used. In this study, twelve (12) earthquake records were selected (six near and six far) from (PEER Strong Motion Database) [22].

Table 1. Properties of selected near-fault and far-fault ground motion records.

N°	Earthquake	Type	PGA [m/s^2]	Epicentral distance [km]	Magnitude
1	Cap Mendocino CPM000 (1992)	Near fault	1.497	10.36	7.1
2	Cap Mendocino CPM090 (1992)	Near fault	1.039	10.36	7.1
3	KOCAELI/IZT180 (1999)	Near fault	0.152	5.31	7.4
4	KOCAELI/IZT090 (1999)	Near fault	0.22	5.31	7.4
5	WHITTIER/A-GRN180 (1987)	Near fault	0.304	4.77	6
6	WHITTIER/A-GRN270 (1987)	Near fault	0.199	4.77	6
7	Northridge-NORTHR/L09000 (1994)	Far fault	0.165	44.3	6.7
8	Northridge -NORTHR/L09090 (1994)	Far fault	0.217	44.3	6.7
9	N Palm Springs PALMSPR/ARM270 (1986)	Far fault	0.104	46.2	6
10	N Palm Springs PALMSPR/ARM360 (1986)	Far fault	0.129	46.2	6
11	San Fernando-(1971)	Far fault	0.157	23.1	6.6
12	San Fernando-SFERN/L09291 (1971)	Far fault	0.134	23.1	6.6

All signals of six near-fault earthquakes that occurred between 1987 and 1999 were considered. Their magnitudes vary from 6 to 7.1 according to the change of epicenter distances from 4.77 to 10.36 km. Moreover, six other far-fault earthquakes that occurred between 1971 and 1994 were also exploited. Their epicenters have depths which range from 23.1 to 46.2 km versus the change in magnitudes of 6.1 to 6.7.

The near-fault records are characterized by high peak acceleration (PGA) and high peak velocity (PGV). Contrarily to far-fault records, the presence of distinct velocity can cause significant damage to the structures.

Each earthquake record was calibrated and scaled at various spectral accelerations ranging from 0.2 g to 2 g with a step of 0.2 g generating 120 different earthquakes. The maximum excitation frequency chosen for the analysis should be higher than the frequencies of all main harmonics in the input ground acceleration record. Additionally, the highest excitation frequencies must be sufficiently wide to encompass the frequency range during which the dynamic response of the structure is substantial.

Table 1 presents the most important parameters that are considered for these recordings, where PGA is the peak ground acceleration.

4. Non-linear Analysis

Linear dynamic and nonlinear dynamic analyses were performed to develop capacity curves for the system under investigation. The nonlinear time history analysis must be carried out if the linear response exceeds the tolerable limit.

Because of uncertainties and structural behavior, the linear behavior assumed by the dynamic analyses does not give a precise and complete evaluation. For this reason, nonlinearities, particularly the ground motion load, must be included to obtain a more realistic dynamic analysis.

The concrete damaged plasticity model and the Mohr-Coulomb model were used to represent the nonlinear conduct of concrete in the dam structure and the foundation rock materials, respectively [20], [23]. For the effective simulation of the damage occurring in the concrete of the dam, the concrete damaged plasticity model was selected. With damage features included, this model faithfully depicts the entire inelastic behavior of concrete under compressive and tensile stresses.

The softening curves utilized for the concrete damaged plasticity model can be integrated from literature [20]. Specific curves concerning the concrete response versus uniaxial loading, both tensile and compressive loads were used and implemented.

In the nonlinear analysis, geometric nonlinearity's impact was judged insignificant in this analysis and excluded from the model under study. The concrete parameters, such as the initial compressive yield stress, compressive ultimate stress and the tensile failure stress are taken as 13 MPa, 25 MPa and 3.75 MPa, respectively. The cohesion and angle of internal friction of the foundation material are specified as 2.5 MPa and 35 degrees, respectively.

4.1. Random variables

Therefore, it is important to define input variables, which are chosen randomly according to their particular probability distributions.

Several sources of uncertainty, described statistically, are present in the sensitivity analysis. Each random variable is associated with a specific probability distribution. This distribution can be normal or uniform. The normal distribution is given with mean and standard deviation as N (μ, σ). This probability distribution is simple and one of the most appropriate models applies for interpreting the probability distribution of the compressive strength of concrete, which is taken as N (35, 4.8) MPa for this study according to reference [24]. Relevant statistical data for the remaining variables are limited and can have a defined interval for an acceptable application. The uniform distribution presented by U (min, max) is appropriate to describe these variables. Therefore, several variables used for this paper, such as the friction angle, cohesion, dilation angle of the foundation, Young modulus of concrete and Young modulus of soil, are expressed by a uniform distribution. These random variables are given by U (34; 45) degrees, U (0.145; 0.435) MPa, U (27; 33) degrees, U (31.2; 36) 10^3 MPa, U (40; 80) 10^3 MPa, respectively. Random variables and their probability distribution are detailed in several works [25], [26], [27], [28].

The sensitivity analysis integrating random variables considered above, which are assumed to be statistically independent, can be achieved effectively by using the Latin Hypercube sampling technique (LHS) [29], [30], [31].

4.2. Quantification of uncertainties

In the last recent years, several numerical methods (FEM, Boundary Elements Method BEM, etc.), statistical techniques (MLR, Robust Regression RR, etc.), advanced tools (machine learning ML, Neural Network NN, etc.) and combined methods have been widely applied to predict dam response and analyze its dynamic behavior. Different studies show that MLR models exhibit excellent predictive capabilities. They can be used to investigate the impact of certain random variables on the model responses [18], [19], [32], [33], [34], [35].

The statistical techniques employed in this context are based on results obtained through the Latin Hypercube Sampling Technique. Moreover, the sensitivity analysis is conducted using the MLR technique. Reference [32] showed that the advantage of the MLR technique is to define the most dominant input variables. The total reduction of each input variable on the residual sum of squares (RSS) must be quantified. The regression equation is expressed as follows:

$$Y = \beta_0 + \sum_{i=1}^{P} \beta_i X_i + \varepsilon_i \tag{3}$$

where Y represents the dependent variable (dependent output variable), X_i denote independent variables (independent input variables), β_0 is the intercept, P is the number of input parameters, ε_i is random error and β_i are partial regression coefficients. If there are N observations (realized tests), Equation 3 is given in the matrix form as:

$$\begin{Bmatrix} Y_1 \\ \vdots \\ Y_N \end{Bmatrix} = \begin{bmatrix} 1 & X_{11} & \cdots & X_{1P} \\ \vdots & & \ddots & \vdots \\ 1 & X_{1n} & \cdots & X_{PN} \end{bmatrix} \begin{Bmatrix} \beta_0 \\ \vdots \\ \beta_N \end{Bmatrix} \begin{Bmatrix} \varepsilon_0 \\ \vdots \\ \varepsilon_N \end{Bmatrix} \tag{4}$$

The regression coefficient is the partial derivative of the dependent variable with respect to each of the independent variables. The regression coefficient is a measure of the linear sensitivity of Y to input X_i. Moreover, the (Xi) are assumed to be independent random variables. It is therefore a question of calculating the vector of regression coefficients β_i defined by the following expression:

$$\{\beta_i\} = \left[[X][X]^T\right]^{-1} [X]^T\{Y_i\} \tag{5}$$

where T and -1 denote the transposed matrix and the inverse matrix of the matrix X, respectively.

The MLR model aim is to find the estimates of the parameters and compare them with those calculated to understand the parameters sensitivity and evaluate their impact on the dynamic response of the dam. The expectation E (Y) and the variance V (Y) can be written as:

$$E(Y) = \beta_0 + \sum_{i=1}^{p} \beta_i E(X_i) \quad (6)$$

$$V(Y) = \sum_{i=1}^{p} {\beta_i}^2 V(X_i) \quad (7)$$

where $E(X_i)$ and $V(X_i)$ are the mean and the variance of X_i, i = 1,…, p, respectively. This expression allows us to identify the contribution of the variance of each X_i in the total variance of Y by ${\beta_i}^2 V(X_i)$. The global sensitivity index called SRC (Standardized Regression Coefficient), representing the part of the variance of the response Y due to the variance of the variable Xi, is defined by:

$$SRC_i = \frac{{\beta_i}^2 V(X_i)}{V(Y)} \quad (8)$$

Unlike the correlation coefficient, the index thus defined in Eq. (8) provides information about the impact of each input variable X_i on the response Y. This coefficient is determined without worrying about the sign of the impact.

As mentioned in the introduction, the admitted random variables in this study are the friction angle, cohesion, dilation angle, Young modulus of concrete, Young modulus of soil and compressive strength of concrete. These variables are denoted by X_1, X_2, X_3, X_4, X_5, X_6, respectively. The dependence of six input parameters and the output value can be expressed using the MLR model as:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 \quad (9)$$

4.3. Limit states

The mean objective in structure analysis is to conclude the failure mode in which model parameters exceed the design limit. The mathematical expression that describes these levels is identified as a performance function, also known as the limit state function. However, the structure state is unsafe when it is unable to ensure its function and safe when not.

Three types of limit state damages can be considered for the desired analysis of sensitivity. These damages represent different failure modes of the dam under consideration, namely:

- LS1: When there is sliding at the interface between the dam and its foundation.
- LS2: When displacement at the dam’s crest exceeds the acceptable value.
- LS3: When there is material failure of concrete at the dam's heel and this failure exceeds the referred maximum.

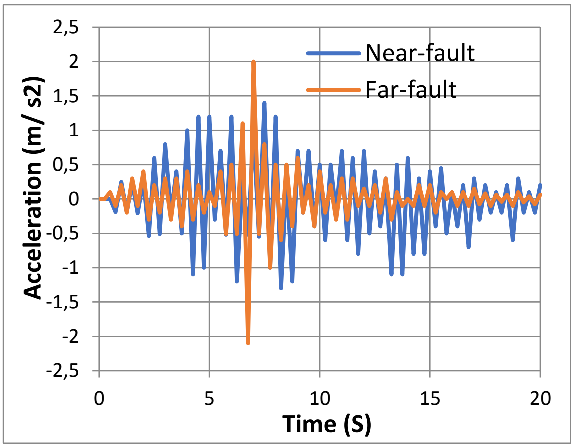
5. Results and Discussion

The problem has been solved on a workstation equipped with 24-Cores/ 32-Threads Intel Core i9 (13th Gen) 13900 K CPU 3 GHz, 68 MB Cache, 128 GB RAM, and 2To SSD hard disk. This workstation reduces the time cost considerably by more than 80% compared to a standard PC with Intel CPU 2.8 GHz, which takes about 4 to 5 hours to run one simulation.

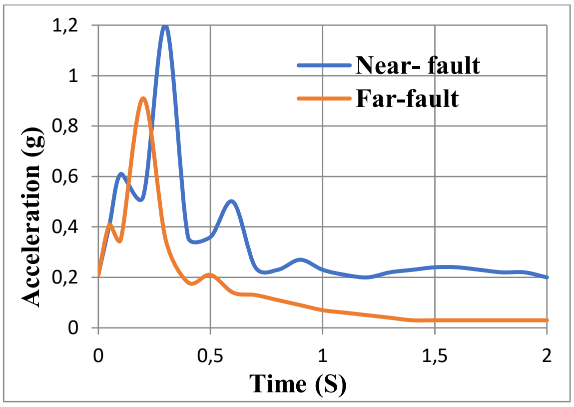
Firstly, static analysis of the dam-foundations model with a full reservoir is performed to simulate the pre-seismic step in order to extract primary values of characteristic parameters. These results can lastly be used as initial conditions of the dynamic analysis. Moreover, the natural frequencies are determined by the resolution of the above equations to conduct the linear and non-linear dynamic analysis. This determination is performed using the ground motion input and its related selection. Under appropriate criteria for the chosen model, static tensile stresses are very small and can be neglected. On the other hand, the compressive stresses of concrete for static loads are lower than the compressive strength of concrete. The principal value of the compressive stresses is 13.2 MPa, which represents 52.8% of the compressive strength. This value is acceptable for a linear behavior of concrete in compression. These findings affirm the dam stability.

The time-domain dynamic analysis is carried out with the selected seismic ground motion to determine the dynamic properties of the system. The ground motion records selected from the PEER Database and their information are used to obtain the acceleration and the acceleration response spectra for each record.

Due to the important number of simulations (120 examples), it is difficult to present all the treated cases. Figure 4(a) only shows the acceleration and the acceleration response spectra of the horizontal component of two chosen records for near-fault and far-fault ground motion. The characteristics of the selected ground motions are M (7.4), PGA (0.15), M (6.7) and PGA (0.22) for near-fault and far-fault ground motion, respectively. Figure 4(b) illustrates that the period response in the case of the near-fault is more excessive than the one of the far-fault.



a- Acceleration.



b- Acceleration response spectrum.

Figure 4. The time-domain dynamic for near-fault and far-fault ground motion.

The displacements are greater for near-fault cases than those obtained for far-fault cases. The supposition of the massless foundation type involves more decreasing of displacement of dam crest. In addition, it leads to a decrease in crack profiles, conjointly with the assumption considering the foundation flexible. Moreover, the presence of dampers permits high absorption of energy. The difference between the Young modulus of concrete and Young modulus of foundation may leads increasing on horizontal displacements.

The statistical models efficiency can be assessed based on the calculus of several statistical error metrics, such as the coefficient of determination R-Square R^2. Statistical results for regression show that the values of the coefficient R^2 describe strength moderation which presents high precision and reliability in the applied model. All analyses were carried out to ensure a level of confidence at almost 92 %.

The massless model for dam-foundation provides realistic evolution on the dynamic analysis. The comparison of the obtained results and those recorded in previous publications [1], [18], [19], [32], [33], [34], [35], [36], [37], shows good resemblances on the evolution and region distributions of stress.

The global sensitivity analysis was conducted on a model that performs 120 samples generated through LHS. The findings were categorized according to the three specified limit states (see previous sections). The MLR technique was applied to obtain β_i coefficients values that decrease the difference between the predicted and measured quantities of interest (limit states) based on the given structure data. The global sensitivity measures, along with total variance values, are computed based on the LS1, the maximum LS2, and the maximum LS3, as illustrated in Figures 5 to 10.

In scenarios involving near earthquakes, the measures of the global sensitivity for LS1 and LS2 show that the most significant variables include cohesion, Young modulus of concrete, Young modulus of soil, and compressive strength of concrete. Figure 5 and Figure 6 illustrate that the ratio of participation in the global sensitivity of each of these variables is greater than 13%. Conversely, the results indicate that the friction angle, dilatation, and cohesion for LS3 are the least influential variables within this model. Figure 7 shows that the sum of these variables presents less than 12% of the global sensitivity value.

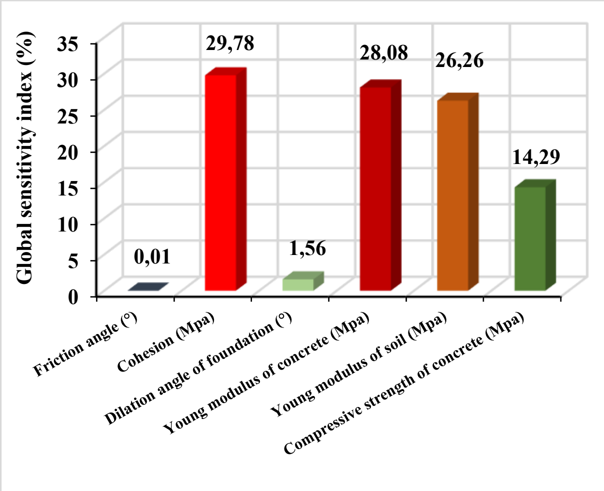


Figure 5. Global sensitivity of LS1 for Near-Earthquake.

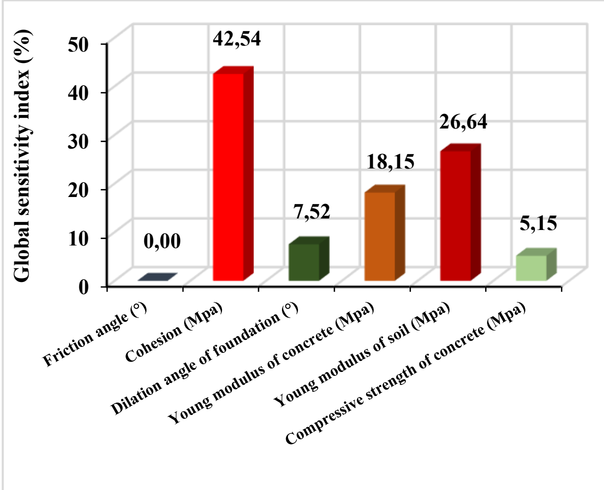


Figure 8. Global sensitivity of LS1 for Far-Earthquake.

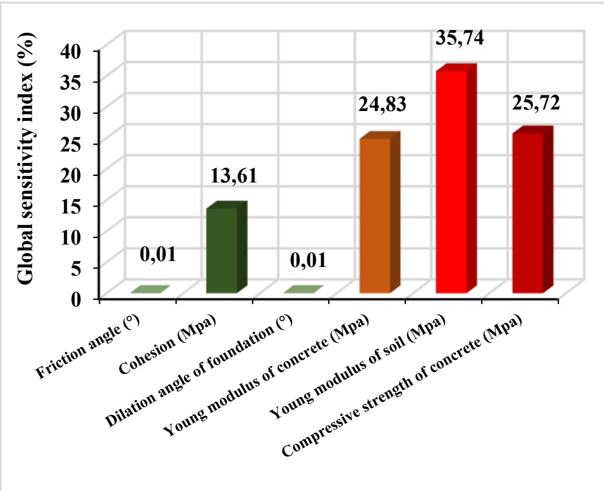


Figure 6. Global sensitivity of LS2 for Near-Earthquake.

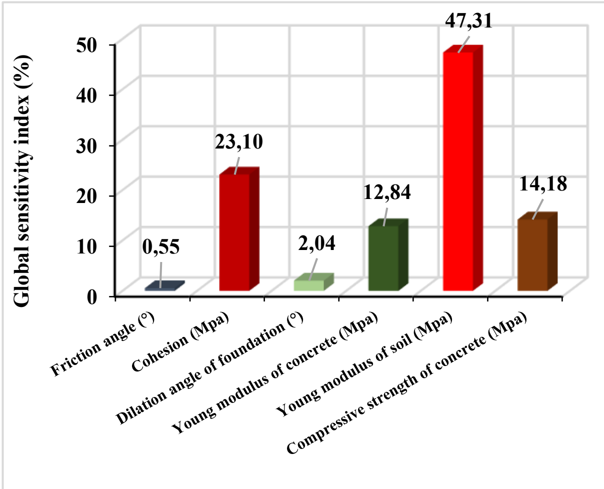


Figure. 9. Global sensitivity of LS2 for Far-Earthquake.

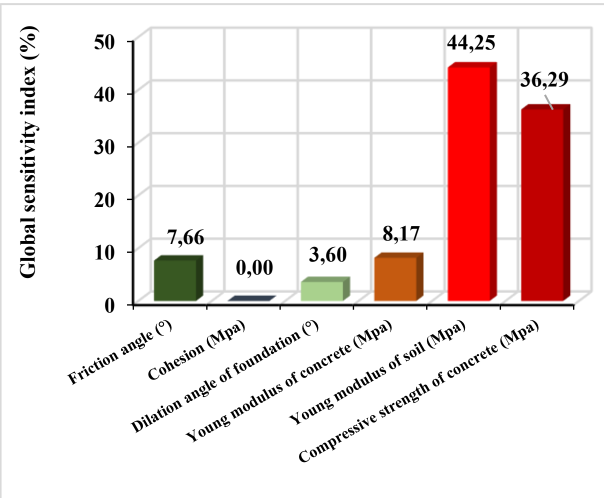


Figure 7. Global sensitivity of LS3 for Near-Earthquake.

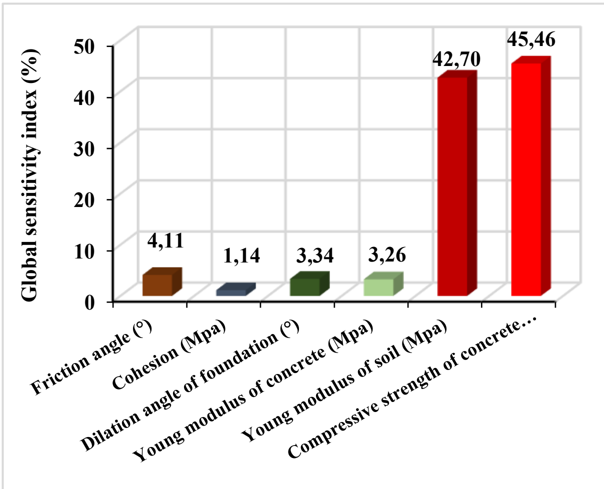


Figure 10. Global sensitivity of LS3 for Far-Earthquake.

Nonetheless, in the case of far earthquakes, the global sensitivity measures, based on the above conditions, reveal that for LS1, LS2, and LS3 the analysis continues to yield critical insights. The same trend is generally observed for all variables for both the near and far earthquakes. The effect of the friction angle is null or almost null for LS1 and LS2, respectively, as mentioned in Figure 8 and Figure 9. It attains 4.11% for LS3 as shown in Figure 10. The ratio of participation in global sensitivity measures varies from one variable to another for all cases. The cohesion is significant for LS1 and has a weak impact of <1.5% for LS3 for both cases considered in this analysis. On the other hand, the compressive strength of concrete presents a feeble influence on LS1 in the case of far earthquakes compared to other cases. In addition, Young modulus of soil gives an important ratio not less than 25% for all cases.

Akaike's information criterion AIC, which measures the quality of the statistical models, is used for the different limit states for both types of near and far earthquakes and is given in Table 2 and Table 3.

Table 2. Akaike's criterion of the most influencing random variables on the response for Near-Earthquake.

Parameter	LS1	LS2	LS3
Friction angle (°)	0	0	0
Cohesion (Mpa)	1	1	0
Dilation angle (°)	0	0	0
Young modulus of concrete (Mpa)	1	1	1
Young modulus of soil (Mpa)	1	1	1
Compressive strength of concrete (Mpa)	1	1	1

Table 3. Akaike's criterion of the most influencing random variables on the response for Far-Earthquake.

Parameter	LS1	LS2	LS3
Friction angle (°)	0	0	0
Cohesion (Mpa)	1	1	0
Dilation angle (°)	1	0	0
Young modulus of concrete (Mpa)	1	1	0
Young modulus of soil (Mpa)	1	1	1
Compressive strength of concrete (Mpa)	1	1	1

However, the model is more suitable if the AIC value is smallest.

The global sensitivity indices (SRC), which indicate the percentage of sensitivities of each input parameter on the response variable for all limit states for near and far earthquakes, are given in Table 4 and Table 5.

Table 4. Global sensitivity index (SRC) for Near-Earthquake.

Parameter	LS1	LS2	LS3
Friction angle (°)	0.01	0.01	7.66
Cohesion (Mpa)	29.78	13.61	0.01
Dilation angle (°)	1.57	0.01	3.6
Young modulus of concrete (Mpa)	28.08	24.83	8.17
Young modulus of soil (Mpa)	26.26	35.74	44.25
Compressive strength of concrete (Mpa)	14.3	25.72	36.29

Table 5. Global sensitivity index (SRC) for Far-Earthquake.

Parameter	LS1	LS2	LS3
Friction angle (°)	0	0.55	4.11
Cohesion (Mpa)	42.54	23.1	1.14
Dilation angle (°)	7.52	2.04	3.34
Young modulus of concrete (Mpa)	18.15	12.84	3.26
Young modulus of soil (Mpa)	26.64	47.31	42.7
Compressive strength of concrete (Mpa)	5.15	14.18	45.46

The parameter influence is stronger if the SRC value is larger. The interpretation of these results reported in Table 4 confirms that for near or far earthquakes, the response for all limit states to each input parameter is given as a linear relationship. This linear relationship assumes that for near earthquakes, LS1 will increase by 29.78%, 28.08%, 26.26% and 14.3% if the cohesion, Young modulus of concrete, Young modulus of soil and compressive strength of concrete, respectively, increase by 1%. It also increases by 1.57% if the dilation angle increases by 1%. The effect of the friction angle has a negligible impact in this case.

Table 4 also shows that LS2 increases by 35.74%, 25.72%, 24.83% and 13.61% if the Young modulus of soil, compressive strength of concrete, Young modulus of concrete and cohesion increase by 1%, respectively. The effects of the friction angle and dilation angle have a negligible impact in this case. Moreover, LS3 increases by 44.25%, 36.29%, 8.17% and 7.66% if the Young modulus of soil, compressive strength of concrete, Young modulus of concrete, and friction angle, respectively, increase by 1%. It also increases by 3.6% if the dilation angle increases by 1%. The effect of cohesion has a negligible effect in this case.

The same approach can be used to interpret all the above findings and analyze the impact of any variable on the desired response (Table 5).

The dependence of six input parameters and the output values can be expressed in the case of far earthquakes as:

$$\begin{aligned} Y(LS1) = \beta_0 &+ 42.54\,X_2 + 7.52X_3 \\ &+ 18.15X_4 + 26.64X_5 \\ &+ 5.15X_6 \end{aligned}$$

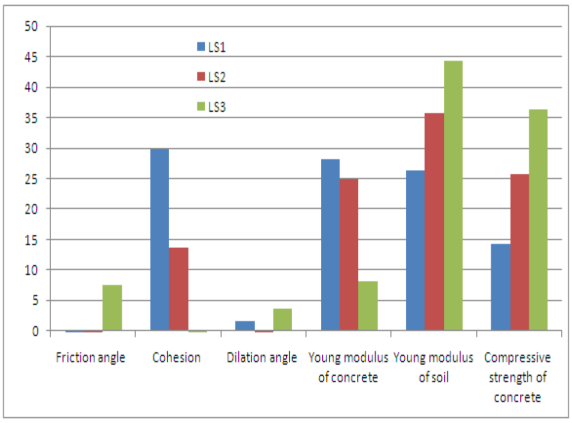
$$\begin{aligned} Y(LS1) = \beta_0 &+ 0.55X_1 + 23.1X_2 + 2.04X_3 \\ &+ 12.84X_4 + 47.31X_5 \\ &+ 14.18X_6 \end{aligned} \quad (10)$$

$$\begin{aligned} Y(LS1) = \beta_0 &+ 4.11X_1 + 1.14X_2 + 3.34X_3 \\ &+ 3.26X_4 + 42.7X_5 \\ &+ 45.46X_6 \end{aligned}$$

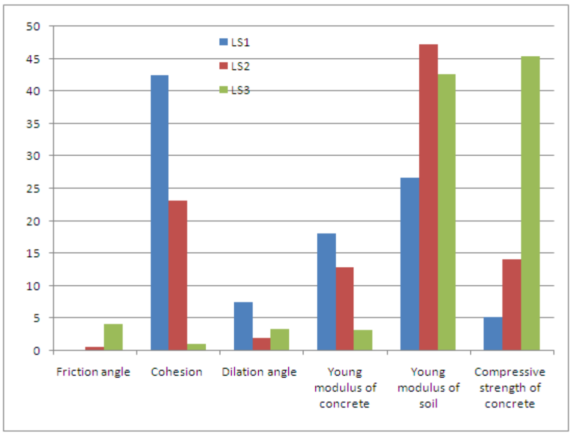
where X_1, X_2, X_3, X_4, X_5, X_6, denote the friction angle, cohesion, dilation angle, Young modulus of concrete, Young modulus of soil and compressive strength of concrete, respectively.

Figure 11 illustrates the influence capacity of each parameter on the dam response. Figure 11(a) shows that parameters X2, X4, X5 and X6 have the most significant influence on the desired response for LS1 and LS2, with a weight of up to 98.42% and 99.9%, respectively. In addition, parameters X5 and X6 participate in the LS3 case with a weight of up to 80.54%. Figure 11(b) shows that parameters X2, X5 and X6 have the most significant influence on the desired response for LS1, with a weight of up to 87.33%. On the other hand, parameters X2, X4, X5 and X6 impact the response with participation up to 97.43% and parameters X5 and X6 participate for the LS3 case with a weight of up to 88.16%.

It is important to interpret and compare the impact of any input variable on another variable. To address this problem, standardized values could be used to evaluate the relative strength of the predicted values within the model. The relation between the observed values (collected values) and predicted values (generated values by the regression model) constitutes the basis of the residual analysis. This analysis plays a critical role in the model comparison. Residual standard deviation is applied to describe the discrepancy in standard deviations between both observed values and predicted values. A small standard deviation indicates that the model is very closely around the mean. The analysis in this study leads to an important reduction in standard deviations for all modes. There was a significant reduction of 72.01% with an R2 value of 0.93 for example.



a) Parameters influence (Near-faults).



b) Parameters influence (Far-faults)

Figure 11. Parameters influence on the dam response.

6. Conclusions

This study examines a probabilistic numerical model of a concrete gravity dam subjected to seismic forces. The analysis focuses on the dam's performance in relation to sliding at the dam-foundation interface and displacement at the dam's crest. In addition, it focuses on the material failure of the concrete at the heel. These damages are defined as limit states. To investigate the effects of ground motion, a parametric study is conducted using the same ground motion at varying intensity levels. The primary aim of this research is to accurately assess the impact of key design parameters, taken as random variables, on the sensitivity of the dam-foundation-reservoir system under seismic loading.

A global sensitivity analysis utilizing Latin Hypercube sampling was employed for this purpose. Sensitivity measures were derived for three limit state functions. The multi-linear regression MLR analysis was carried out to predict the concrete dam behavior using six variables. These variables, namely, are the friction angle, cohesion, dilation angle, Young modulus of concrete, Young modulus of soil and compressive strength of concrete. The MLR model was developed for the concrete dam for different limit states.

Results reveal that for near earthquake scenarios, the most significant variables affecting global sensitivity across all limit states are the Young’s modulus of soil and concrete. In contrast, for far-earthquake scenarios, the key variables influencing the global sensitivity index include the compressive strength of concrete, the Young’s modulus of soil, the Young’s modulus of concrete, and the cohesion. The most influential parameters are those on which uncertainty must be reduced as a priority in order to provide a reduction in uncertainty on the most important output. Conversely, the least influential parameters can be set to a nominal value, which simplifies the model.

The significant practical implication of this study is that the six input parameters are positively correlated with the selected three limit states. Some finite element models used to analyze the structural problem, such as the dam response to earthquake excitation, are based on prototype dynamic testing. These tests, which use artificial excitation, can cause undesirable effects on the structure and are relatively costly. Therefore, in order to obtain more accurate results, damping must be incorporated using mathematical calculations. This research can be explored to reduce the possible losses caused by seismic loads, evaluate the seismic resistant capacity of a dam, and reduce the maintainability and design costs. On the other hand, system optimization and decision-making are significant practical implications of the findings for the interpretation of the selected model.

However, the dynamic response of a concrete dam to the seismic load produces great dynamic stresses. For instance, further research is needed on terms of foundation rock type and behavior, applied criteria, and constitutive relations. It is therefore recommended to involve more data issued from predictive numerical methods to enhance the dam safety.

Conflict of Interest

The authors declared no potential conflicts of interest concerning the research, authorship, and publication of this article.

Data Availability Statements

No data or additional materials were utilized for the research described in the article.

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7. References

[1] R. Hellgren, R. Malm, A. Ansell, “Performance of data based models for early detection of damage in concrete dams”, *Structure and Infrastructure Engineering*, vol. 17, no. 2, pp. 275-289, 2021, https://doi.org/10.1080/15732479.2020.1737146.

[2] V. Khoroshilov, N. Kobeleva, M. Noskov, “Analysis of possibilities to use predictive mathematical models for studying the dam deformation state”, *J. Appl. Comput. Mech.*, vol. 8, no. 2, pp. 733-744, 2022, https://doi.org/10.22055/JACM.2022.38005.3129.

[3] G. Scala, G. Festa, and S. Del Gaudio, “Relation between near-fault ground motion impulsive signals and source parameters”, *Journal of Geophysical Research:*

Solid Earth, vol. 123, pp. 7707-7721, 2018, https://doi.org/10.1029/2018JB015635.

[4] D. Ertuncay, P. Malisan, G. Costa, S. Grimaz, “Impulsive signals produced by earthquakes in Italy and their potential relation with site effects and structural damage”, *Geosciences*, vol. 11, no. 261, 2021, https://doi.org/10.3390/geosciences11060261.

[5] D. Ertuncay, G. Costa, “Determination of near-fault impulsive signals with multivariate naïve Bayes method”, *Natural Hazards*, vol. 108, pp. 1763-1780, 2021, https://doi.org/10.1007/s11069-021-04755-0.

[6] D. Yang, J. Zhou, “A stochastic model and synthesis for near-fault impulsive ground motions”, *Earthquake Engineering and Structural Dynamics*, vol. 44, no. 2, pp. 243-264, 2015, https://doi.org/10.1002/eqe.2468.

[7] P. G. Somerville, “Magnitude scaling of the near fault rupture directivity pulse”, *Phys. Earth. Planet. Inter.,* vol. 137, no. (1–4), pp. 201-212, 2003, https://doi.org/10.1016/S0031-9201(03)00015-3.

[8] S. U. Sigurdsson, R. Rupakhety, R. Sigbjörnsson, “Adjustments for baseline shifts in far-fault strong-motion data: an alternative scheme to high-pass filtering”, *Soil. Dyn. Earthq. Eng.*, vol. 31, no. 12, pp. 1703-1710, 2011, https://doi.org/10.1016/j.soildyn.2011.07.006.

[9] B. Sevim, S. Atamturktur, A. Can Altunisik, A. Bayraktar, “Ambient vibration testing and seismic behaviour of historical arch bridges under near and far fault ground motions”. *Bull. Earthquake Eng.*, vol. 14, no. 1, pp. 241-259, 2016, https://doi.org/10.1007/s10518-015-9810-6.

[10] D. Vafaei, R. Eskandari, “Seismic response of mega buckling-restrained braces subjected to fling-step and forward-directivity near-fault ground motions”, *Struct. Design Tall. Spec. Build*, vol. 24, no. 9, pp. 672-686, 2015, https://doi.org/10.1002/tal.1205.

[11] E. K. Murat, B. B. Hasan, B. Alemdar, “Probabilistic nonlinear analysis of CFR dams by MCS using Response Surface Method”, *Applied Mathematical Modelling*, vol. 35, pp. 2752-2770, 2011, https://doi.org/10.1016/j.apm.2010.12.003.

[12] P. Sun, T. Bao, C. Gu, M. Jiang, T. Wang, Z. Shi, “Parameter sensitivity and inversion analysis of a concrete faced rock-fill dam based on HS-BPNN algorithm”, *Science China Technological Sciences*, vol. 59, no. 9, pp. 1442-1451, 2016, https://doi.org/10.1007/s11431-016-0213-y.

[13] Y. Chen, C. Gu, C. Shao, X. Qin, “Parameter sensitivity and inversion analysis for a concrete face rockfill dam based on CS-BPNN”, *Advances in Civil Engineering*, 2019:9742961, 2019, https://doi.org/10.1155/2019/9742961.

[14] Jherimae C. Ancheta et al, “Road construction analysis using regression technique”, *World Journal of Advanced Research and Reviews*, vol. 18, no. 03, pp. 658-664, 2023, https://doi.org/10.30574/wjarr.2023.18.3.1125.

[15] Peggy Suenie Anak Achong, Nickholas Anting Anak Guntor, “Concrete strength prediction using linear regression of machine learning algorithm”, *Recent Trends in Civil Engineering and Built Environment,* vol. 2, No. 1, pp. 691-699, 2021, https://doi.org/10.30880/rtcebe.2021.02.01.075.

[16] J. Mata, “Interpretation of concrete dam behavior with artificial neural network and multiple linear regression models”, *Engineering Structures*, vol. 33, no. 3, pp. 903-910, 2011, https://doi.org/10.1016/j.engstruct.2010.12.011.

[17] S. Charhate, M. Subhedar, N. Adsul, “Prediction of concrete properties using Multiple Linear Regression and Artificial Neural Network”, *Journal of Soft Computing in Civil Engineering*, vol. 2-3, pp. 27-38, 2018, https://doi.org/10.22115/SCCE.2018.112140.1041.

[18] A. K. Chopra, *Earthquake engineering for concrete dams: Analysis, design, and evaluation*, Wiley-Blackwell, 2020, https://doi.org/10.1002/eqe.3660.

[19] *EM 1110-2-6051 Time-history dynamic analysis of concrete hydraulic structures*, US Army Corps of Engineers, Washington, D.C, 2003.

[20] *Abaqus Analysis user’s, examples problem, and theory manuals Version 6.7*, The Dassault Systèmes Simulia. Providence, RI, 2007.

[21] G. R. Darbre, “Phenomenological two-parameter model for dynamic dam–reservoir interaction”, *J Earthquake Eng*, vol. 2, no. 44, pp. 513-524. 1998.

[22] PEER Strong Motion Database, http://peer.berkeley.edu/smcat/search.html.

[23] J. Lee, G. L. Fenves, “A plastic-damage concrete model for earthquake analysis of dams”, *Earthquake Engineering and Structural Dynamics*, vol. 27, pp. 937-956, 1998.

[24] C. Kafali, M. Grigoriu, “Seismic fragility analysis: application to simple linear and nonlinear systems”, *Earthquake Engineering and Structural Dynamics*, vol. 36, no. 13, pp. 1885-1900, 2007, https://doi.org/10.1002/eqe.726.

[25] S. Soroushian, E. Rahmanishamsi, K. Ryu, M. Maragakis, A. Reinhorn, “Experimental fragility analysis of suspension ceiling systems”, *Earthq Spectra*, vol. 32, no. 2, pp. 881-908, 2016, https://doi.org/10.1193/071514eqs109m.

[26] O. C. Celik, B. R. Ellingwood, “Seismic fragilities for non-ductile reinforced concrete frames – role of aleatoric and epistemic uncertainties”, *Structural Safety*, vol. 32, no. 1, pp. 1-12, 2010, https://doi.org/10.1016/j.strusafe.2009.04.003.

[27] E. M. Güneyisi, G. Altay, “Seismic fragility assessment of effectiveness of viscous dampers in R/C buildings under scenario earthquakes”, *Structural Safety*, vol. 30, no. 5, pp. 461-480, 2008, https://doi.org/10.1016/j.strusafe.2007.06.001.

[28] D. M. Seyedi, P. Gehl, J. Douglas, L. Davenne, N. Mezher, S. Ghavamian, “Development of seismic

fragility surfaces for reinforced concrete buildings by means of nonlinear time-history analysis", *Earthquake Engineering and Structural Dynamics*, vol. 39, no. 1, pp. 91-108, 2010, https://doi.org/10.1002/eqe.939.

[29] Lupoi, C. Callari, "The role of probabilistic methods in evaluating the seismic risk of concrete dams". *In Protection of Built Environment Against Earthquakes*, Dolšek M (eds). Ljubljana: Springer 309-329. 2011.

[30] Lupoi, C. Callari, "A probabilistic method for the seismic assessment of existing concrete gravity dams", *Struct. Infrastruct. Eng.*, vol. 8, pp. 985-998, 2012, https://doi.org/10.1080/15732479.2011.574819.

[31] X. Yao, A. Elnashai, J. Jiang, "Analytical seismic fragility analysis of concrete arch dams", *Proceedings of the 15th World Conference on Earthquake Engineering*, Lisbon, Portugal, 2012.

[32] W. Mengchao, W. Jonathan, B. Alexander, B. Richard, "A comparison of approaches to stepwise regression on variables sensitivities in building simulation and analysis", *Energy and Buildings*, vol. 127, pp. 313-326, 2016, https://doi.org/10.1016/j.enbuild.2016.05.065.

[33] F. Salazar, R; Morán, M. A; Toledo, O. Eugenio, "Data-Based models for the prediction of dam behaviour: a review and some methodological considerations", *Arch Computat Methods Eng*, vol 24, pp. 1-21, 2017, https://doi.org/10.1007/s11831-015-9157-9.

[34] E. Hadzalic, A. Ibrahimbegovic, I. S. Dolarevic, "Theoretical formulation and seamless discrete approximation for localized failure of saturated poro-plastic structure interacting with reservoir". *Computers & Structures*, vol. 214, pp.73-93, 2019, https://doi.org/10.1016/j.compstruc.2019.01.003.

[35] V. Khoroshilov, N. Kobeleva, and M. Noskov, "Analysis of possibilities to use predictive mathematical models for studying the dam deformation state". *J. Appl. Comput. Mech*, vol. 8, no. 2, pp. 733-744, 2022, https://doi.org/10.22055/JACM.2022.38005.3129.

[36] Z. Heirany, M. Ghaemian, "Effect of foundation in dynamic analysis of concrete gravity dams", *GRAĐEVINAR*, vol. 64, no. 8, pp. 641-646, 2012.

[37] R. K. Saithawar, et al, "Seismic response analysis of concrete gravity dams using ABAQUS", *Erudite Journal of Engineering Technology and Management Sciences*, vol. 4, no. 1, pp. 01-08, March 2024.