3D SEISMIC ANALYSIS OF ARCH DAM FOR RANDOM GROUND MOTION

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Abstract: *Most studies on the dam's seismic response considered earthquakes a deterministic process. There are very few studies for dams where the earthquake was considered a random process. The present study deals with the three-dimensional seismic analysis of the Morrow Point arch dam under the Kern County earthquake (1952), where the earthquake is considered a fully correlated ground motion. Assuming the ground motion to be an ergodic process, the power spectral density function (PSDF) of the Kern County earthquake represents the random ground excitation of the dam. C3D8R stress elements model the arch dam structure. The fluid-structure interaction is included by modeling the upstream water as AC3D8R acoustic elements. Direct spectral analysis is performed by obtaining the responses of the dam under harmonic base excitations considering fluid-structure interaction. The amplitude and frequency of the base excitation are varied to obtain the transfer function of the response quantities of interest; this part of the analysis is executed by ABAQUS. With the transfer functions of the responses known, the PSDF of response is determined by standard spectral analysis technique. For this purpose, a separate program is written using MATLAB code. The response quantities of interest are the mean peak top displacement at the top center of the arch dam and mean peak stresses at some critical locations. The mean peak values of response obtained from Kern County spectral analysis are compared with the peak responses obtained from the time history analysis.*

1 Introduction

Seismic vulnerability evaluations were conducted for concrete dams commonly utilized in water and river management projects. These assessments covered Gravity and Arch dam designs and integrated water-structure interactions into the seismic response analysis. Gravity dam assessments used a simplified 2D slice analysis method, analyzing various dam sections for critical stress and displacements. However, this method wasn't suitable for dynamic analysis of arch dams, as it couldn't adequately capture their critical responses.

Hence, most analyses of arch dams now focus on a thorough 3D analysis, considering various interactions, to comprehensively evaluate their behavior. Höllinger and Wein presented solutions for the interacting vibrations of a linear elastic arch dam with a linear compressible, three-dimensional, irregularly shaped fluid body. The vibration response was derived for both time-harmonic excitation of the arch dam and nonstationary stochastic excitation processes relevant to earthquake analysis. In the time-harmonic solutions, a substructure synthesis method was utilized. The arch dam was treated using the finite element method, while the fluid domain employed a boundary integral equation method, also known as the boundary element method(Höllinger and Wein, 1983). Fok and Chopra studied how the Morrow Point arch dam responded to the Taft ground motion under different water levels and foundation rock conditions. Their findings indicated that the dam's earthquake response was amplified due to the interaction between the dam and water. At the same time, it was reduced by the reservoir boundary's capacity to absorb seismic effects (Fok et al.,1986). Duron and Hall conducted experiments and finite element studies to investigate how the Morrow Point arch dam responds to forced vibrations. Their work effectively isolated and analyzed the dam's response related to its fundamental vibration mode (Duron and Hall, 1988). Connor and Boot created a method for studying the reservoir system of an arch dam, with particular attention to considering the compressibility of water. Their analysis approach applied the Newmark implicit integration scheme(O'Connor & Boot, 1988). Yang et al. conducted a study analyzing a circular section spanning 90 degrees and extending infinitely on two sides. They formulated solutions for nonstationary random vibrations and hydrodynamic forces. Their main goal was to understand how a basic arch dam reservoir system responds to nonstationary random forces, effectively depicting earthquake ground movements. To simplify their analysis, they treated the dam as elastically deformable, primarily focusing on its first symmetric mode shape for simplicity. They described earthquake acceleration using a zero-start stationary process characterized by a Kanai-Tajimi spectral density function. The outcome of their study provided solutions for stochastic vibration and hydrodynamic force responses, which were expressed in generally nondimensional forms using nonstationary power spectral density functions and mean square functions (Yang et al.,1991). Tan and Chopra conducted a study focusing on the response of dam-foundation rock interaction to various ground motions. They examined critical factors like dam properties, rock properties, reservoir boundary materials, and boundary absorption. Their findings revealed that a flexible foundation lowered the dam's fundamental resonant frequency. They also observed that this interaction became more important as the ratio of the foundation rock's elasticity to the dam concrete's elasticity increased (Tan and Chopra, 1995). Sani and Lotfi assessed the interrelationships between the concrete arch dam, reservoir, and foundation rock concerning their seismic response (Sani and Lotfi, 2011). Akbari et al. studied the impact of nonuniform excitation due to spatially varying ground motions and explored the nonlinear responses of concrete arch dams. They analyzed a high arch dam, where the reservoir was treated as an incompressible material, and the foundation was assumed to be a massless medium. Contraction and peripheral joints were modeled, considering their ability to open and close. Monte Carlo simulation was employed to generate spatially nonuniform ground motion. The study investigated random seismic characteristics, including incoherence and wave passage effects, and compared their effects on structural response with uniform excitation at the design base level earthquake (Akbari et al., 2013). Ardebili and their research team conducted a study to investigate how hydrodynamic pressures under various reservoir operational conditions influenced the seismic performance of an arch dam. They chose the Dez Arch Dam in Iran as their case study. They utilized node-to-node contact elements to model all peripheral and contraction joints, allowing for simulations of tangential movement (Hariri-Ardebili et al., 2013). Løkke and Chopra conducted a comprehensive study on the nonlinear seismic analysis of a 3D arch dam model with reservoir water and foundation rock. They considered all the essential factors that affect how dams respond to earthquakes and their seismic performance. To achieve this, they created a direct finite element method to analyze the nonlinear dynamic behavior of these systems, using readily available finite element analysis software. Their analysis used viscous-damper type absorbing boundaries to simulate the semi-unbounded reservoir water and foundation areas. Additionally, they applied effective seismic forces at these boundaries based on deconvoluted ground motion data collected from a specific control point on the ground surface (Løkke and Chopra, 2019).

The available literature indicates a scarcity of studies regarding the seismic behavior of arch dams when earthquakes are treated as random occurrences. The challenge in conducting random vibration analysis for a dam with a reservoir lies in the complexity of constructing a frequency response function matrix due to the interaction between the dam and water. Unlike the dam alone, direct frequency domain spectral analysis is not feasible for the entire dam-reservoir system. The transfer function approach, commonly employed in offshore structures, becomes essential to address this issue. Surprisingly, there is a lack of studies specifically evaluating the validity of spectral analysis using the transfer function approach for arch dam-reservoir systems. No previous research has explored a hybrid technique wherein the dam is modeled, and transfer functions of dam responses are obtained using standard methods. In this unique approach, a separate MATLAB program is developed to perform spectral analysis utilizing the extracted transfer functions. This current study focuses on conducting a 3D seismic analysis of the Morrow Point arch dam, assuming that earthquakes follow a random process. The earthquake is considered to be fully correlated ground motion. The analysis utilizing a transfer function approach is performed. The method is applied to a full reservoir dam. The approach is used to determine the response of the arch dam reservoir system. The earthquake's Power Spectral Density Function (PSDF) is assumed to follow the PSDF of the Kern County earthquake from 1952, treating it as representative of ergodic random excitation. The choice compares the response obtained from the spectral analysis using the transfer function approach with the time history analysis results. The critical response parameters of interest are the mean peak displacement values near the top of the crown cantilever section of the arch dam, and the mean peak stresses at specific critical locations.

2 Theory

Seismic analysis is conducted using spectral analysis, with earthquake excitation treated as a random process. The analysis utilizes both ABAQUS software and custom MATLAB code. MATLAB code is employed for the spectral analysis, while ABAQUS is used to create a model of the arch dam and reservoir water to extract its modal properties. The spectral analyses were carried out through the system's transfer function in MATLAB.

2.1 Modeling

In ABAQUS, the issue of Dam-water Interaction is approached by employing the coupled-acoustic-structural (CAS) finite element approach. Acoustics is the field of science that examines the generation, absorption, transmission, and reflection of sound waves in fluid environments. The acoustic wave equation can be expressed with pressure 'p' as an independent variable as follows (Abaqus, F.E.A., 2014):

$$\frac{\partial^2 p}{\partial t^2} + \upsilon^2 \nabla^2 p = 0 \qquad (2.1.1)$$

Where υ is the speed of sound in the fluid media

$$\upsilon = \sqrt{\Upsilon/\rho_L} \qquad (2.1.2)$$

Where Υ is the Bulk modulus of the fluid, and ρ_L is the density of the fluid. The CAS (coupled-acoustic-structural) approach is a relatively straightforward and efficient numerical solution method that assumes no material flow and does not lead to mesh distortion in the material. In this approach, only pressure degrees of freedom are considered for the acoustic element at each node. This reduction in degrees of freedom results in shorter computational times for simulations. In the CAS approach, water is represented using acoustic elements based on linearized wave theory, while the dam is represented using Lagrangian elements. Impedance properties at the boundary connect the pressure within the acoustic element with the perpendicular motion at the interface between the acoustic and structural elements. The acoustic element propagates in the fluid's outward perpendicular direction, which can be described in the following way.

$\dot{u}_{out}$ (outward velocity) is related to the pressure, as follows

$$\dot{u}_{out} = \frac{1}{k_1}\dot{p} + \frac{1}{c_1}p \qquad (2.1.3)$$

Where p is acoustic pressure; $\dot{p}$ is time rate change of the acoustic pressure; $\frac{1}{k_1}$ is the Coefficient of proportionality between pressure and displacement in the perpendicular direction of the surface; $\frac{1}{c_1}$ is the Coefficient of proportionality between pressure and velocity in the perpendicular direction of the surface. Surface-based tie constraint governs the interaction between the water on the upstream surface of the dam. With this interaction, both surfaces can remain in contact throughout the simulation. Under this constraint, every node on the fluid surface of the acoustic element experiences the same pressure and motion. An eight-node 3D acoustic continuum element with reduced integration (AC3D8R) is employed to model the water.

Eight-node 3D stress continuum elements with reduced integration (C3D8R) are used for the dam. The seismic analysis is carried out using the ABAQUS Explicit Module (Abaqus, F.E.A., 2014). The finite element analysis employs a dynamic explicit time integration method, which utilizes the central difference integration method incorporated within the ABAQUS software.

$$\dot{v}^{(i+1/2)} = \dot{v}^{(i-1/2)} + \frac{\Delta t^{(i+1)} + \Delta t^{(i)}}{2}\ddot{v}^{(i)} \quad (2.1.4)$$

$$v^{(i+1)} = v^{(i)} + \Delta t^{(i+1)}\dot{v}^{(i)} \quad (2.1.5)$$

Here, $\dot{v}$ is the nodal velocity and $\ddot{v}$ is the nodal acceleration. The initial acceleration of each increment is calculated as follows.

$$\ddot{v}^{(i)} = M_N^{-1} \cdot \left(F^{(i)} - I^{(i)}\right) \quad (2.1.6)$$

In this context, '*M*' denotes nodal mass, *'I'* signifies the internal forces acting on the water, and '*F*' represents the generalized force. To improve the simulation's accuracy, smaller time increments (Δt) are utilized, and this Δt remains consistent throughout the simulation. Ensuring precision is crucial and involves adhering to the Courant time limit, which specifies that Δt should be less than or equal to ' *l* / υ.' Here, *'l'* corresponds to the smallest element length, and ' υ ' represents the material's speed of sound wave propagation, known as the dilatational wave speed (Rawat et al. 2019)**.** The wave reflection factor describes the interaction between water and the foundation, which accounts for the reflection of pressure waves in acoustic elements (such as water) in the vicinity of the structure. Consequently, it has an impact on the dynamic response of the structure. Hall and Chopra conducted a comprehensive study on this phenomenon in 1983 (Hall and Chopra, 1983). The properties of the foundation material determine the degree of reflection, and the extent of this reflection is quantified by the wave reflection factor, denoted as α. This α factor can be expressed as follows:

$$\alpha = \frac{1 - D}{1 + D} \quad (2.1.7)$$

$$D = \frac{\rho_w C_w}{\rho_f C_f} = \frac{\sqrt{\rho_w E_w}}{\sqrt{\rho_f E_f}} \quad (2.1.8)$$

In this equation, ρ_w represents the density of water, ρ_f is the density of the foundation or canyon material, C_w denotes the wave propagation speed in water and C_f signifies the wave propagation speed in the foundation or canyon material. E_w and E_f are modulus of elasticity of water and foundation, respectively. When α equals 1, the surface behaves as a complete reflector, and when α equals 0, the surface acts as a complete absorber.

2.2 Analysis Methodology

Spectral analysis is carried out for the dam with a full reservoir using the direct analysis method. In this analysis, a unit of sinusoidal excitation $\ddot{x}_g$ is applied at the dam and reservoir water boundaries. The dam is represented using 3D elements, specifically C3D8R/C3D8 (3D stress elements). The sinusoidal excitation is defined by sampled amplitude values at intervals of Δt, spanning 10 cycles of oscillation to reach a steady-state response of the dam. The solution is computed using ABAQUS, and the steady-state response amplitude (A_j) is determined for various frequencies of excitation (Løkke and Chopra, 2019). The magnitude $|A_j|$ is referred to as the transfer function TR_j at the frequency ω_j for the response parameter. Once TR_j is established, it can be used to calculate the Power Spectral Density Function (PSDF) of the response quantity of interest, which is expressed as:

$$S(\omega_j) = |TR_j|^2 S_{\ddot{x}_{gj}}$$

Or

$$S(\omega) = |TR(\omega)|^2 S_{\ddot{x}_g}(\omega) \quad (2.2.1)$$

This formula represents the Power Spectral Density Function (PSDF) of the response quantity of interest $S(\omega)$, where $S_{\ddot{x}_g}(\omega)$ Signifies the PSDF of the excitation.

The n^{th} moment of the Power Spectral Density Function (PSDF) can be expressed as:

$$\lambda_n = \int_0^{\omega_c} \omega^n S(\omega)\, d\omega \tag{2.2.2}$$

The cut-off frequency of the Power Spectral Density Function (PSDF), denoted as ω_c , represents the frequency where the PSDF's tail portion is truncated. λ_0 corresponds to the mean square value of the ground acceleration. The central frequency Ω can be calculated as follows:

$$\Omega = \sqrt{\frac{\lambda_2}{\lambda_0}} \tag{2.2.3}$$

Ω serves as a metric for the frequency concentration within the Power Spectral Density Function (PSDF). Utilizing the provided parameters along with the earthquake's duration T_d, the mean peak ground acceleration / mean peak values of the response quantities of interest can be calculated (Datta, 2010).

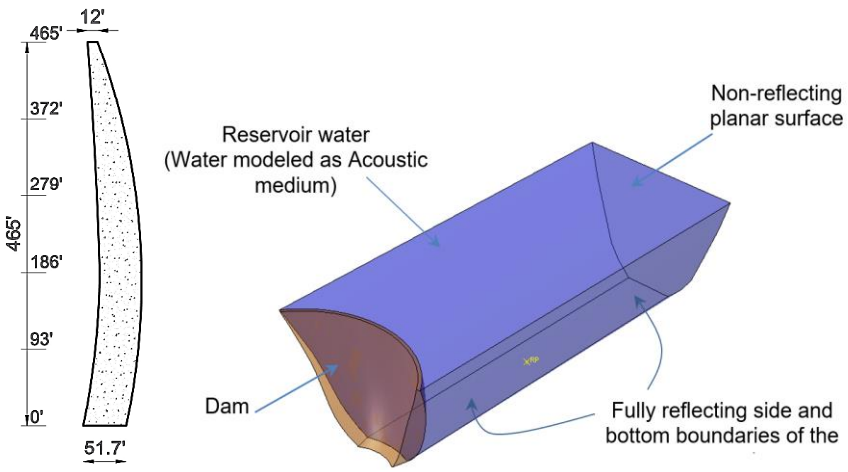
$$\ddot{x}_{gmax} = \sqrt{2\lambda_0\, ln\left(\frac{2.8\Omega T_d}{2\pi}\right)} \tag{2.2.4}$$

2.2.1 Analysis of the Dam with a Full Reservoir

While modal spectral analysis can be applied to the empty dam, it cannot be used for analyzing a dam with a full reservoir. This limitation arises because the mode participation factor considers only the inertia forces and does not account for the added mass effect in the dam caused by ground excitation. In the case of a dam with reservoir water, an additional force acts on the dam due to hydrodynamic action in addition to the inertia force. This force can be divided into two components: the inertia force resulting from added mass and the hydrodynamic force generated by the movement of water particles. The mode participation factor cannot accommodate the second part of this force. Therefore, the analysis of the dam with reservoir water is conducted using a direct transfer function approach, similar to the approach used in offshore structures. The 3D acoustics stress elements (AC3D8R/AC3D8) are utilized for finite element modeling of the water. The complete dam-water model is subjected to harmonic ground motion at the sides and base of the dam reservoir system, aiming to calculate the transfer function for the response parameters of interest. The dam-water model is exposed to a unit amplitude ground acceleration with varying frequencies in this process. At each frequency, ten cycles of ground acceleration are applied as the boundary excitation. A time/response history analysis is carried out using ABAQUS software to determine the steady-state response, denoted as |A|. The resulting response amplitude is then used to calculate the transfer function. In the context of offshore structures, the steady-state amplitude |A| is determined for harmonic waves of unit amplitude, accounting for nonlinearity resulting from hydrodynamic effects in the analysis. While spectral analysis is typically valid for linear systems, this approach is regularly employed for offshore structures to assess peak responses even in the presence of nonlinearity. In the case of a dam, the boundary excitations create water particle kinematics, leading to hydrodynamic pressure on the dam, which inherently involves nonlinearity. The transfer function TR, obtained for harmonic excitation using ABAQUS software, considers this water-structure interaction. Consequently, conducting spectral analysis for a dam with a full reservoir subjected to random ground motion is not strictly valid, similar to offshore structures, and necessitates validation.

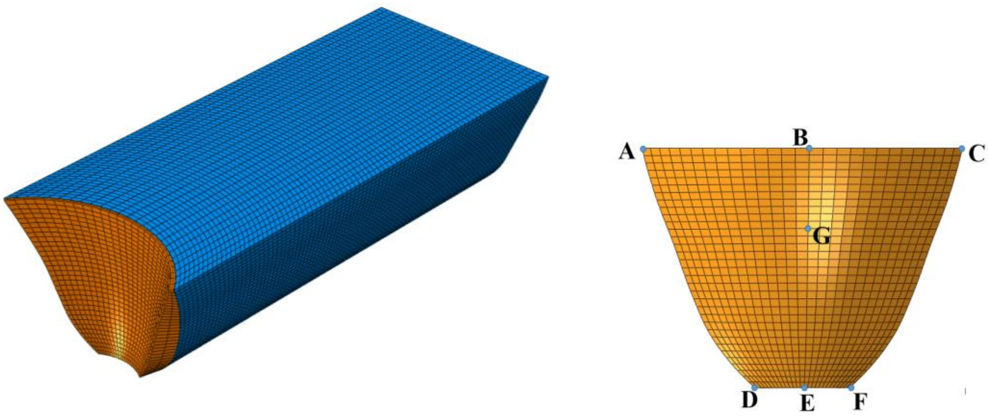
3 Numerical study

A numerical analysis is conducted on the Morrow Point Arch dam, chosen for its availability of data required for 3D modeling from previous literature (Hall and Chopra, 1983). The Morrow Point arch dam is situated on the Gunnison River in Colorado, USA, with a total height of 465 feet. It is characterized as a double curvature thin arch dam. The dam's concrete properties include a Modulus of Elasticity (E_d) = 4 X 10^6 psi (2.75 X 10^{10} Pa), a density w_d= 155 pcf (2483 Kg/m^3), a Poisson's ratio m = 0.2, and a damping ratio (ξ) of 5% for all vibration modes. The water has a density w = 62.4 pcf (1000 kg/m^3) and a Bulk Modulus K = 3.19 X 10^5 psi (2.2 X 10^9 Pa). The value of α is set to 1, assuming fully reflective boundaries. In the ABAQUS software, suitable boundary conditions are applied to replicate fully reflective boundary conditions at the base and sides of the reservoir water. Plans are generated at each elevation level with 93-foot increments to generate 3D geometry of the Morrow Point arch dam. These plans are then lofted using AutoCAD software. AutoCAD software is also utilized to model the 3D shape of the reservoir water. These 3D representations of the dam and reservoir water are imported into the ABAQUS environment. The reservoir water length is assumed to be nearly three times the height of the dam, with the cross-section of the reservoir matching the upstream surface profile of the dam. The upstream end of the reservoir is designed as a non-reflecting planar surface, as depicted in Figure 1. The boundaries of the dam are considered fixed. For the acoustics water medium, a natural boundary condition is assumed, which creates a fully reflective boundary due to the presence of a rigid wall around the fluid. No user input is required for this natural boundary condition in the acoustics medium. Surface-to-surface tie-type interactions are implemented between the dam's upstream surface and the water. At the top surface of the reservoir water, it is assumed that the acoustic pressure is zero. Finite element meshing is done, as depicted in Figure 2. A fine mesh is used to determine modal properties, while a coarse mesh is employed for the direct analysis method and time-history analysis of the dam with a full reservoir. Specific details of the finite element meshing are outlined in Table 1.



(a) *(b)*

Figure 1. (a)Crown cantilever section of morrow point arch dam (b)3D model of the arch dam – reservoir water.



(a) *(b)*

Figure 2. (a) Meshed 3D model of the Morrow point arch dam - reservoir water (b) Selected critical points at the dam's upstream face

Table 1. Mesh properties of the dam-reservoir model

Part of the Model	Element type	Coarse Mesh	Fine Mesh
		Number of elements	Number of elements
Dam	C3D8R/C3D8	1782	13780
Reservoir water	AC3D8R/AC3D8	70400	583440

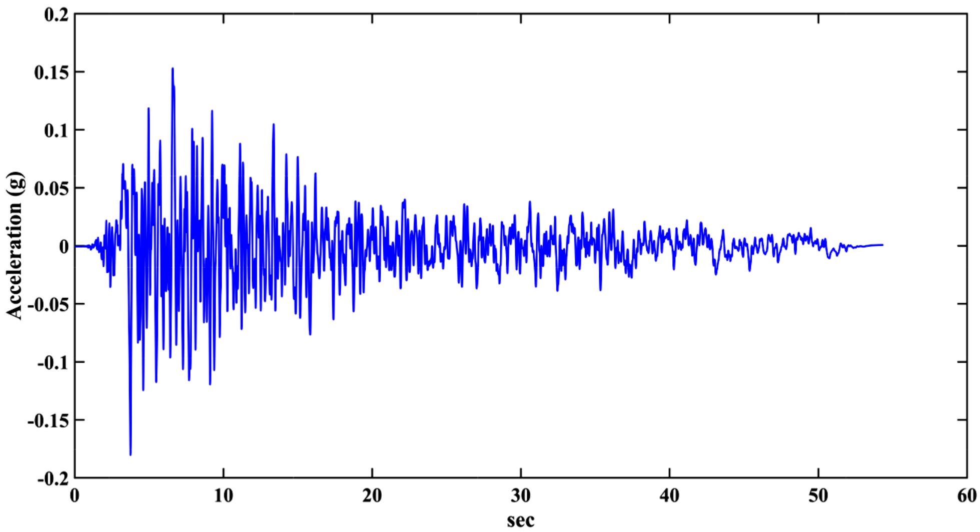


Figure 3. Kern County (1952) acceleration time history

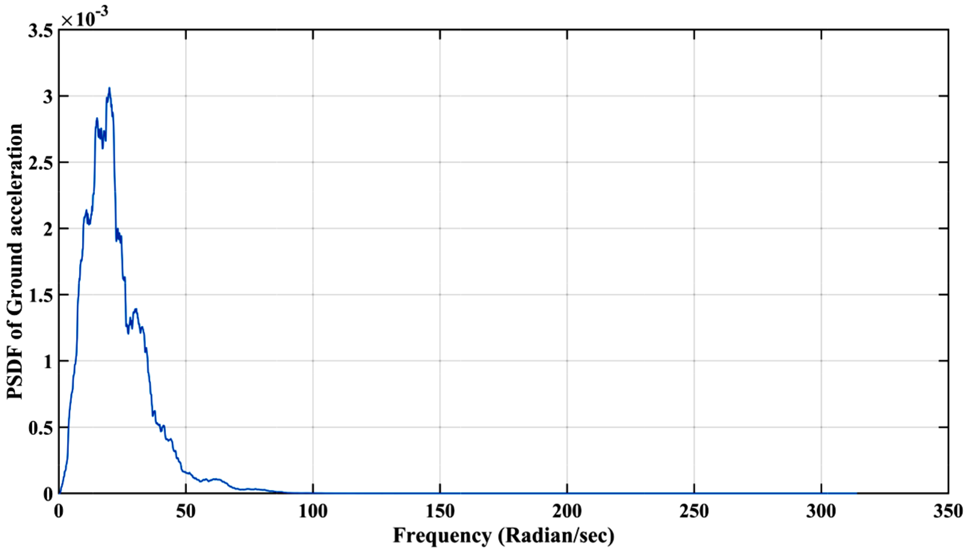


Figure 4. PSDF of the ground acceleration

The acceleration time history of the Kern County earthquake from 1952 (depicted in Figure 3), specifically the Taft component 111 with a peak ground acceleration of 0.18g, is used as input at both the dam's base and sides. This same time history is also applied at a designated reference point (RP, as shown in Figure 1(b)). However, there is no application of time history in the vertical and cross-stream directions. A uniform earthquake loading is assumed at the dam and reservoir boundaries. The study includes conducting a time-history analysis for the dam with a full reservoir. Figure 4 presents the Power Spectral Density Function (PSDF) of the ground acceleration for the Kern County Earthquake. The area beneath the curve is equivalent to the variance of the acceleration time history. A moving average filter method in MATLAB is employed to smooth the PSDF curve.

4 Discussion and results

Table 2 displays the first five mode shapes of the arch dam with a full reservoir. Conditions. Table 2 demonstrates that water–structure interaction reduces the dam's natural frequencies compared to the dam without water case. The decrease is more pronounced for higher frequencies.

Table 2. Modal shapes and Modal frequencies of the full reservoir dam

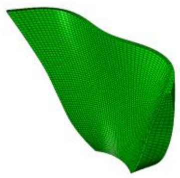
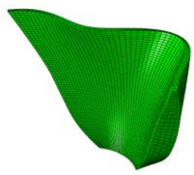
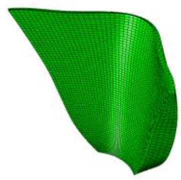
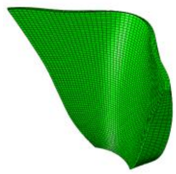
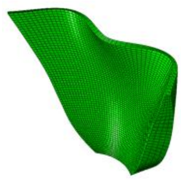
Mode No.	1	2	3	4	5
Modal Shape					
Modal Frequency (Hz)	2.84	2.97	3.24	3.71	4.48

Figure 5 displays the squared magnitude of the transfer function, denoted as $|TR|^2$, for the displacement at point B in the dam with a full reservoir. Figure 6 presents the corresponding Power Spectral Density Function (PSDF) for the displacement at point B. It's evident from Figure 6 that the PSDF of the displacement is narrow, with the peak occurring at the same frequency as the $|TR|^2$ plot. The nature of the PSDF and the $|TR|^2$ plot indicates that the fundamental mode of oscillation primarily governs the response. Figures 7 and 8 depict the PSDF of the arch and cantilever stresses at point B, respectively.

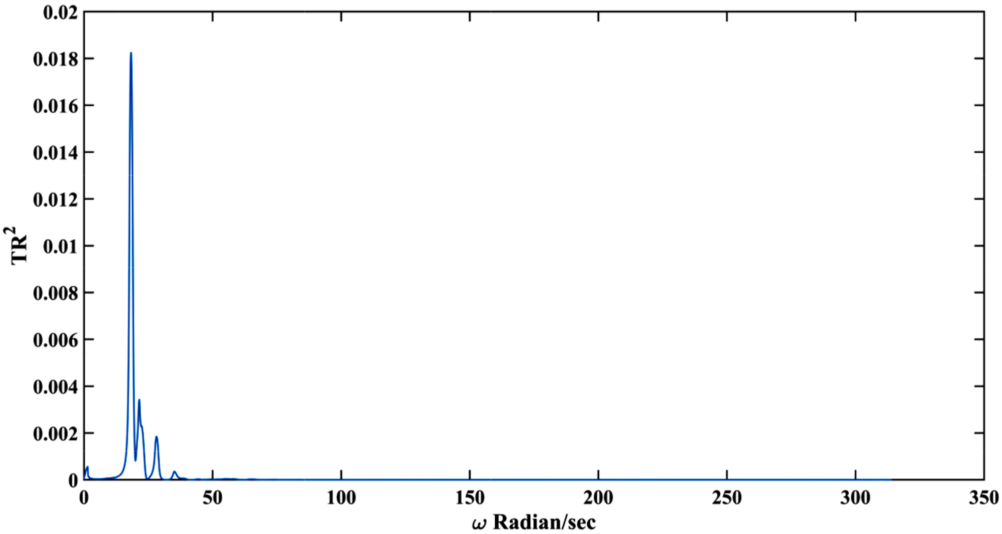


Figure 5. Square of the transfer function of displacement in upstream-downstream direction at point B of the full reservoir dam obtained by direct analysis

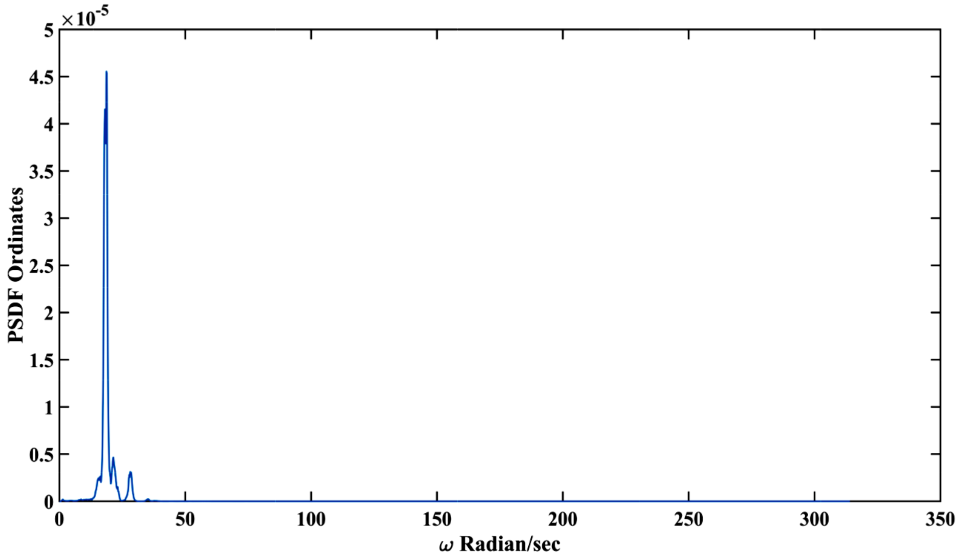


Figure 6. PSDF of the displacement at point B of the full reservoir dam in an upstream-downstream direction obtained by direct analysis (m)

Table 3 compares the absolute mean peak and RMS (root mean square) values of displacements obtained through spectral and time history analyses. The variation between these two responses falls within 10-15 percent. Consequently, the direct spectral analysis offers a reasonably accurate prediction of mean peak displacement. It's worth mentioning that the time history analysis yields slightly higher response values. Table 4 compares RMS and mean peak values of the arch and cantilever stresses at points A, B, C, D, E, F, and G, as determined by the spectral analysis (direct method) and the time history analysis. The disparities between these two stress values stay within a 15 percent range, with the time history stresses slightly higher.

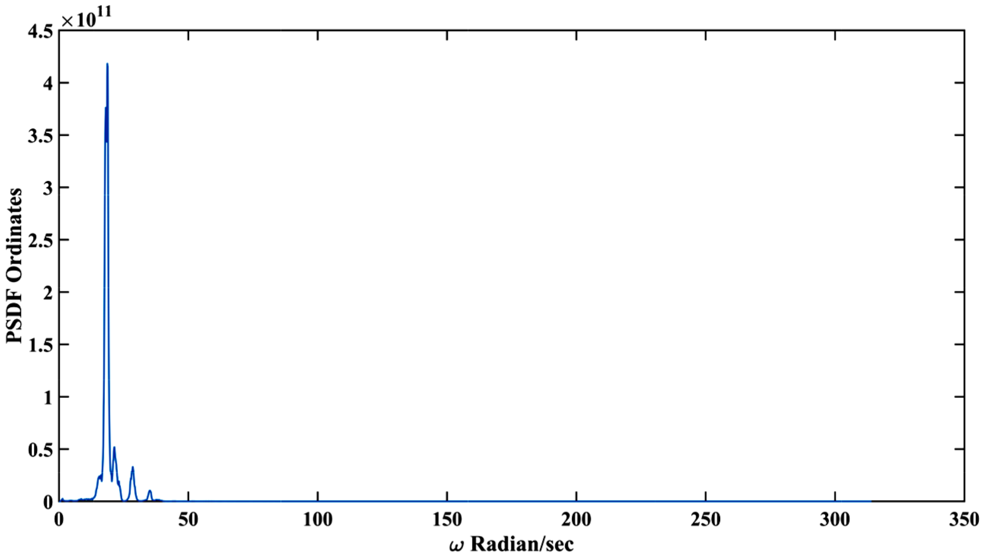


Figure 7. PSDF of the arch stress at point B of the full reservoir dam (N/m^2)

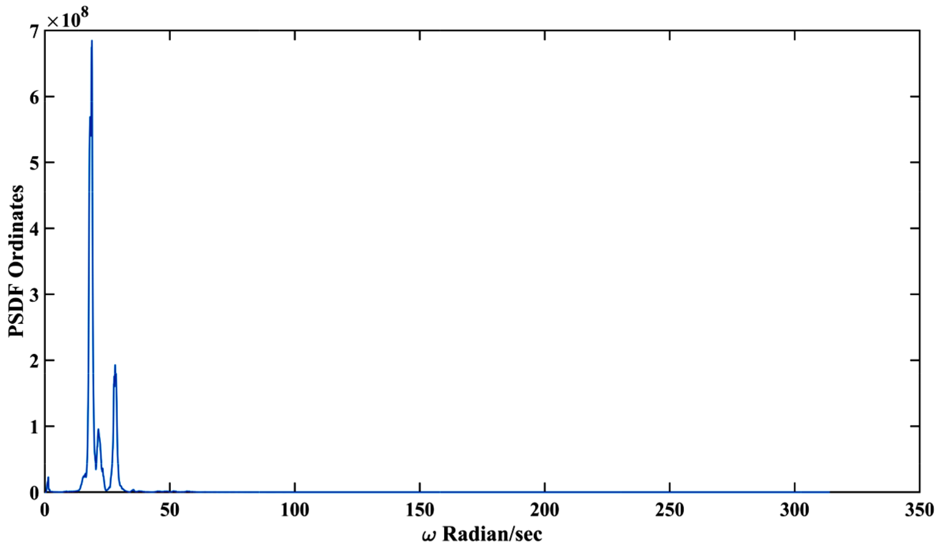


Figure 8. PSDF of the cantilever stress at point B of the full reservoir dam (N/m^2)

Table 3. Absolute mean peak and Root mean square (RMS) values of displacement (m) at point B

	Spectral Analysis Direct method	**Time History Analysis**
B(RMS values)	0.0098	0.0112
B(absolute mean peak values)	0.0355	0.0408

Table 4(a). Absolute mean peak values of Cantilever and Arch stresses at points A, B, C, D, E, F, and G

Point	**Arch Stress (Mpa)**		**Cantilever Stress (Mpa)**	
	Spectral Analysis(Direct method)	**Time History analysis**	**Spectral Analysis (Direct method)**	**Time History analysis**
A	0.9026	1.0019	0.2104	0.2403
B	3.6632	4.2072	0.1557	0.1728
C	0.9026	1.0239	0.2104	0.2386
G	3.4244	3.7668	0.6004	0.6860
D	0.2418	0.2689	0.7489	0.8424
E	0.4076	0.4592	2.1936	2.4349
F	0.2418	0.2689	0.7489	0.9159

Table 4(b). RMS values of Cantilever and Arch stresses at points A, B, C, D, E, F, and G (All points located on the dam upstream face see Figure 2(b))

Point	**Arch Stress (Mpa)**		**Cantilever Stress (Mpa)**	
	Spectral Analysis (Direct method)	**Time History analysis**	**Spectral Analysis (Direct method)**	**Time History analysis**
A	0.2507	0.2660	0.0581	0.0614
B	1.0111	1.0665	0.0427	0.0440
C	0.2507	0.2660	0.0581	0.0614
G	0.9505	1.0054	0.1614	0.1625
D	0.0672	0.0715	0.2081	0.2211
E	0.1132	0.1202	0.6092	0.6470
F	0.0672	0.0715	0.2081	0.2211

Therefore, the direct spectral analysis accurately estimates dam responses when the dam and reservoir water are subjected to random ground excitation. Additionally, it's noted that arch stresses are substantially higher than cantilever stresses at the top, with the reverse trend occurring near the base.

5 Conclusion

The study involves conducting spectral analysis of the arch dam when subjected to random ground motion. Specifically, the Morrow Point arch dam is examined under the Power Spectral Density Function (PSDF) of the ground motion based on the PSDF of the Kern County earthquake. The ground motion is applied to the bottom and side boundaries of the dam-reservoir system. The applicability of the transfer function approach for spectral analysis of the dam with reservoir water under random ground motion is validated by the time history analysis. The Power Spectral Density Function (PSDF) reaches its highest value at the fundamental frequency of the dam. The frequency at which the excitation peak occurs is significantly distant from the first two natural frequencies of the dam. The Power Spectral Density Function (PSDF) of stresses for the dam with the reservoir is essentially characterized by a single peak, which aligns with the dam's fundamental frequency. The stresses in the arch section of the dam are considerably higher near the top compared to the cantilever stresses. However, near the bottom, the trend is the opposite.

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