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Dynamic Analysis of Concrete Arch Dam due to Earthquake Force

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ABSTRACT

A gravity dam with concrete is a vast construction that keeps a large volume of water on its upstream side, and its ability to withstand seismic vibrations is critical. So, it is a question of investigation to determine the fluctuating performance of a dam under various dynamic loads, which is an essential and highly complex component of dam safety criterion. The fluctuating behaviour of the various 3D models of the arch-gravity concrete dam, including the dam amid the earth interface, a dam devoid of earth interface, and a dam situated among earth and water systems, has been developed using finite element software ANSYS. These computational models can be improved to perform seismic examination of concrete gravity arch dams, exploring both the foundation-structure interaction and the reservoir water level, which influence stress distribution within the dam. The linkage among the dam and the reservoir is examined by implementing a modified Westergaard's technique, and the dam body is represented with 3D Soild 186 elements. Furthermore, damping effects are used to assess their impact on fluctuating investigation. The responses of this dam are compared to the Seismic shaking acceleration of the Chamba seismic information occasion (1995), which is derived from Earthquake Databases. As per the dynamic analysis outcomes, the time-dependent variation of various displacements and stress on various dam locations, such as the dam's crest, heel, and toe, has been computed and analyzed, as well as their maximum values during earthquake time duration. The computation outcomes demonstrated that the interplay among the dam, foundation, and reservoir is critical in accurately estimating the fluctuating performance of dams. The exploration concluded that the simulated results of earthquake ground motion offer maximum displacement and maximum pressure for a dam devoid of earth interface than the dam amid earth interface, and fewer displacement for a dam situated among earth and water systems, The hydrodynamic water pressure from the reservoir induces stresses within the dam framework and horizontal displacements that range on the crest. Dam engineers can utilize this research to enhance the integrity and reliability of the dam, laying the groundwork for future experimental and fatigue assessments of the dam under numerous dynamic loads.

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1. Introduction

The arch-gravity dams with concrete are attractive due to their arch framework spanning two mountains, presenting innovative difficulties for the functions they play in irrigation, and agriculture, flooding protection, and producing clean energy, which are vital for national growth and sustainability. These dams are geometrically complex frameworks with combinations of various exterior and inside radius or arc angles and variable, irregular centres for exterior and interior arches. The dynamic vibration behaviour of these dams might influence their durability, safety, and comfort of living, as well as societal, financial, and ecological losses. The effects of time-varying dynamic forces caused by ground motion on the concrete arch-gravity dam during an earthquake are investigated in this work. Hence, this study attempts to identify the forced vibration response of this type of dam due to hydrodynamic and seismic forces. Yaghin and Hesari [1] evaluated the dynamic characteristics of arch concrete dams without support and those without bedrock support systems using ABAQUS finite element method software. Depending on the outcomes, the time-dependent variation in principal stress, overall stress, crest deformation, and riverbed elevation has been computed, with a comprehensive analysis of their peak values during the seismic events. Parametric research was conducted to explore the significance of these factors in the non-linear analysis of Berrabah et al. [2] persistent modal analyses of the Brezina Arch dam using FE ANSYS software. 3D models were formed for dams devoid of soil foundation, dams with soil with no mass, and dams with soil foundation to revise the consequence of the foundation on the arch dam. A result demonstrates that any damped vibration ratio is considered inferior, with an incomplete value, to the dam without earth mass and also compared to the dam amid soil foundation, and considerably inferior to that via the dam devoid of soil foundation model. Linda and Kadid [3] reported the responses for the Pine Flat Dams against seismic activities, bearing in mind hydrodynamic stress on the upstream side. The study exemplifies an essential deviation in the predictable seismic reaction when hydrodynamic pressure is incorporated into the design. Using ANSYS, Zhang et al. [4] investigated a Concrete Gravity Dam's Static and Dynamic Analysis. This study includes these security evaluations of an RCC gravity dam project and some references for comparable engineering studies using the response spectrum analysis approach for dynamic analysis.Hariri-Ardebili and Kianoush [5] investigated a current high-curve dam's adjustment methodology and nonlinear-linear unstable reaction. The initial phase processed the directed examinations for the static and heat changes of the dam, as well as the seeable website estimations. The second half examined the nonlinear-linear unstable investigation of the aligned simulation taking into account the impact of joints, mass solid breaking, dam-shake affiliation, fluid mechanics weight within the opened joints, and joint nonlinearity. Varughese and Nikithan [6] published research that uses finite element software to perform static, modal, and fluctuating performance evaluations of a dam-foundation-reservoir framework by ANSYS. The dam and substructure are modeled using the 2D plane of strain element "PLANE 42," while the water body is represented by the fluid acoustics component "FLUID 29," incorporating water-structure interplay. An expression for the initial phase of dams made of concrete is formulated by the technique of modal analysis. Peak displacement and stress are utilized to evaluate the impact of earthquakes of dams subjected to seismic accelerating. Rampure and Mangulkar [7] presented the dynamic analysis and response spectrum means for arch dams by utilizing STAAD-PRO to carry out the study after obtaining all the results. The assessment was done using both methods. The results concluded that dynamic analyses are necessary to support dams under 100 m and above 100 m. Wang et al. [8] explored the earthquake reaction and harmful affectability of curve dams to counterfeit ground movements. Karabulut et al. [9] investigated an arch dam's three-dimensional linear seismic response. Finite element calculations account for movement of the ground impacts and both stiff and flexible basis constraints. SAP2000 is used to do all numerical studies on the condition of empty reservoirs. This investigation conducts a linear simulation of the time-dependent variation evaluations of the arched dam and its basis interface mechanisms using a 3D FEM simulation. Numerical studies show peak horizontal displacements and peak daily loads by altitude analyzing both base circumstances. Robbe [10] compared earthquakes reported on a dam with a concrete arch and gravity in Japan to FEM studies done in 2D and 3D: There are traditional studies with massless foundations/Westergaard added masses, as well as greater precision, with better earth-structure and water-structure interplay features that take into consideration viscous-spring constraints and possible base fluid finite-element. Chen et al. [11] explored input dam-foundation-reservoir models of seismic excitation of the viscous-spring constraints, and the viscous boundaries are calculated and confirmed using an impulsive load via foundation analysis. Esmaielzadeh et al. [12] aided in detecting any structural harm to the dam body and determining the precise position of the damage, taking into account the dam's height. 3D FEM simulations of the Pine Flat, Bluestone, and Folsom dams have been selected as examinations of cases to achieve these objectives. The dams have been simulated using SAP2000 software to analyze their geometric, physical, and mechanical characteristics in undamaged and damaged conditions. Various modal investigations were used to identify the frequencies and configurations of the structural movements. Messaad et al. [13] established a model to analyze the complete system's performance by considering the link among the dam water and its base. This approach considers the presence of both the reservoir and the foundation, resulting in a more accurate study. The study utilized the ANSYS finite element model to examine the dynamic features of a dam- foundation-reservoir framework when subjected to seismic activity. Mendomo Meye et al. [14] examined a crucial technical issue and a significant strategic objective in hydraulic structure design. Their study addresses the problem and guides governments to implement efficient procedures to minimize the damage caused by dam breaches in exceptional situations. Shiyam Sundar et al. [15] conducted a 2D analysis of the dry dam utilizing three different methods. Two slices are obtained for the 2D analysis: one through the spill portion and another through the most elevated non-overflow region. The earthquake capabilities of both of these segments are assessed and contrasted by three FORMS analyses. Zhang et al. [16] examine the division of base layers and investigate the fluctuating behaviour of a dam with gravity when subjected to waves from earthquakes that are incident at an angle. The initial phase entails configuring the connection mechanism involving the gravitational dam and the stratified substructure within the FEM application. The CDP simulation is employed for the dam. The base displacements under various earthquake waveforms with unlimited incidence orientations are ascertained by integrating the 1D time frame technique with the unrestricted wave fields computation technique. Sarkar et al. [17] established a method called two-dimensional Spectral Finite Element Methods (SFEMs) to explore the dynamic behaviour of dams. The dam base has been simulated utilizing two-dimensional infinite elements in both FEM and Time based Stochastic Finite Element Method (TDSFEM) analysis. This is a unique use of TDSFEM in this particular scenario. Rasa et al. [18] proposed a modified FEM simulation for analyzing dam-reservoir-foundation interaction (DRFI). This model incorporates wave radiation effects in both rock and reservoir domains. The near-field reservoir uses Lagrangian elements, while the far-field leverages newly developed infinite elements (likely coded in FORTRAN). The study investigates how close proximity zone reservoir dimension impacts the fluctuating performance of the entire DRFI system and dam foundation (DFI) and dam reservoir (DRI) interactions. Their findings suggest the model offers improved accuracy and speed compared to existing methods. The infinite elements effectively absorb reflected pressure waves. Determining the optimal near-field reservoir size remains challenging, but the authors recommend 1.5 times the dam height as a starting point.

This research presents a potentially valuable tool for dam engineers by offering a more efficient and accurate way to assess dam safety during dynamic events. Rasa et al. [19] examined how ageing concrete dams respond to dynamic events. The authors create a computer model to simulate the dam-reservoir system, factoring in concrete deterioration and water movement. Their findings suggest that a dam's natural vibration frequency and movement increase as the concrete weakens, compromising its seismic safety. They identify a critical frequency where the dam experiences the most significant stress. This research emphasizes the need to consider concrete ageing and critical vibration frequencies in dam design and safety assessments, particularly for earthquake preparedness. Rasa and Budak [20] presented a finite element (FEM) approach to analyze the static and fluctuating performance of a dam reservoir-foundation system. Their 2D model considers linear elasticity and incorporates water compressibility and sloshing effects. The study explores three foundation scenarios, including an infinite flexible foundation with energy dissipation. However, the presented results focus on a constant-depth reservoir without radiation and only show dam crest displacements for static and dynamic analyses (all coded in FORTRAN 90). This research highlights the potential of FEM for dam safety assessments, considering foundation flexibility and dynamic loads. Rasa et al. [21] proposed a new finite element model (Laplace domain-FE) to assess concrete dam response to earthquakes. Their study examines how horizontal and vertical ground motions and earthquake duration (10-80 seconds) affect dam behaviour. The model incorporates elements for near-field and far-field water domains (likely coded in FORTRAN and MATLAB). Results show longer durations of strong shaking lead to increased dam deformations, stress, and potential damage. Specific earthquake scenarios caused overstress in significant dam sections, indicating potential failure. This research highlights the importance of considering earthquake magnitude and duration in dam safety assessments and design. Rasa et al. [22] present a new model to assess how ageing concrete impacts gravity dam performance during earthquakes. This model incorporates water behaviour (compressibility, sloshing) and far-field water effects. They use a 2D finite element model (FORTRAN, MATLAB) to analyze dam response under various earthquake scenarios (real and normalized records with durations of 10-80 seconds). Their findings show that concrete degradation over time (75 years+) leads to critical responses in the dam, potentially causing severe damage. Earthquakes like Chi-Chi and Loma pose significant threats (over 36% damage) to older dams. This research underlines the importance of factoring in concrete ageing for accurate dam safety assessments and design, particularly for earthquake preparedness. The research by Rasa et al. [23] explored how aged concrete and soil type affect machine foundation response during impacts. They develop a 2D finite element model (FORTRAN, MATLAB) to simulate the system, considering both near and far-field soil behaviour. The study finds that concrete degradation over time significantly increases the area experiencing high stress in the foundation. For medium soil, stress responses were reduced by 32.6% for a 50-year-old foundation compared to a new one. Softer soils lead to larger foundation displacements. This research underlines the importance of considering concrete ageing and soil properties for accurately designing and analyzing machine foundations under dynamic loads. Hashempour et al. [24] introduced a simplified, non-linear, non-linear model for analyzing the impact of earthquakes on concrete arch dams. Compared to intricate models, it more accurately reflects concrete behaviour when subjected to load changes. The model successfully predicts both crack patterns and final strength. The analysis of the Morrow Point dam considers the hyperlink among a dam and the stream and utilizes two algorithms to reduce vibrations. According to the research, this efficient model can potentially substitute complex models. Additionally, it emphasizes the significance of selecting suitable damping for precise outcomes. Li et al. [25] studied the interaction of dams, water, and foundation rocks in a Intricate stratified semi-infinite medium. A novel SBFEM has been simulated to analyze the interaction between a three-dimensional dam and its base. Three distinct models depict the foundation rock: a uniform half-space, a horizontally stacked semi-infinite space, and a tending to semi-infinite space. The study by An investigation was conducted by Banerjee et al. [26] to explore the many obstacles in modelling dam seismic activity, including scenarios involving reservoirs with limited boundaries and soil mediums with finite regions. In addition, it has been recommended that a dam-reservoir-foundation system be accurately modelled and that seismic input be simulated to analyze the dam's response. The finite element technique was used by Burman et al. [27] to assess the dam-base simulation subjected a time dependent load, concrete degradation caused by hygro-mechanical stress must be considered. Elprince et al. [28] utilized ANSYS to create a 2D FEM simulation of the Koyna dam. The model explored both the mass and elasticity of the dam's base when analyzing its seismic reaction. The findings show that the foundation soil's mass and rigidity significantly influence the dam's natural frequency and crest displacement. Huang and Zerva [29] constructed a nonlinear-linear FEM model to analyze the performance of structures under both irregular and regular movement of ground sensations. The research found that uneven earth vibrations caused a big hole to appear toward the front of the dam and slippage at the base. These factors should be considered important for assessing the integrity of a dam built with gravity during seismic activity. Mohammadnezhad et al. [30] introduced a Finite Element Method (FEM) to analyze the mass, the ratio of damping, and propagation of wave effects in the base of the dam–base–water framework. They employed the ABAQUS software for their study. Ouzandja and Tiliouine [31] conducted nonlinear as well as linear seismic investigations on the dam, including base motion. The study demonstrated that the coefficient of friction influences the slippage at the dam's base. Furthermore, the sliding displacement resulted in a decrease in the basic shear loads within the dam framework. Sevim [32] constructed 2D FEM simulations of dams with different ratios of aspect using ANSYS. These models included the dam, base and water linking. Additionally, the study found that the ratios of aspect of a dam has an impact on the way the dam behaves dynamically. A dam with an aspect ratio of 1 exhibited an extremely accurate representation of the reaction to a seismic. Sarkhel et al. [33] utilized ABAQUS finite element software to construct a 2D FEM simulation of the Koyna dam. This model aimed to examine the impact of modal evaluation and water pressure on stiff and elastic bases. The results demonstrated that the principal stress endured in the dam reduced in the former situation relative to the dam having a stiff base. Tidke et al. [34] created a 2D FEM simulation to analyze the static behaviour of the Peechi dam. They considered the impact of soil-structure interaction and examined the dam's foundation's ideal breadth, depth, and stiffness. The study examined the seismic impact on the performance of the dam-base-water frame work by analyzing ground motion criteria such as mean and effective period. The results demonstrated that SSI (soil-structure interaction) substantially influences the dam's structural reaction.

Several scholars have used closed-form solutions analytic approaches to analyze the concrete gravity dam system, as evidenced by the literature study. In addition, various research on the protection and reliability of dams in operation and seismic loadings have been done during the last few decades. Furthermore, a small number of researchers used non-closed-form-based analysis techniques (FEM) to conduct parametric evaluations on the fluctuating performance of different concrete gravity dam models. Not many researchers have created finite element models (FEM) for dam-reservoir-foundation interaction (DRFI). The detailed aims presented in this study are summarized below.

1. This study aims to develop practical 3D Finite element modelling approaches to Employ the fluctuating performance of concrete arch-gravity dams with different configurations under earthquake loading conditions using ANSYS[35] software, leading to more efficient and

safer dam designs essential for dam engineers.

2. In this paper, a coupled analysis was conducted by Developing models that consider the dam, foundation, and water as a unified system through which the influences of the base and effects of the storage area water on the fluctuating performance of the concrete arch-gravity dam are investigated. This provides a more accurate understanding of dam behaviour under earthquakes. The hydraulic force of the water in the reservoir is simulated by employing the additional mass approaching.
3. The dam simulation's reliability was confirmed by comparing it with previous research findings. The results pertain to displacements and stresses at the dam's crest, heel, and toe under void, fifty per cent, as well as full reservoir circumstances. The results were obtained regarding stresses and displacements at the dams' crest, heel and toe for empty, half and full reservoir conditions. Multiple parametric investigations were carried out to explore the dynamic characteristics of concrete gravity dams.

2. Materials and methods

The process diagram in Appendix-A (Figure 27) delineates the steps for conducting a dynamic analysis of a concrete arch dam due to earthquake force using the FEM model.

2.1. Modeling and dynamic investigation of the dam-base-water reservoir system using FEM mathematical formulations

Dynamic studies of buildings and dams are highly intricate phenomena. Mathematical models are commonly utilized to address these intricate processes, considering specific presumptions employed in the real scenario. The formula of structural behaviour, which incorporates the dam and base under the influence of the motion of the ground can be articulated using the finite element method(Khosravi and Heydari [36]).

$$\lfloor M_{df} \rfloor [\ddot{u}_c] + \lfloor C_{df} \rfloor [\dot{u}_c] + \lfloor K_{df} \rfloor [u_c] = \lfloor F(t) = -\lfloor M_{df} \rfloor [\ddot{u}_g] + [Q_{pe}] \rfloor \tag{1}$$

where $\lfloor M_{df} \rfloor, \lfloor C_{df} \rfloor$ and $\lfloor K_{df} \rfloor$ denote the mass, damping, and stiffness matrices of the system, respectively., $[u_c]$ is the nodal displacement vector relative to the base, $[\dot{u}_c]$ represents the velocity and $[\ddot{u}_c]$, is the acceleration, $[\ddot{u}_g]$ is the ground acceleration and $\lfloor Q_{pe} \rfloor$ represents the nodal force associated with the hydrodynamic pressure that is generated by the water reservoir (Khosravi and Heydari [36]). The discrete waves formula is presented (Khosravi and Heydari [36]) as follows:

$$[M_w][\ddot{p}_c] + [C_w][\dot{p}_c] + [K_w][p_c] = [F(t) = -p_w Q^T (\ddot{u}_g + \ddot{u}_e)] \tag{2}$$

where $[M_w], [C_w]$ and $[K_w]$ are related to the mass, damping and stiffness matrices of fluid, $[p_c]$ is the nodal pressure. $p_w Q^T$ It is a coupling term. The General governing Coupled fluid-structure (Khosravi and Heydari [36])eq

$$\begin{bmatrix} M_{df} & 0 \\ M_{dfw} & M_w \end{bmatrix} \begin{bmatrix} \ddot{u}_c \\ \ddot{p}_c \end{bmatrix} + \begin{bmatrix} C_{df} & 0 \\ 0 & C_w \end{bmatrix} \begin{bmatrix} \dot{u}_c \\ \dot{p}_c \end{bmatrix} + \begin{bmatrix} K_{df} & K_{wdf} \\ 0 & K_w \end{bmatrix} \begin{bmatrix} \dot{u}_c \\ \dot{p}_c \end{bmatrix} = \begin{bmatrix} -M_{df}\ddot{u}_g \\ -M_{wdf}\ddot{u}_g \end{bmatrix} \tag{3}$$

where $M_{wdf} = p_w Q^T$ and K_{wdf} =Q is a 2nd order linear differential equation that is characterized by asymmetrical matrices and can be resolved through direct integration.

2.2. Dimensional configurations of the dam

The geometry variables of the dam are listed in Table 1, and Figure 1 shows the cross-section of the dam with geometry variables. The proposed gravity dam undertaking at Jankar Jangal within Chamba, H.P, India, in the Ravi river region is investigated in this manuscript. The performances of the dam are evaluated against the ground motion acceleration of the Chamba Earthquake (1995), which is obtained from Earthquake Databases.

Table 1. The geometry variables of the dam.

	Form of Simulation	Concrete arch-gravity dam	
Concrete dam	Crest breath (in m)	4	
	Bottom breath (in m)	36.3	
	Height (in m)	25.94	
	Length (in m)	20.05	
	Greatest water height (in m)	25.44	
Foundation soil	Form of Simulation	Terrain Level 1 supports the dam in meters.	Terrain Level 2 under the dam in meters.
	X-axis	27	30
	Y-axis	48.3	72
	Z-axis	95	115

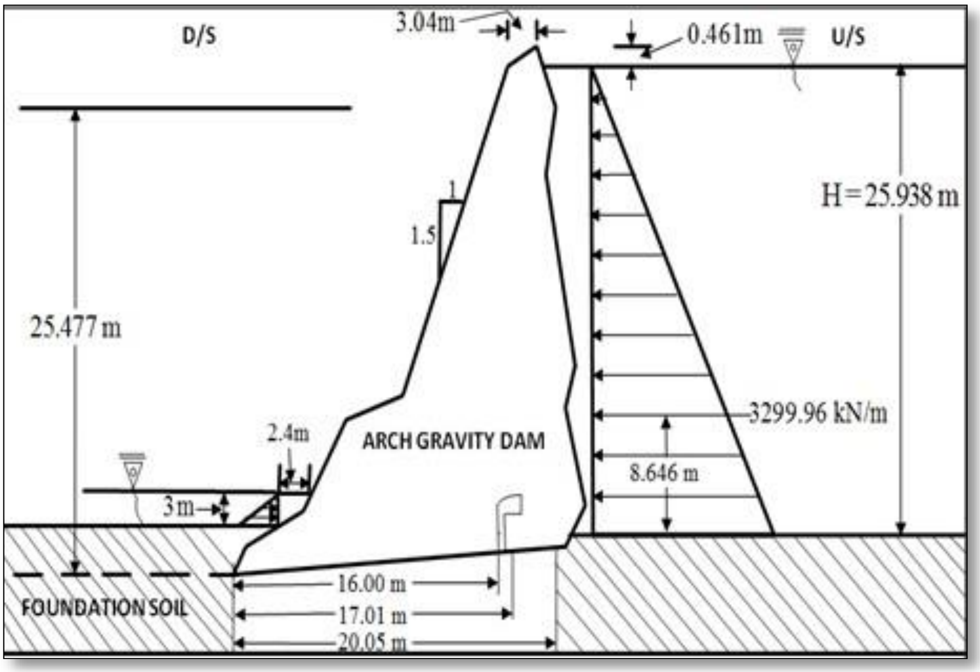


Fig. 1. The Geometry of the Concrete Arch Gravity Dam (Punmia et al. [37]).

2.3. Dam mathematical idealization using FEM simulation

The FEM has become a vital tool for numerically addressing diverse technological issues. This study utilized the FEM scheme ANSYS to simulate the dam. Figure 2-4 illustrates the three various forms of simulation dam discretization. To examine the modal activity of the dam, multiple model situations are considered as follows:

Model 1: Dam with rigid support (dam lacking an earthen base) and an unfilled reservoir designated as “fixed-empty” (Fig. 2)

Model 2: A dam with a dirt base and an unfilled reservoir, designated as “mass-empty” (Figure 3)

Model 3: Dam with an earthen base and an entire reservoir, referred to as “mass-fluid” (Figure 4)

The dam is regarded as an irremovable constraint at the bottom for model 1 and remains fixed at the base for models 2 and 3. The reservoir's length is specified as half of its depth.

The dam has been treated to a three-dimensional examination. ANSYS [35] was implemented for modelling and analysis. The dam, soil foundation, and reservoir have all been designed using 3D solid components. Every element's node has 6 DOF, that consist of translations and rotational motions in the X, Y, and Z measurements.

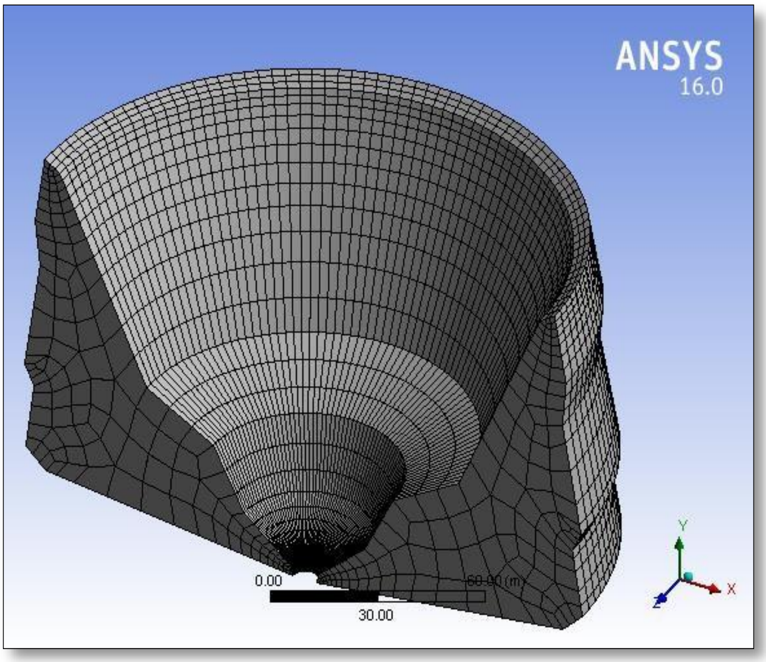


Fig. 2. Model 1 Dam lacking an earthen base model (ANSYS[35]).

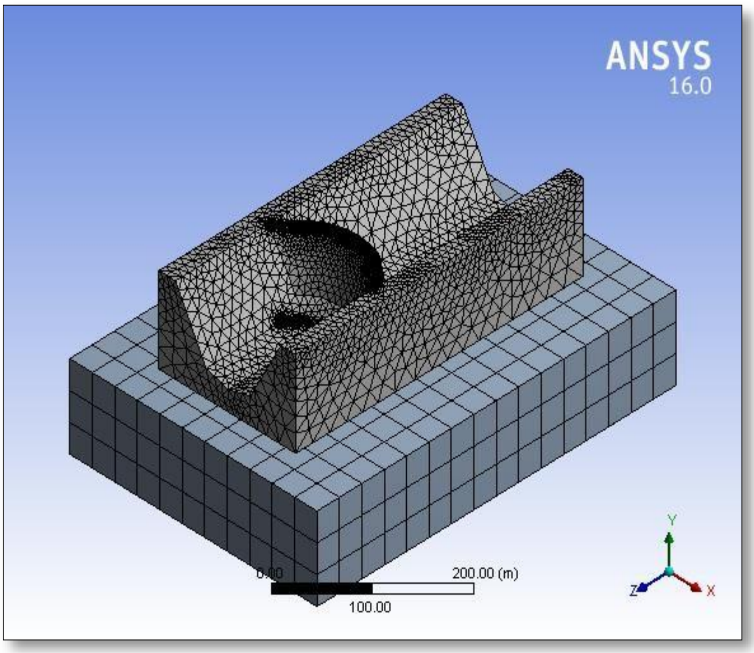


Fig. 3. Model 2 Dam with a dirt base model(ANSYS[35]).

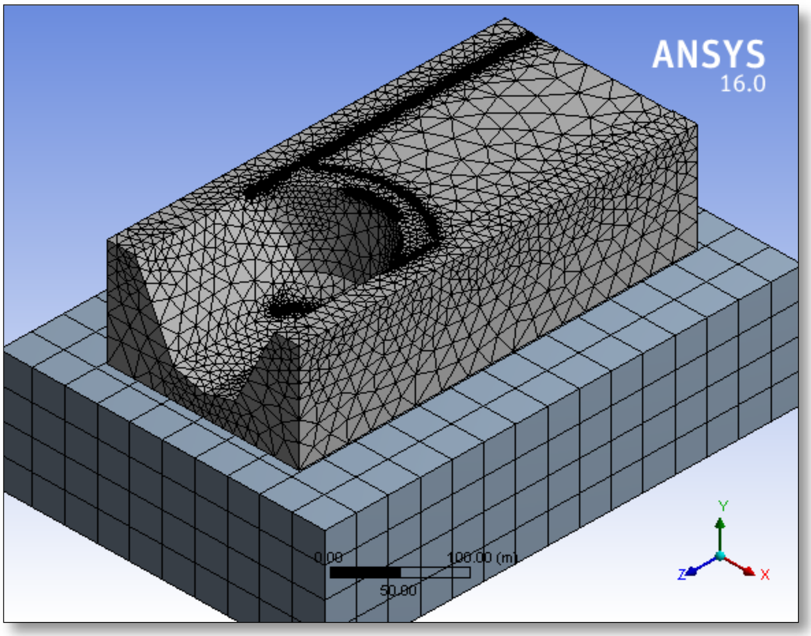


Fig. 4. Model 3 Dam with a dirt base and water on the model (ANSYS [35]).

2.4. Material properties

The properties of the material for the concrete arch dam soil base, as well as reservoir water, are given in Table 2. Numerous groups delineate this knowledge for secure development. The mass of concrete is regarded as uniform in nature, isotropic, and elastic. The optimal base soil is an evenly distributed and isotropic in nature material.

Table 2. Material properties of the concrete dam, reservoir water, and foundation soil (Berrabah et al.[2]).

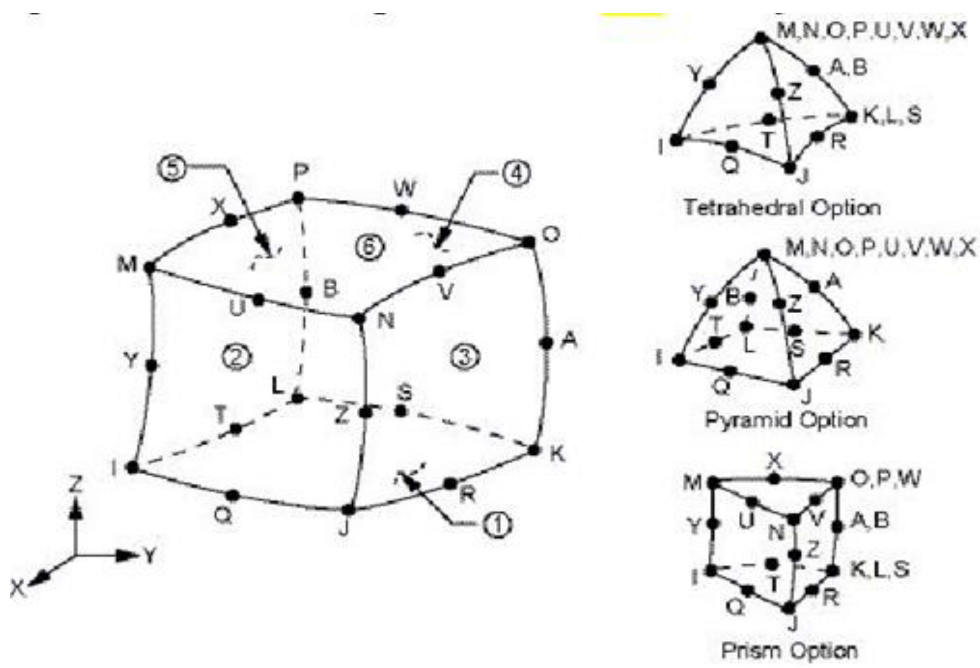
Concrete dam	Mass density (ρ) kg/m^3	2500
	Young's Modulus (E) MPa	28500
	The ratio of Poisson's (μ)	0.2
Water on reservoir	Density (ρ) kg/m^3	1000
	Bulk modulus (K) MPa	2020
	Sonic velocity m/s	14500
	Coefficient of wave reflection	0.25
Earth l base	The mass density (ρ) kg/m^3	2100
	Young's Modulus (E) MPa	14500
	The ratio of Poisson's (μ)	0.25

2.5. Element type and meshing

Figure 5 illustrates the SOLID186 elements, which are 3D solid elements with 20 nodes and exhibit quadratic displacement behaviour. Meshing is a crucial component in a finite element model. Using finer meshes in the FEM model can yield more accurate outcomes. Still, it also results in a more significant number of elements and nodes, leading to higher computational costs. Choosing the optimal element size is critical since it directly affects the computational expense and solution precision trade-offs. The ANSYS Manual [35] is a robust Finite Element Method (FEM) tool that offers users the ability to configure and adjust element dimensions according to the specific characteristics of the investigated simulation. The choice of element dimension and suitable meshing procedures is a critical determinant in ensuring the accuracy and efficiency of simulations conducted using software like ANSYS [35] in the domain of FEM. Table 3 delineates the attributes of the element form and mesh dimension utilized for various parts of the present simulation. A denser mesh with a more significant number of smaller pieces typically produces more precise outcomes, particularly in regions with intricate geometry, as depicted in Fig. 2-4.

Table 3. Types of element and meshing size(ANSYS [35]).

Part	Mesh dimension (mm)	Element form
Dam	250	Solid 186 3D
Base	300	Solid 186 3D
Water on reservoir	300	Solid 186 3D



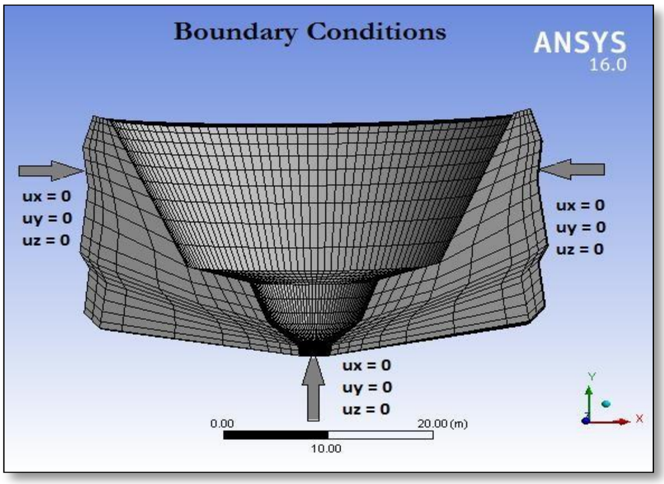
(a) Solid 186

Fig. 5. Multiple elements are utilized to model different components of a concrete arch-gravity dam(ANSYS[35]).

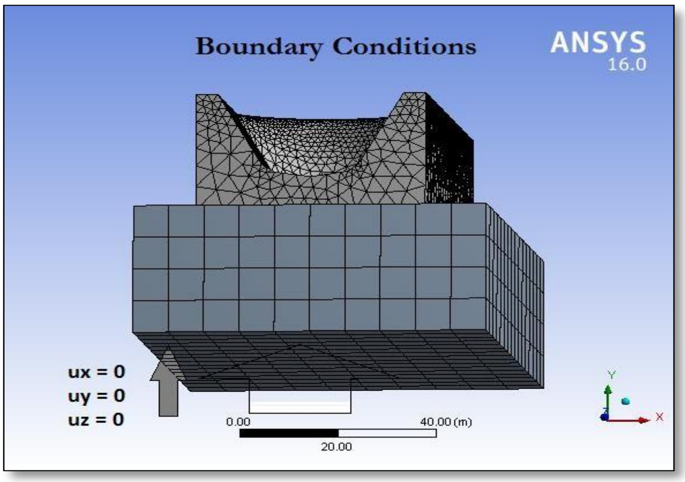
2.6. Boundary conditions

When creating a FEM simulation, selecting limit constraints is crucial. It is vital to choose appropriate boundary conditions to produce meaningful results precisely. The limit constraints for the framework, as indicated in Fig. 6 (Berrabah et al. [2]), may be categorized into two primary divisions: internal boundary conditions, which involve the interaction among every part, and outer limit constraints, which involve the interaction with the external environment.

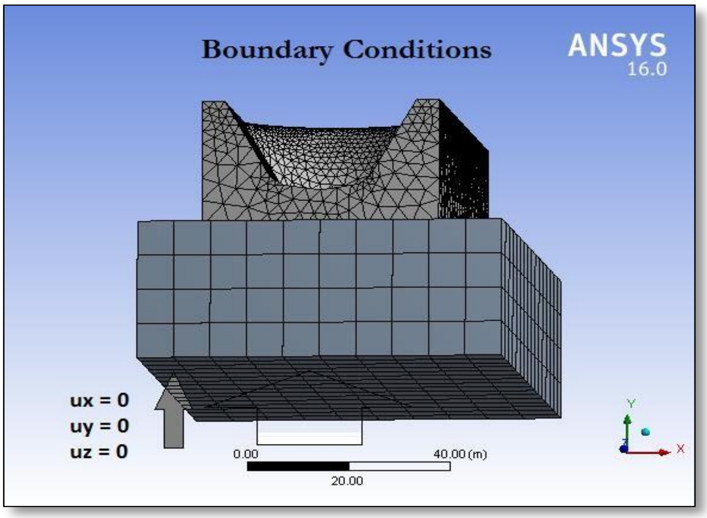
Regarding the outer boundary condition, it is essential to note that the lower and 4 sides of the base were simulated with fixed constraints, meaning that all DOF were restrained. The internal boundary condition was established by implementing a bonded interaction requirement among the interface of the dam and the base.



(a) Model-1: Fixed limit constraints at the base of the dam and side of the dam.



(b) Model-2: Fixed limit constraints at the base of the foundation and side of the dam and Bonded boundary constraint between the interface of the dam and base.



(c) Model-3: Fixed limit constraints at the base of the foundation and side of the dam and Bonded boundary constraint between the dam interface and base.

Fig. 6. limit constraints (Berrabah et al. [2]).

2.7. Damping on a concrete arch dam system

Damping is an inherent occurrence that impacts all dynamic processes in the natural world. In actuality, it is not possible to detect a vibration that is entirely free from damping. Dams undergo vibrations as a result of the hydrodynamic forces and seismic activity. A dam system is a vibrating structure designed to dampen vibrations, functioning like energy absorbers. They scatter the vibrational energy, preventing its accumulation and the generation of significant vibrations. Ongoing research is being conducted to enhance the effectiveness of damping technologies for dams. This can entail improving the architecture of a dam or utilizing novel materials with higher damping qualities. The two primary factors contributing to dam damping are Inherent Damping and the inherent ability of the dam components to dissipate energy. Reservoir The soil base and concrete dam construction both possess intrinsic damping characteristics. For example, the friction between the dirt foundation absorbs a portion of the vibration energy. External dampers are specialized devices that are meant to absorb vibrations. They commonly comprise elastomeric materials, such as rubber and metal components. ANSYS [35] offers multiple options for simulating the impacts of structural damping. The modal analysis permits the utilization of both Rayleigh damping (also known as classical damping) and material-dependent damping (often referred to as non-classical damping) methodologies.

Here, we assume the dam's viscous damping is by the Rayleigh damping model, as explained by Chopra [38] and Rasa et al. [39]. In this scenario, in this context, the damping is proportionate to either the mass, the stiffness, or an assembly of the two.

This is because the undamped mode forms are orthogonal for each of these factors, as demonstrated by the following equations (Chopra [38] and Rasa et al. [39]).

$$[c] = \alpha[m] + \beta[k] \tag{4}$$

It is also referred to as Rayleigh damping. The relationship among the ratio of damping and frequency is determined by Rayleigh damping(Chopra [38] and Rasa et al. [39]).

$$\xi_n = \frac{\alpha}{2\omega_n} + \frac{\beta\omega_n}{2} \tag{5}$$

in which the proportionality constants α & β have units of sec^{-1} and sec, respectively. These are called constant of mass proportional damping (α) and constant of stiffness proportional damping (β). The two damping factors α & β can be assessed through the resolution of a set of simultaneous formulas if the ratio of damping ξ_m , ξ_n associated with two frequencies ω_m and ω_n in the mth and nth modes, is recognized. Formulating Eq.(5) for both scenarios and representing the resulting formulas in matrix notation yields (Chopra [38] and Rasa et al. [39]) to

$$\begin{Bmatrix} \xi_m \\ \xi_n \end{Bmatrix} = 0.5 \begin{bmatrix} 1/\omega_m & \omega_m \\ 1/\omega_n & \omega_n \end{bmatrix} \begin{Bmatrix} \alpha \\ \beta \end{Bmatrix} \tag{6}$$

and if the damping coefficients of the two modes are equal, the $(\zeta = \zeta_m = \zeta_n)$ solution of the simultaneous equations leads to the following(Chopra [38] and Rasa et al. [39]):

$$\begin{Bmatrix} \alpha \\ \beta \end{Bmatrix} = \frac{2\xi}{\omega_m + \omega_n} \begin{bmatrix} \omega_m\omega_n \\ 1 \end{bmatrix} \tag{7}$$

According to the ANSYS theory manual [35], alpha or mass damping may be disregarded in numerous practical structural issues when the value of (α = 0) equals zero. This disregard is typically observed in bodies that exhibit resistance to wind or in undersea applications. In such instances, the value can be assessed based on the known value(Chopra [38] and Rasa et al.[39]) ζ_i & ω_i, as:

$$\beta = \frac{2\zeta_i}{\omega_i} \tag{8}$$

2.8. Characteristics of free vibration

The time taken to react to an assembly is influenced by its proportion of external force frequency (ϖ) to the structure's inherent frequency relative to its weight. The frequencies of nature (ω)align with the external force frequency, potentially resulting in resonance and damage to the structure.

2.8.1. Validation of the method

The modal analysis results for the first five modes of the current work's concrete arch-gravity dam have been confirmed by the investigation carried out by Berrabah et al.[2]. The validity of this analysis regarding the dam problem, considering both the presence and absence of soil-structure interaction, is confirmed by comparing it with ANSYS[35] results obtained from simplified analyses of the fundamental mode response. The SOLID 186 element was employed to replicate the behaviour of the dam. The dam was meshed with a mesh size of 200 mm. The numerical problem involves a concrete arch-gravity dam with specific geometric dimensions. The problem focuses on the geometric dimensions, material properties, element forms, and constraints of different dam components, as Table 1-3 and Figure 2-3 outlines. By utilizing ANSYS[35] software, the outcomes of prior research publications are juxtaposed with the findings of the present study, as depicted in Figure 7. Given the strong concurrence between the current findings and the established results in existing literature, the methodology employed in this study is deemed suitable for addressing the dam-soil interaction phenomenon and accurately determining the fundamental natural frequency.

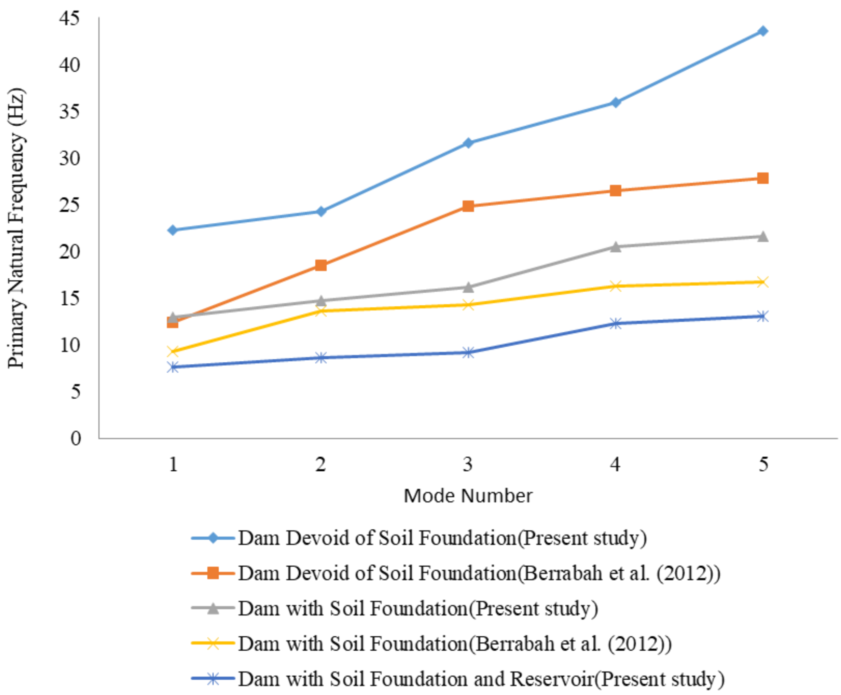


Fig. 7. Frequency of first five modes for undamped free vibration compared with Berrabah et al. [2] Results.

2.9. Forces applied on arch dam

For finding the magnitude of forces on an arch dam, the dam is modelled (2D), and forces are shown (Fig. 8) acting on the dam and being calculated subsequently.

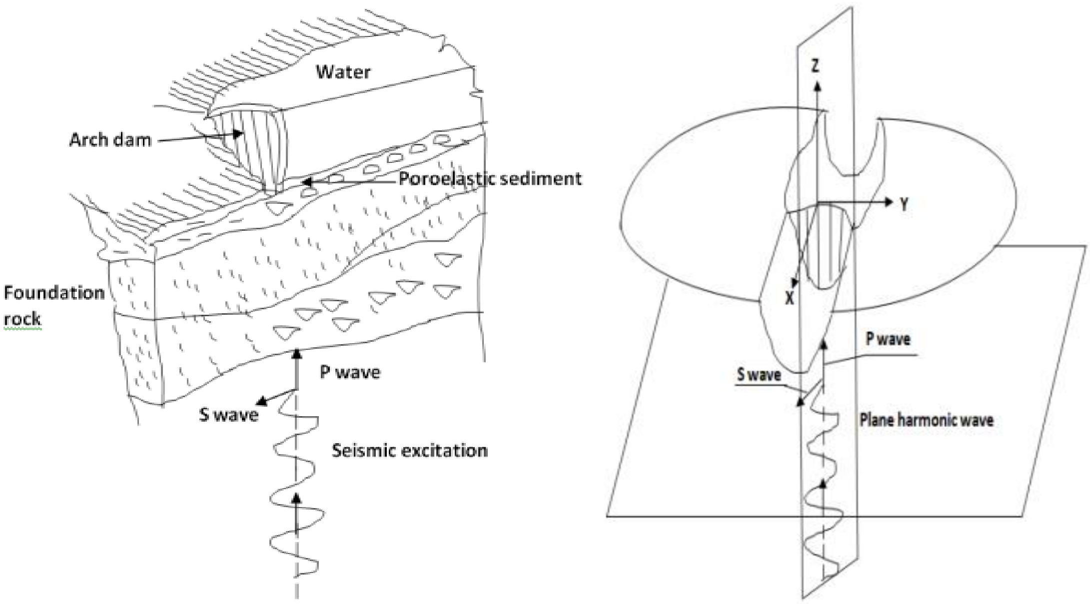


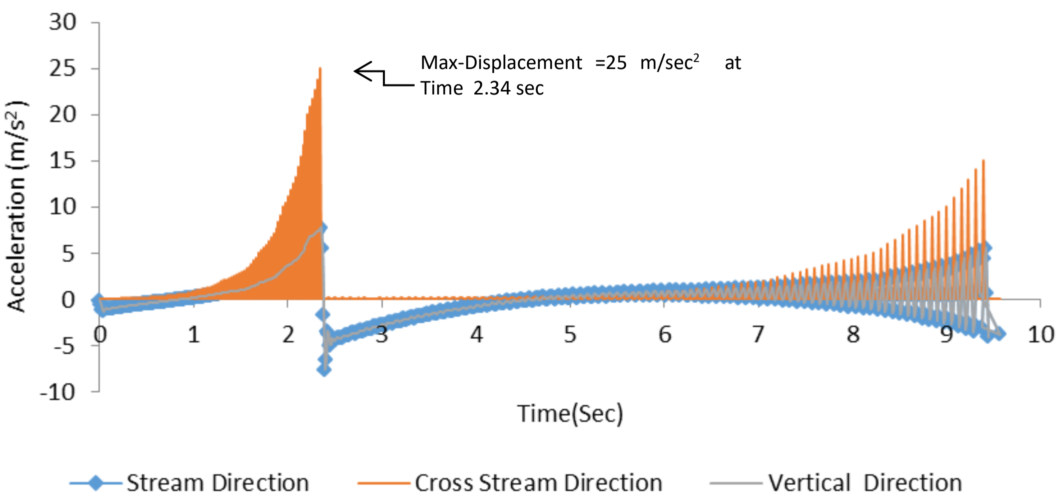
Fig. 8. Dam-water-sediment-foundation systems under vertical earthquake stimulation in the y-z region (Punmia et al. [37]).

2.10. Input of ground movement acceleration

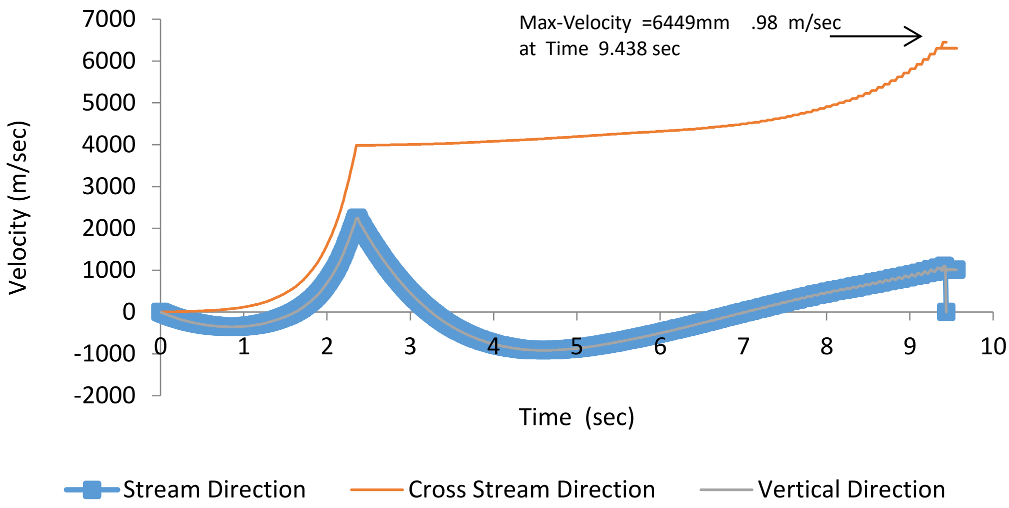
For the dynamic performance of the dam, time response is obtained from accelerograms of the Chamba Earthquake (1995) from the Earthquake Database provided in IIT Roorkee website called COSMOS Virtual Data Center, India, which is downloaded and imported in SeismoSpect software as shown in Fig. 28 (Appendix-B). It gives acceleration, Displacement and Velocity of the ground motion, which are used for analysis. The ground motion Input Data are as follows

2.11. Synthesized ground motion accelerograms

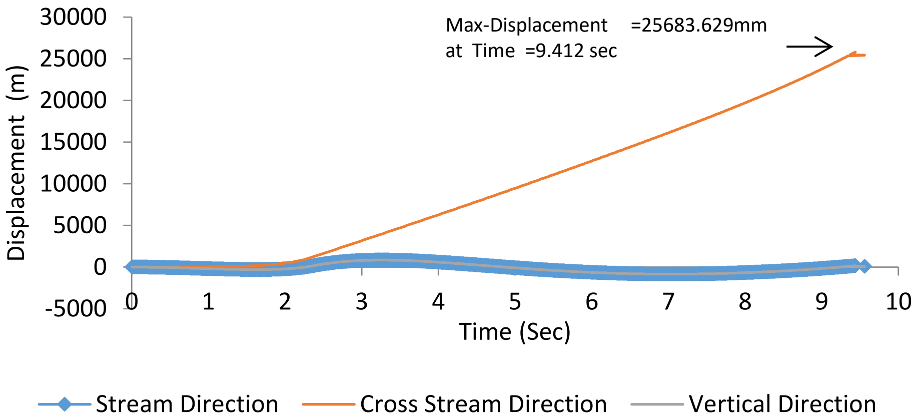
Based on Ground Motion obtained from the record, accelerograms are synthesized in the stream, cross-stream, and vertical orientations (shown in Fig. 9).



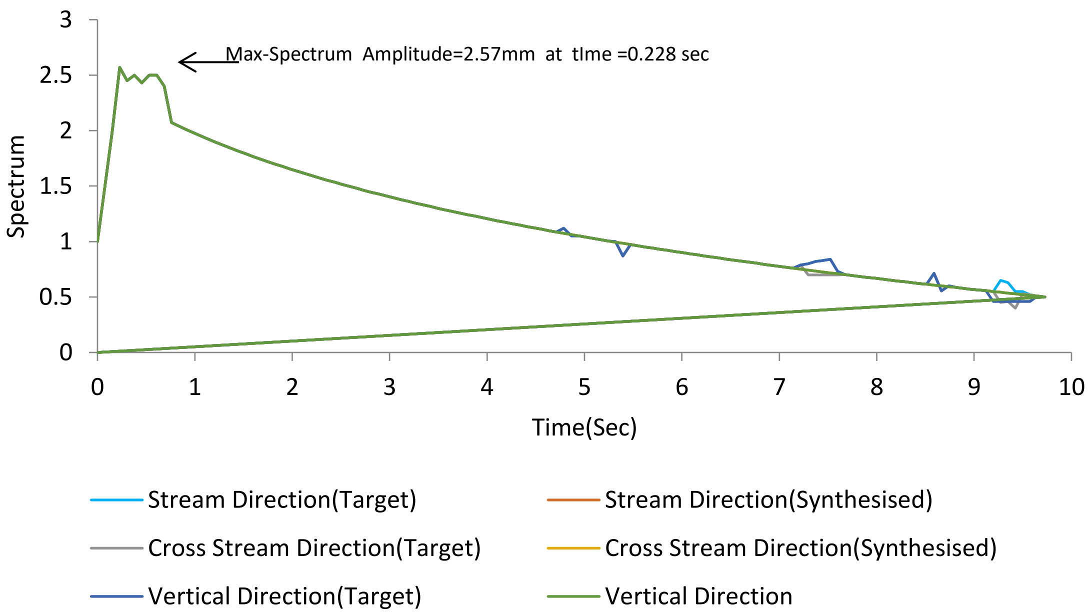
(a) Time vs Acceleration history in various directions



(b) Time vs Velocity history in various directions



(c) Time vs Displacement history in various directions



(d) Time vs Spectrum history in various directions

Fig. 9. A sample of artificial accelerogram in the Various direction.

The graphical representation of the Fourier spectrum from 1995 Chamba ground motion acceleration is shown in Fig. 10. Displacement comparisons of Acceleration histories for linear and nonlinear-linear cases are illustrated in Fig. 11. Hydrodynamic pressure distribution due to horizontal earthquake movement towards the reservoir is illustrated in Fig. 12. Time history of horizontal acceleration (m/s^2) for 1995 Chamba, Himachal Pradesh earthquake record scaled by factor 2.5 (first 10 sec) as Fig. 13.

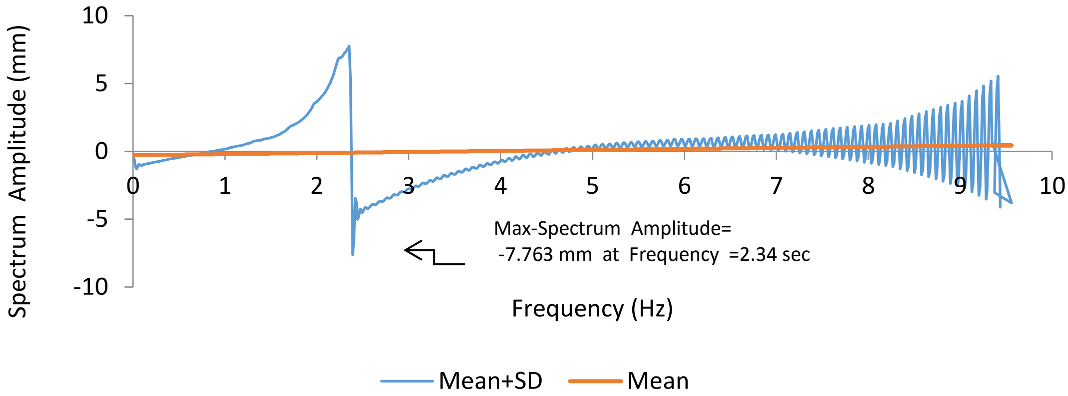


Fig.10. Graphical representation of Fourier spectrum from 1995 Chamba ground motion acceleration.

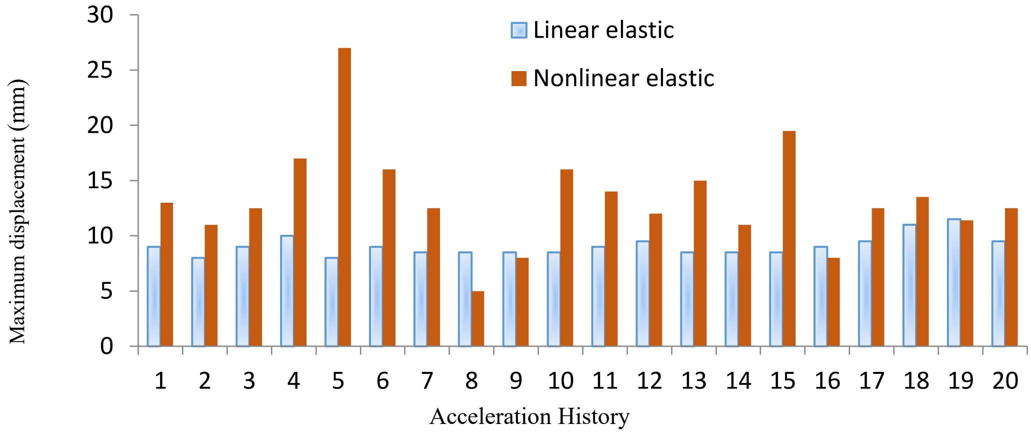


Fig. 11. Displacement comparisons of acceleration histories for linear and nonlinear-linear cases.

2.12. Dynamic analysis of various models of dam subjected to ground motion acceleration

The dam is being analyzed, keeping the bottom fixed with ground acceleration taken from the Chamba earthquake for the first 10 sec as input.

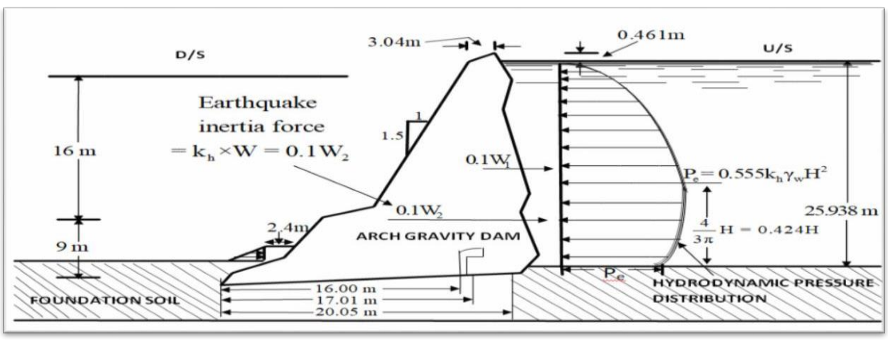


Fig. 12. Hydrodynamic pressure distribution due to horizontal earthquake movement toward the reservoir(Punmia et al. [37]).

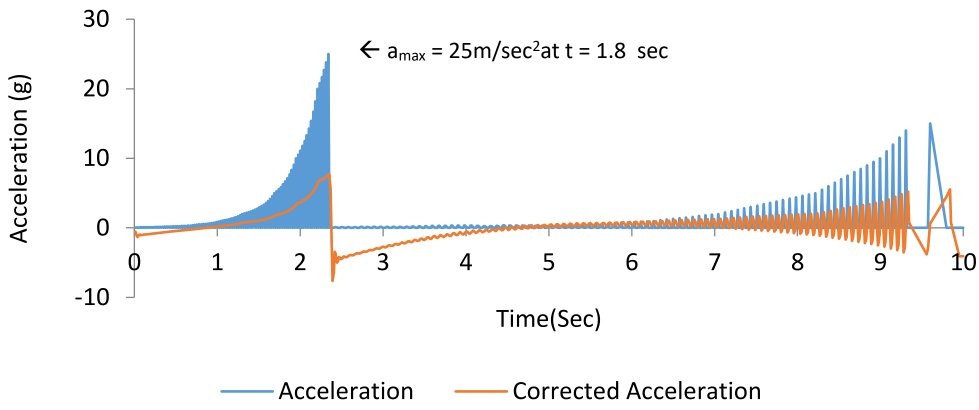


Fig. 13. Time history of horizontal acceleration (m/s^2) for the 1995 Chamba, Himachal Pradesh earthquake record scaled by factor 2.5 (first 10 sec).

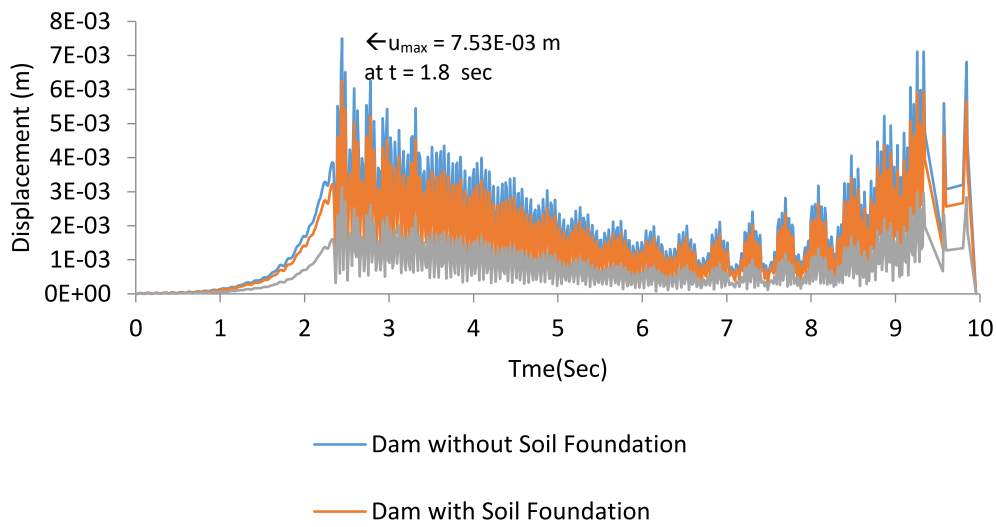


Fig. 14. Simulated result of displacement (mm) varying with time for earthquake ground motion.

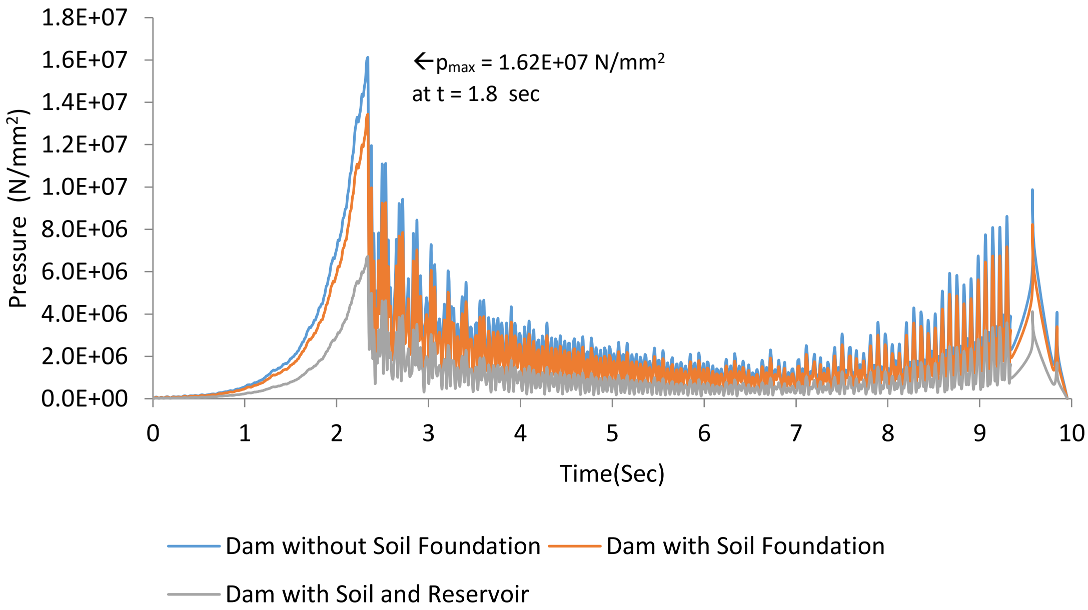


Fig. 15. Simulated result of pressure (N/mm^2) varying with time for earthquake ground motion.

From Fig. 14 and Fig. 15, it can be seen that the simulated results of ground motion accelerations give maximum displacement $u_{max} = 7.53E^{-03}$ m at t = 1.8 sec for Dam without Soil Foundation and maximum pressure $p_{max} = 1.62E^{+07}$ N/mm^2 at t = 1.8 sec for Dam without Soil Foundation.

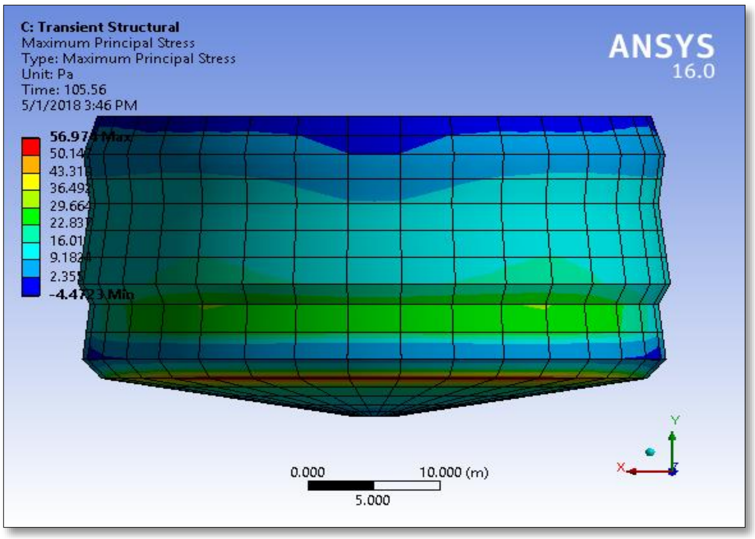
3. Results and discussions

3.1. Characteristics of forced vibration

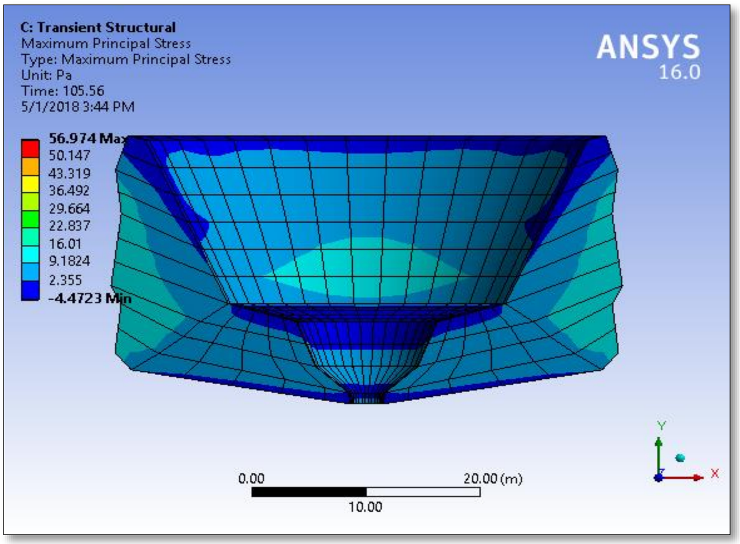
The wave reflection out of the dam's upstream side is studied in seismic responses of dam-reservoir interaction. The instantaneous hydrodynamic pressure results in the elastic deformation of the dam. In this study, the connection of reservoir water dam structures during earthquake excitation is modelled using a finite element technique, and the ANSYS[35] code is adopted via transient analysis. In the dam and reservoir boundary, displacement standards to the dam-reservoir interface are companionable in the structure and fluid.

3.1.1. Simulated results of earthquake ground motion on dam-reservoir systems

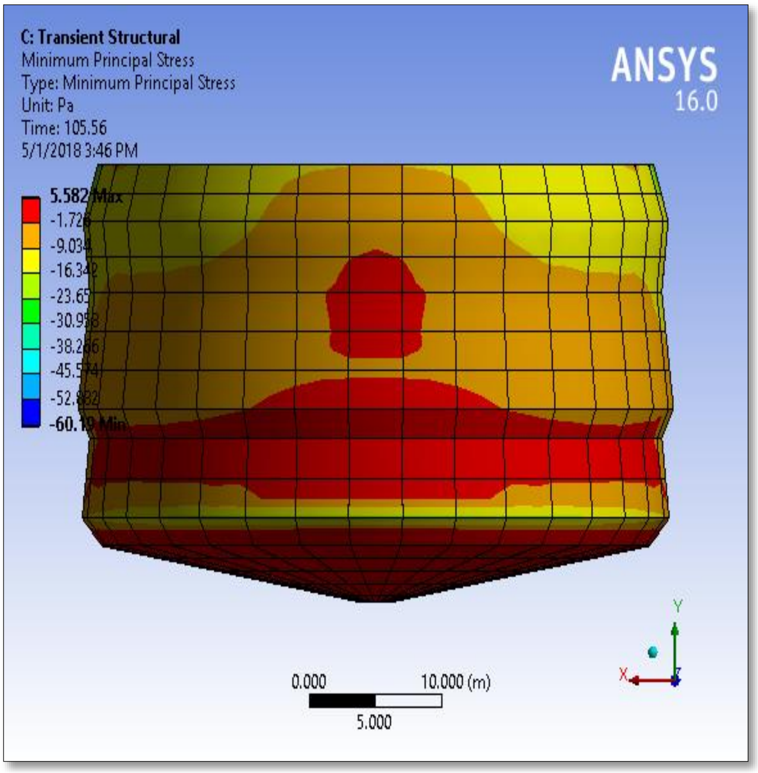
A failure mode of upstream and downstream side cracks in 4.93 sec .78 sec as shown in Fig. 16.



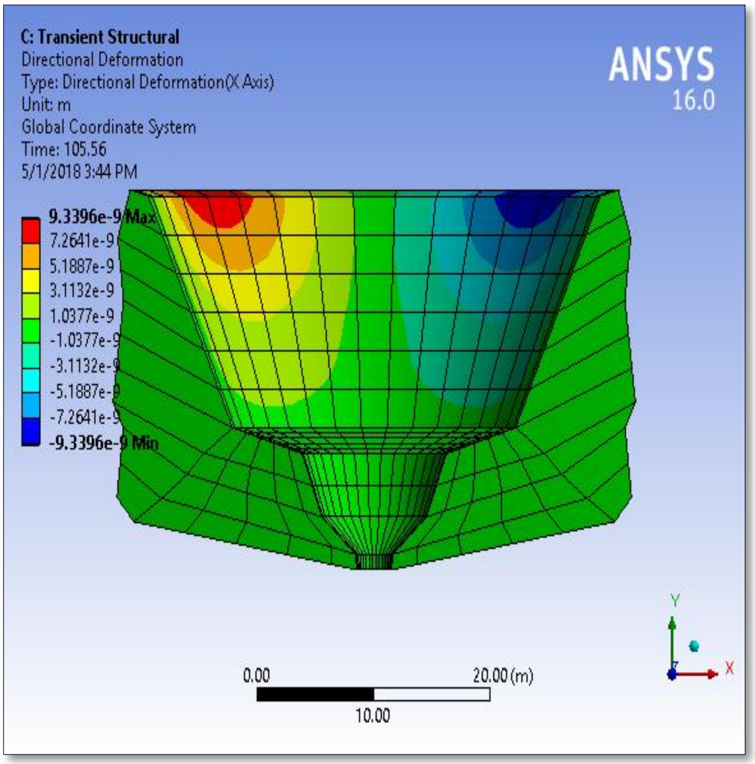
(a) Failure modes: upstream side cracks in 4.9 s



(b) Failure modes: Downstream side cracks in 4.93 s



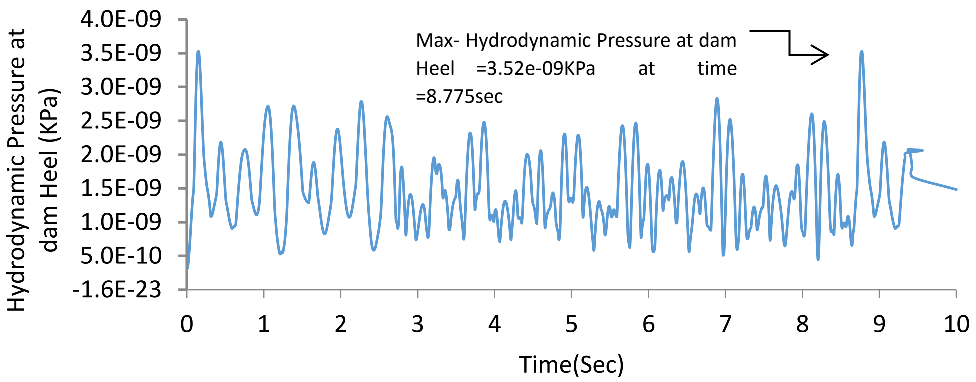
(c) Failure modes: upstream side cracks in 9.78 s



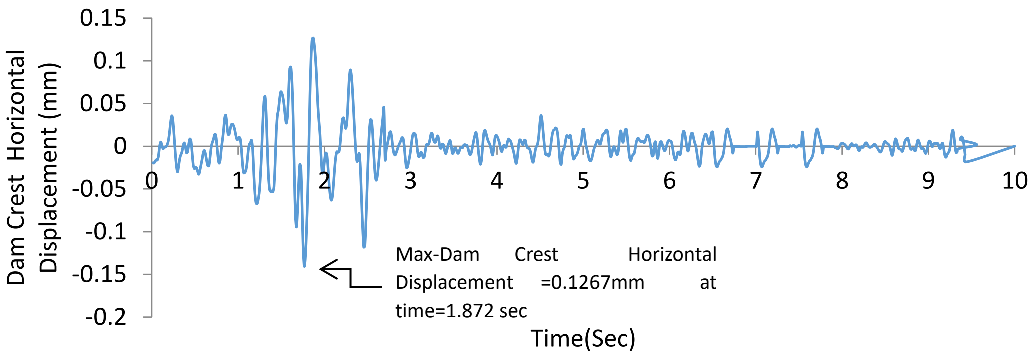
(d) Failure modes: Downstream side cracks in 9.78 s

Fig. 16. Failure modes of dam (ANSYS[35]).

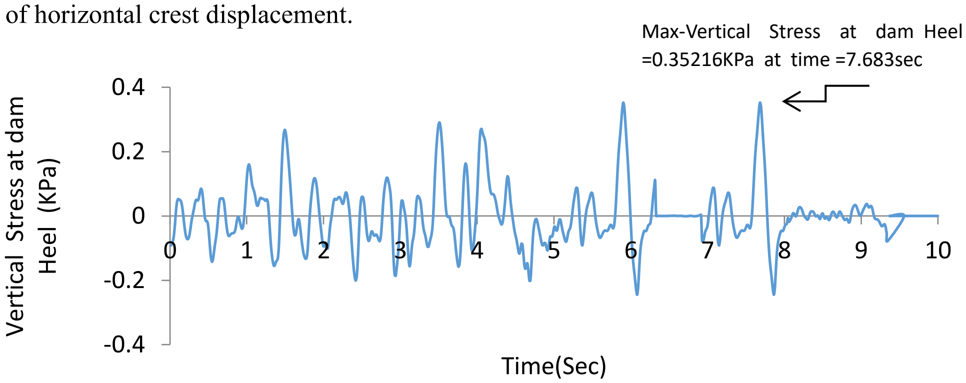
The simulated results of the output obtained from ANSYS [35] are plotted against time and represented in Figure 17.Observations from the figures are discussed, and a conclusion is offered at the end of this paper.



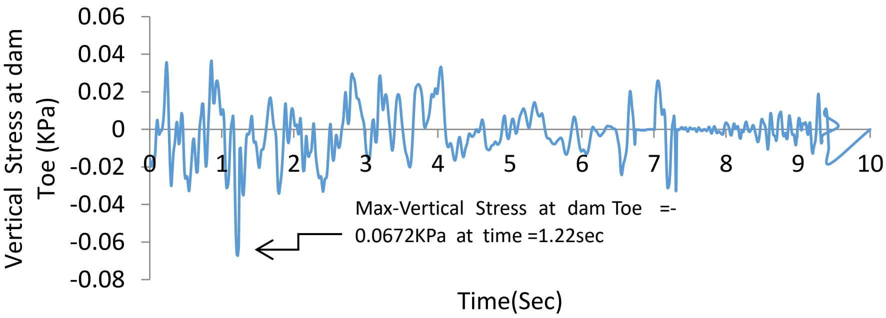
(a) Time history of hydrodynamic pressure at the heel.



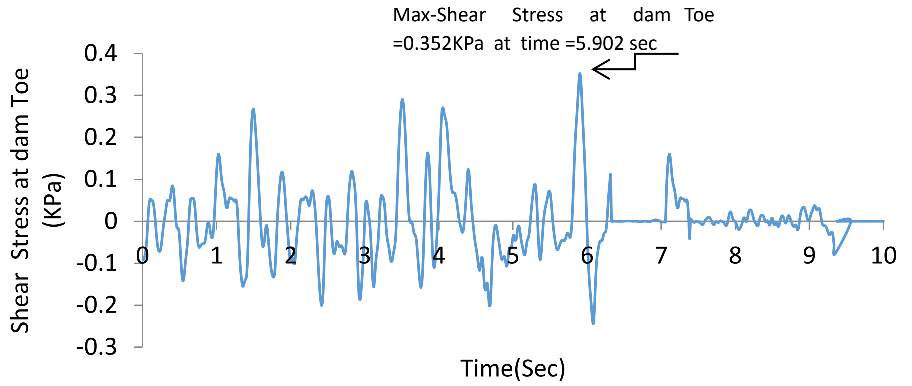
(b) Time history of horizontal crest displacement.



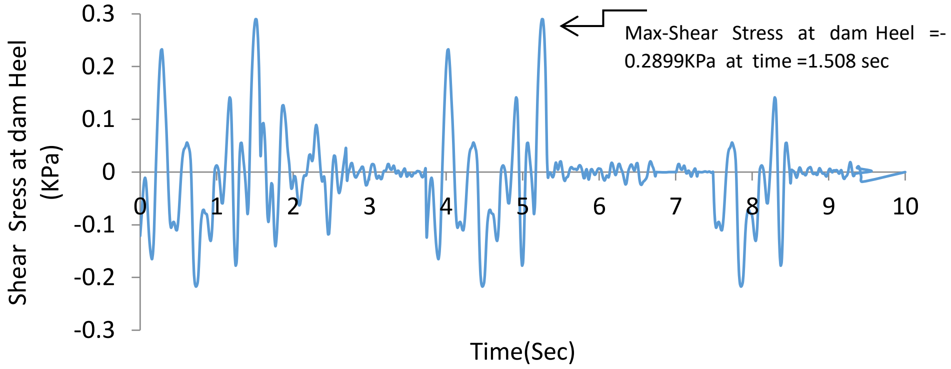
(c) Time history of vertical stress at dam heel.



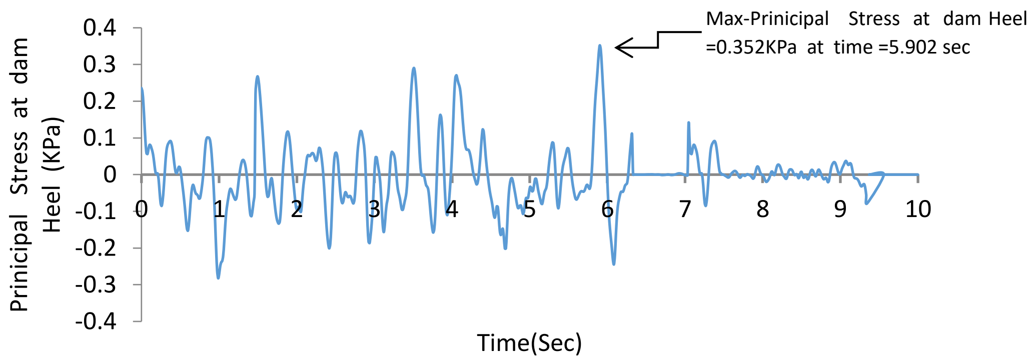
(d) Time history of vertical stress at dam toe.



(e) Time history of shear stress at dam toe.



(f) Time history of shear stress at dam heel.



(g) Time history for principal stress at dam heel.

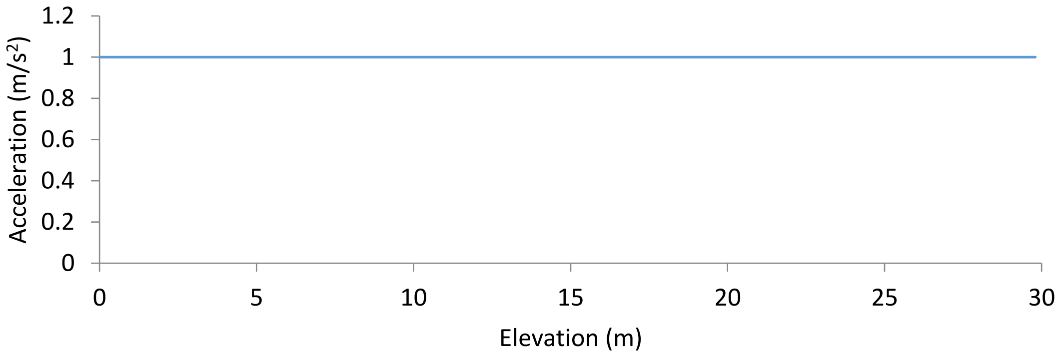
Fig. 17. Various Time histories from simulated outcomes of the dam with soil foundation model.

Investigating the time histories of the dam by the fluctuating performance of dam-reservoir interaction with frequency (Hz), plotted in Fig. 17(a-g) shows the hydrodynamic pressure over hydrostatic pressure computed at the heel of the dam, the time history for horizontal displacements simulated at the dam crest assigns the time history for the vertical stress component at the dam heel with maximum compression value, the time history for the vertical stress component at the dam toe with maximum tension value, the time history for the shear stresses at the dam heel, time history for the shear stresses at the dam toe and the time domain analysis for the shear stresses at the dam heel. Time history results demonstrate that the dam toe is subjected to stresses that vary from compression to tension while the dam heel is subjected to compression stresses.

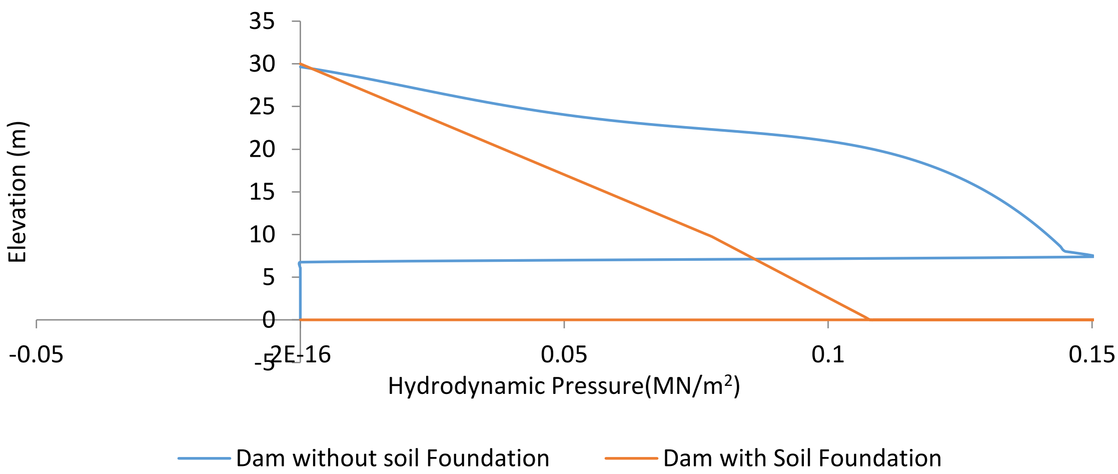
3.1.2. Hydrodynamic pressure acting on an arch dam due to seismic response

Hydrodynamic pressure on a dam during seismic events arises from the accumulation of water as a compressible, non-cohesive fluid mass. The compressible nature of water, leading to hydraulic pressure, is amplified by the frequency of earth acceleration, while the timbre phenomena arise from certain frequencies. Suppose the energy amalgamation at the foot of the reservoir is measured. In that case, the resonance frequency acting on the dam transforms into a milder state, and the definite seismic movement accounts for a range of frequency mechanisms. Hence, the resonance occurrence in water on the reservoir becomes insignificant. Thus, if it acts as a non-compressible (non-cohesive) water body, it gives estimated precision. The analysis uses ANSYS [35] to analyze the dam body's natural frequency with the input Earthquake ground motion. In case of vibration of lower order on the dam body, the value is dominating, evaluating.

the pressure that water exerts experienced during a seismic event because of the dam without soil foundation response, but if there is a higher order vibration of the dam body, Dam without Soil Foundation responses might lead to disproportionate hydrodynamic pressure. Thus, assessing the hydrodynamic pressure is necessary after considering the dam and the reactions of the earth base. Subsequent exploration is carried out concerning the concept mentioned above.

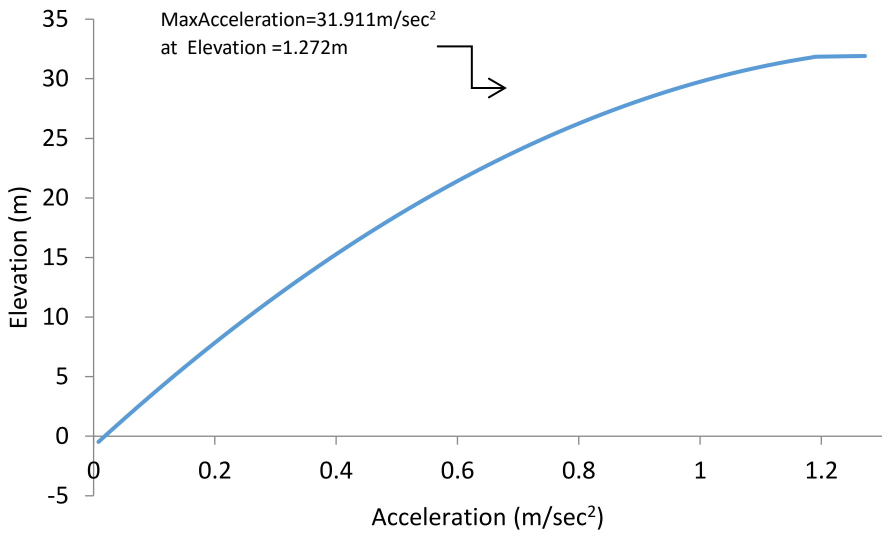


(a) Acceleration (m/s2).

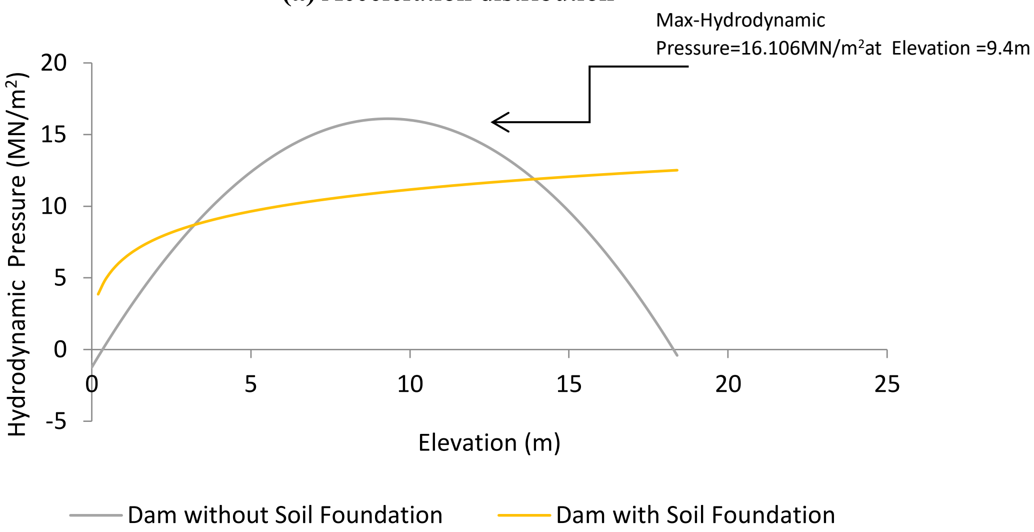


(b) Hydrodynamic pressure (MN/m^2).

Fig. 18. Uniform rigid vibration in Arch Dam.

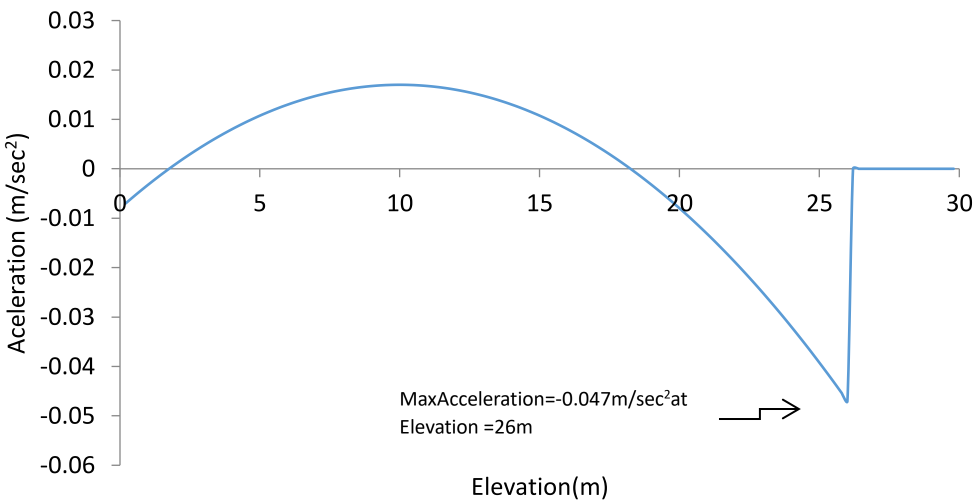


(a) Acceleration distribution

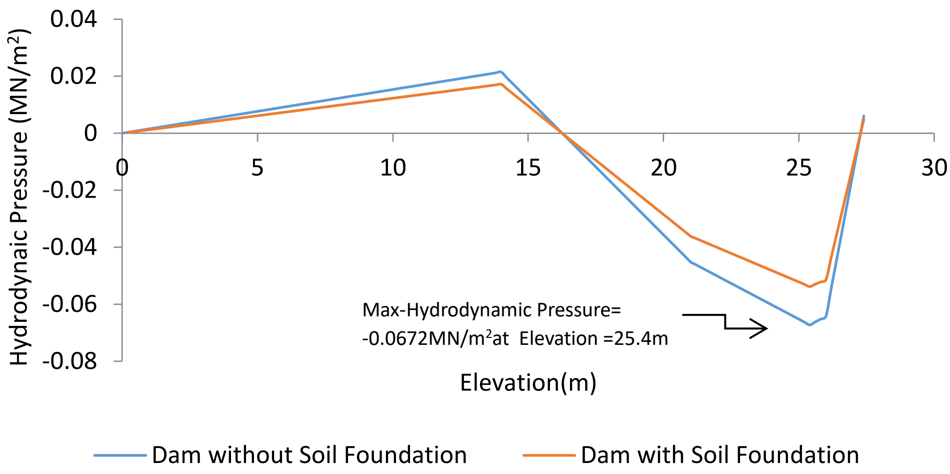


(b) Hydrodynamic pressure distribution

Fig. 19. 1st Mode of vibration for arch dam.

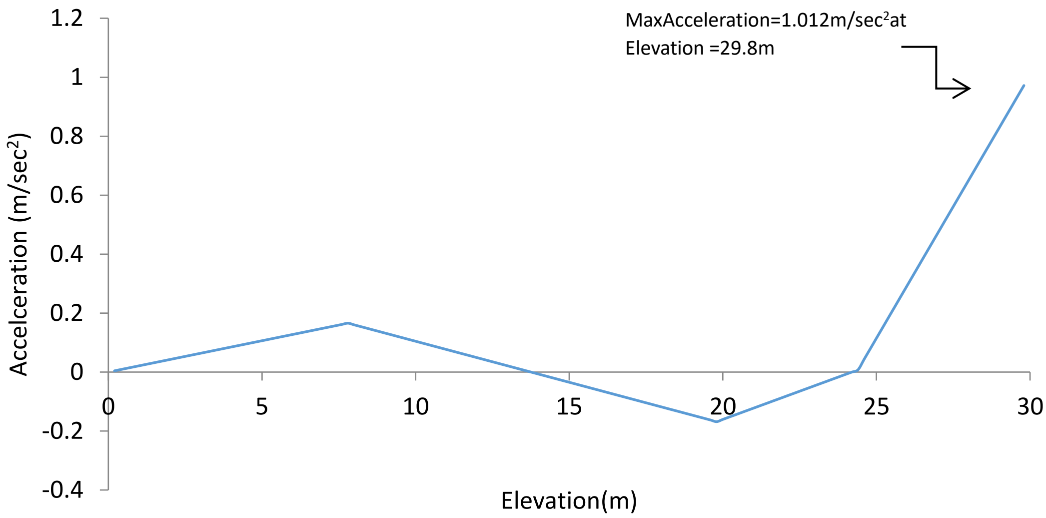


(a) Acceleration distribution

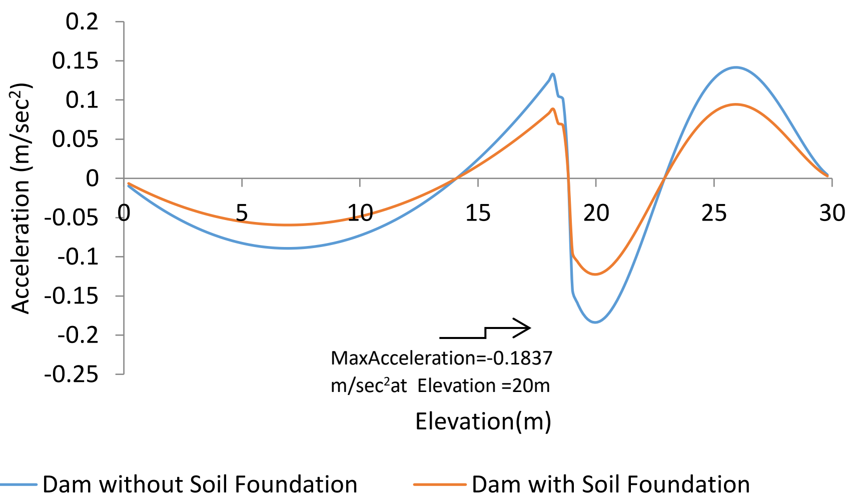


(b) Hydrodynamic pressure distribution.

Fig. 20. 2nd Mode form for arch dam.

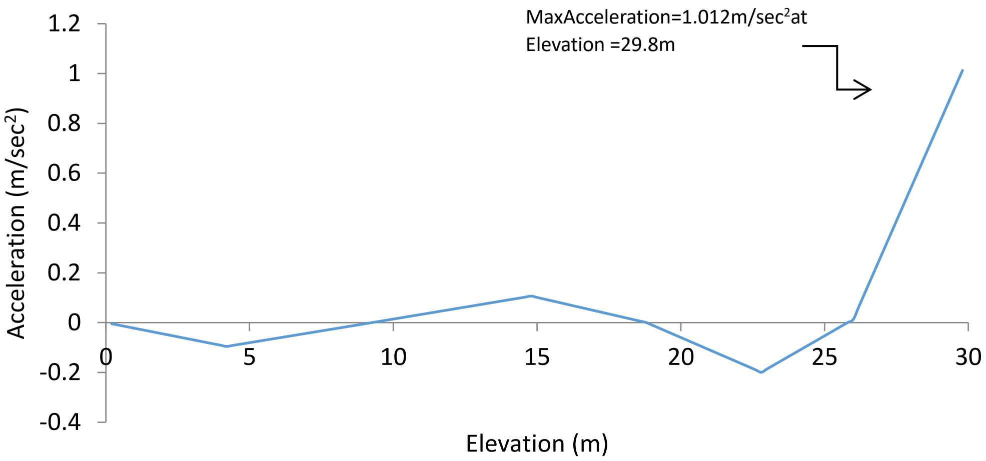


(a) Acceleration distribution.

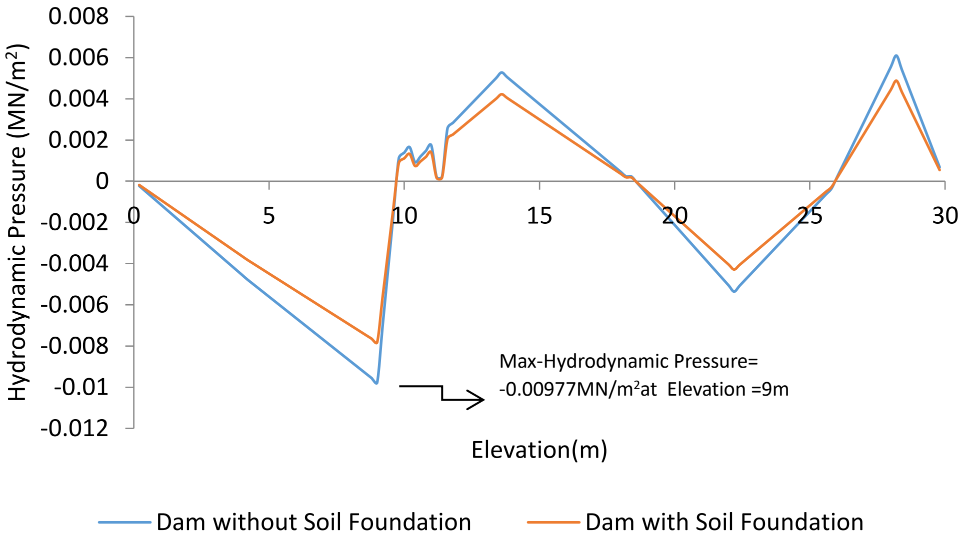


(b) Hydrodynamic pressure distribution.

Fig. 21. 4th Mode form for dam.



(a) Acceleration distribution.



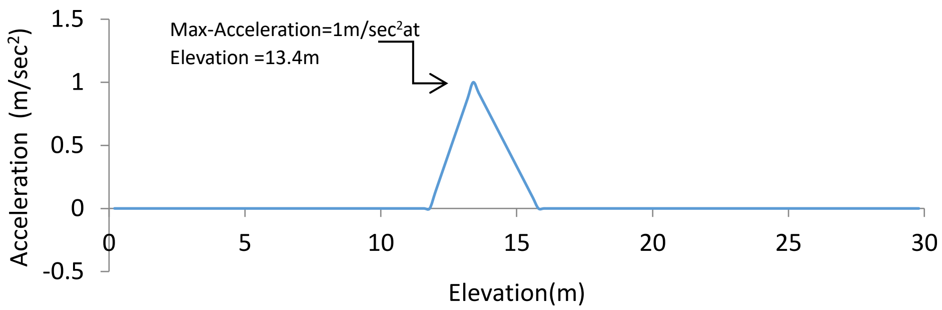
(b) Hydrodynamic pressure distribution.

Fig. 22. 5th Mode form for dam.

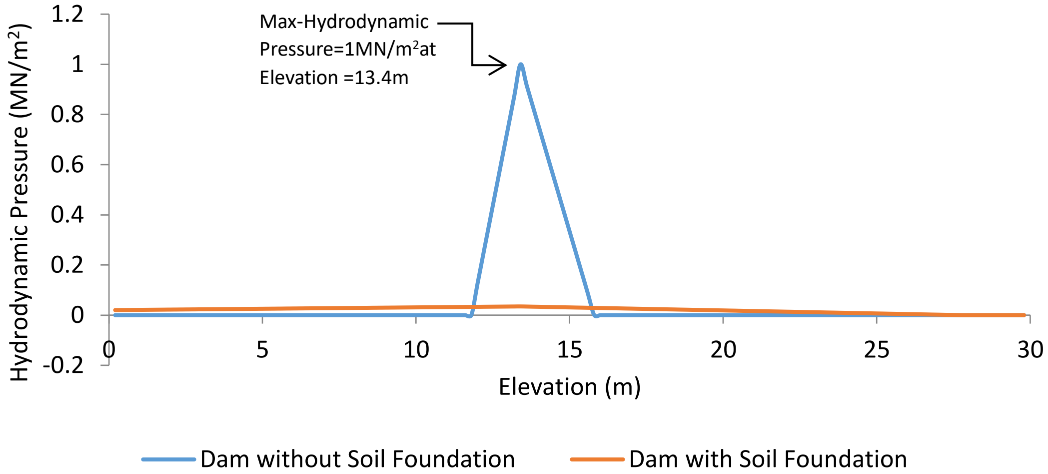
The evaluation of maximum values for horizontal total forces of hydrodynamic pressure exerted on the face of the upstream of the arch dam across several scenarios is presented in Tables 4 and 5.

Table 4. Assessments of maximum horizontal sum forces of hydrodynamic pressure applied on the face of upstream the arch dam.

Study Case	Dam without Soil Foundation (A)		Dam with Soil Foundation (B)		B/Ah	
	Max	Sum force	Max	Sum force	Max	Sum force
Constant rigidity oscillations	0.12	13.19	0.12	12.08	1.19	1.06
1st mode form	0.024	3.05	0.036	3.24	1.49	1.06
2nd mode vibration	-0.013	-1.07	-0.023	-1.03	1.73	0.95
3rd mode vibration	0.005	0.45	0017	0.53	3.18	1.19
4th mode vibration	-0.002	-0.12	0.014	-0.13	-5.38	1.13



(a) Acceleration (m/s2).



(b) Hydrodynamic pressure (MN/m^2).

Fig. 23. Vibration of one point at intermediate height.

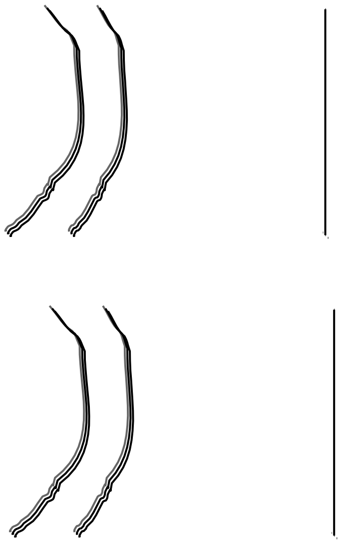
From Fig. 18-23, it can be observed that vibration of lower order in the arch dam has dominated values; Hydrodynamic pressure for higher order vibration of the arch dam, taking into account only Dam without Soil Foundation response, could outcome in superfluous hydrodynamic pressure; therefore, evaluating hydrodynamic pressure for a dam with an earthen base is crucial.

Table 5. Assessment of maximum values with horizontal total forces of hydrodynamic pressure applied on the upstream face of the dam.

Study Case	Dam without Soil Foundation		Dam with Soil Foundation		B/Ah	
	Max	Sum force	Max	Sum force	Max	Sum force
1 point vibration at intermediate height	0.01	0.72	0.09	0.72	8.33	1.03

3.1.3. Ground motion acceleration of dam with sediments and without sediments

The ground mentioned above motion is imported into the ANSYS [35] transient structural window in the ANSYS [35] Workbench project schematic. The graph for the amplitude of acceleration frequency-response in x and y coordinates w.r.t first 50 Frequencies (rad/s) are as follows: Here, two cases relating to silt and the reservoir water levels are considered, as seen in Fig. 24.



	Reservoir level
No sediments	5H /5 (full)
	4H /5
	3H /5
	2H /5
	H /5
	0 (empty)

	Reservoir level
With sediments of H/5 thickness	5H /5 (full)
	4H /5
	3H /5
	2H /5
	H /5 (empty)

Fig. 24. Dam responses concerning the presence of silts and varying reservoir water levels.

Varied reservoir levels of water are noted, devoid of bottom sediments. The arch dam elevations are designated as H, and a permeable sediment level having a thickness of H/5 is taken into account. The investigation encompasses all 11 instances, incorporating both occupied and vacant reservoir circumstances, as illustrated in Fig. 25.

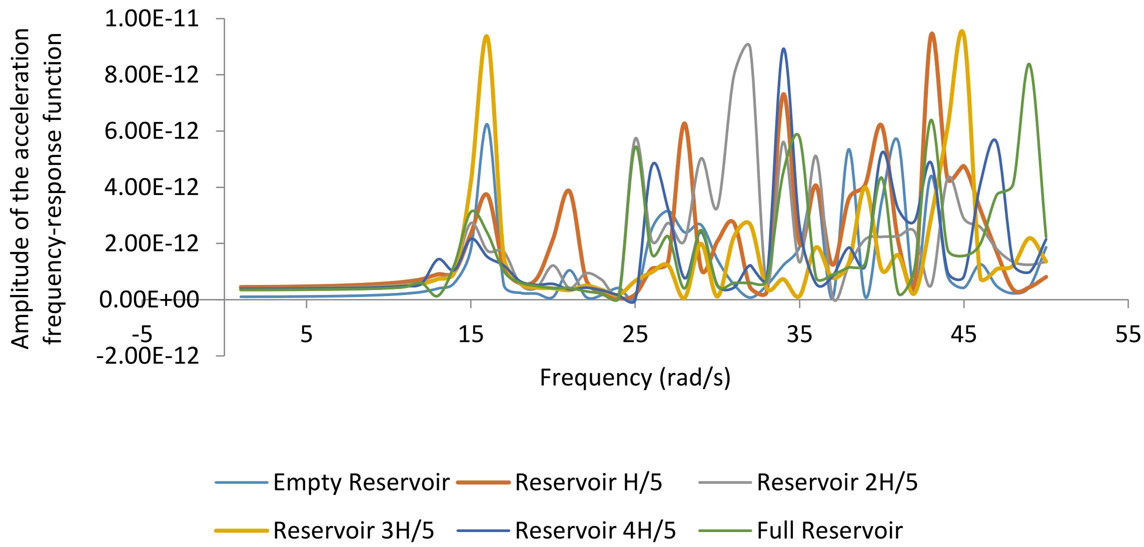


Fig. 25. Acceleration-frequency response amplitude along the "x" coordinates of the S-wave.

Varied reservoir levels of water are noted, devoid of bottom sediments. The arch dam elevations are denoted as H, and a permeable sediment layer with a thickness of H/5 is taken into account. The examination encompasses all 11 instances, including both occupied and vacant reservoir circumstances, as illustrated in Figure 26.

The study is conceded to two dissimilar models: dam with earth interplay, dam with earth, and reservoir with ground motion acceleration of Chamba earthquake in ANSYS [35]. Seismic responses are obtained using p and s waves under the *x* and *y* axes that perpendicularly invade the dam field.

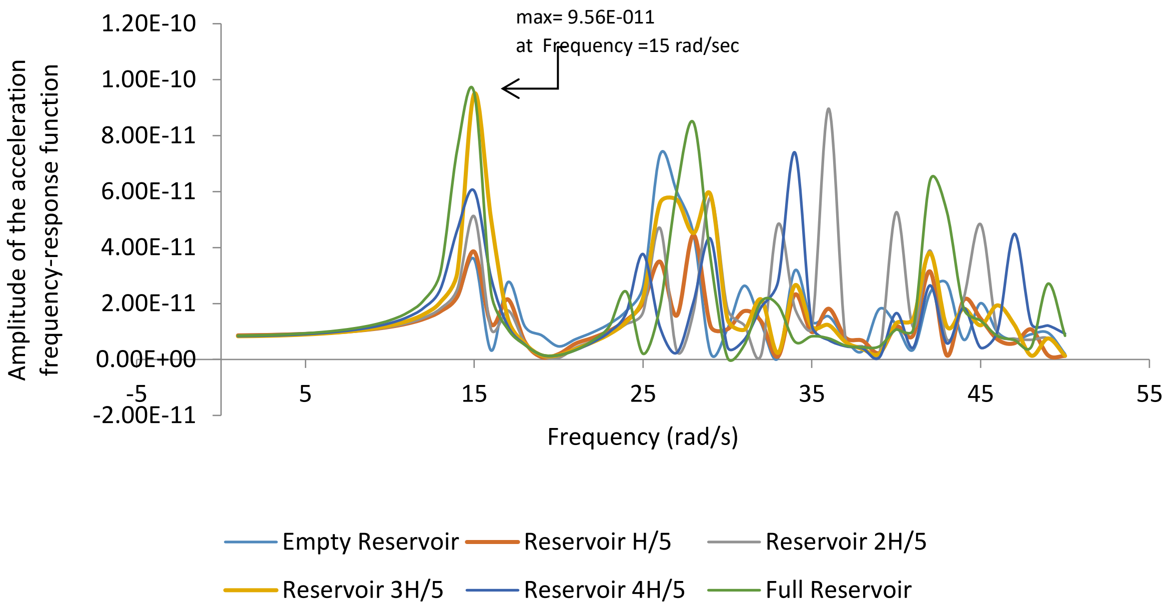


Fig. 26. Amplitude of the acceleration frequency-response function along the "x" coordinate for P-waves.

Figure 25 and 26 illustrate the magnitude of the frequency-response curve along the x coordinate, modeled at a location corresponding to the dam crest on an axis of symmetry, at various reservoir a height, with a vertical time harmonics axis and accompanying p waves. A variation in reservoir height produces considerable differences in dynamic responses for the arch dam versus the frequency range simulated. The steady increase in water heights results in the reduction of fundamental frequencies. From Figure 25, it is observed that if there are negligible bottom sediments, the reservoir's geometry results in substantial changes in the responses of the dam. Also, the open and closed reservoirs have identical significance in dynamic responses for both waves. Figure 26 illustrates that the presence of bottom sediments somewhat influences the motion of the dam's soil foundation across both wave kinds. As a result, reservoir elevation and foundational silts significantly affect the fluctuating performance of the dam-reservoir complex.

4. Conclusions

Dams affect any region's social and economic aspects by providing water for irrigation and drinking, generating electricity, and helping curb floods. They must, therefore, be designed correctly in terms of how they respond under varied loading conditions. The gravitational dam segment must be chosen for its affordability while adhering to all stabilizing criteria and requirements. The analysis concluded that the simulated results of Earthquake ground motion give maximum displacement (m) for a dam devoid of earth base than a dam with earth base and comparatively small displacement for a dam with earth and reservoir. Similarly, simulated results of earthquake ground motion give maximum pressure (N/mm^2) for a dam without an earth base than a dam with an earth base and comparatively small displacement for a Dam with Soil and Reservoir.

It was also concluded that vibration with lower order frequency of arch dam has more dominant values, the hydrodynamic pressure can be assessed through evaluation by including dam without earth base, but when there is higher-order vibration for the arch dam taking into account dam without earth base may lead to the extreme dynamic pressure of water, so it is essential to calculate the dynamic pressure of water for dam with soil foundation.

It was also seen from a frequency-response function that moderately saturated silt minimizes the reservoir's effect on the structure's seismic responses. It is seen that the response to the frequency of the configuration diminishes while there is silt, mainly for ground motion P-waves and following the water height of the reservoir. However, the S-Wave reservoir status influences the results to a superior level; moreover, it is additionally located in areas closer to the base of the reservoir. The current study of concrete gravity arch dam systems subjected to earthquake force may be extended to focus on an experimental or field survey for this research.

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Conflicts of interest

The authors assert that they possess no recognized competing financial interests or personal ties that may have seemingly influenced the work presented in this study.

Authors contribution statement

Sougata Mukherjee: Conceptualization, Data curation, Formal analysis, Investigation.

K Nallasivam: Methodology, Project administration, Resources, Software, Supervision, Visualization; Roles/Writing – original draft, Writing – review & editing.

Appendix A

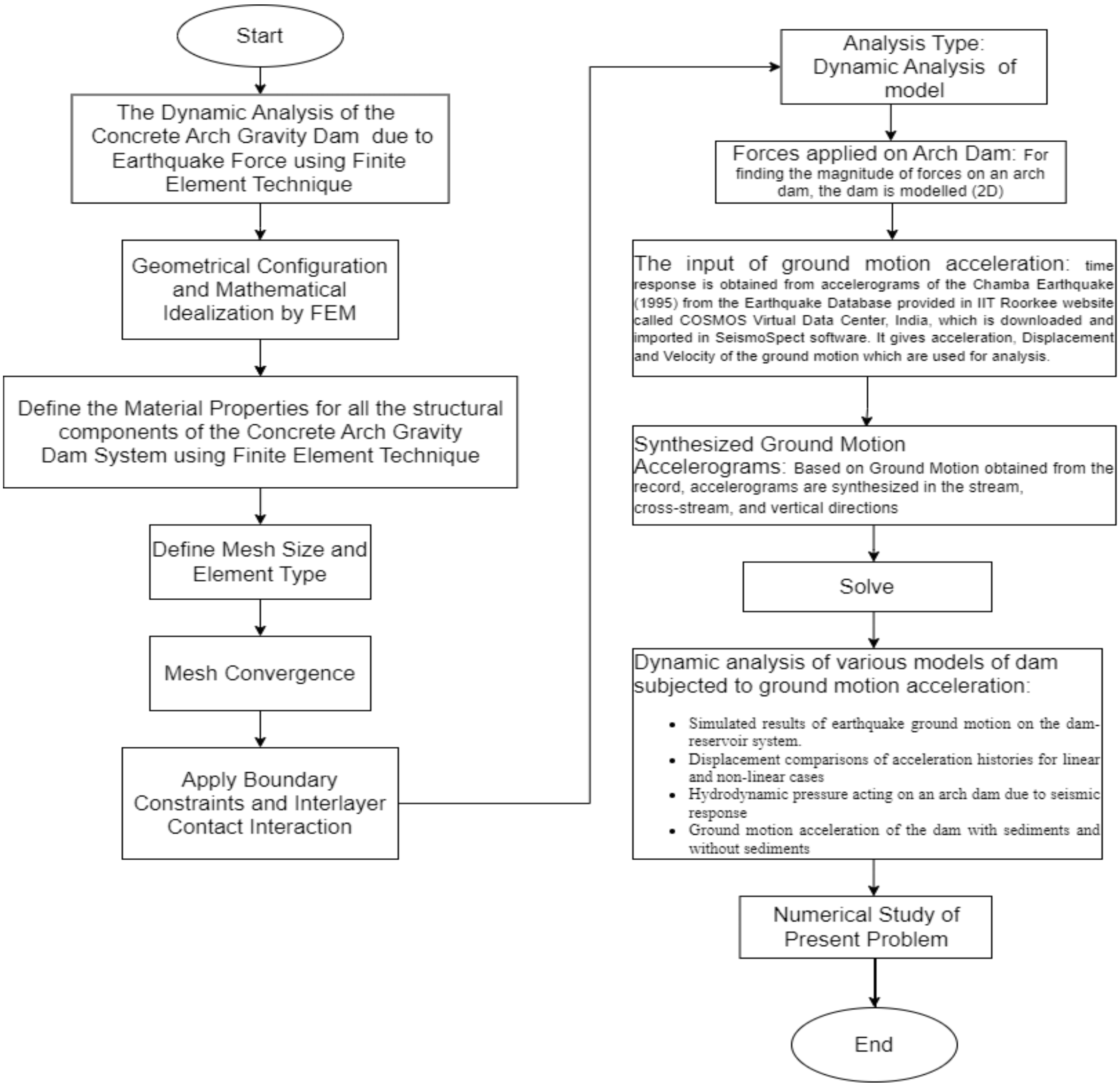

Fig. A1. Flowchart Schematic flow for dynamic analysis of concrete arch dam due to earthquake force using FEM model.

Appendix B

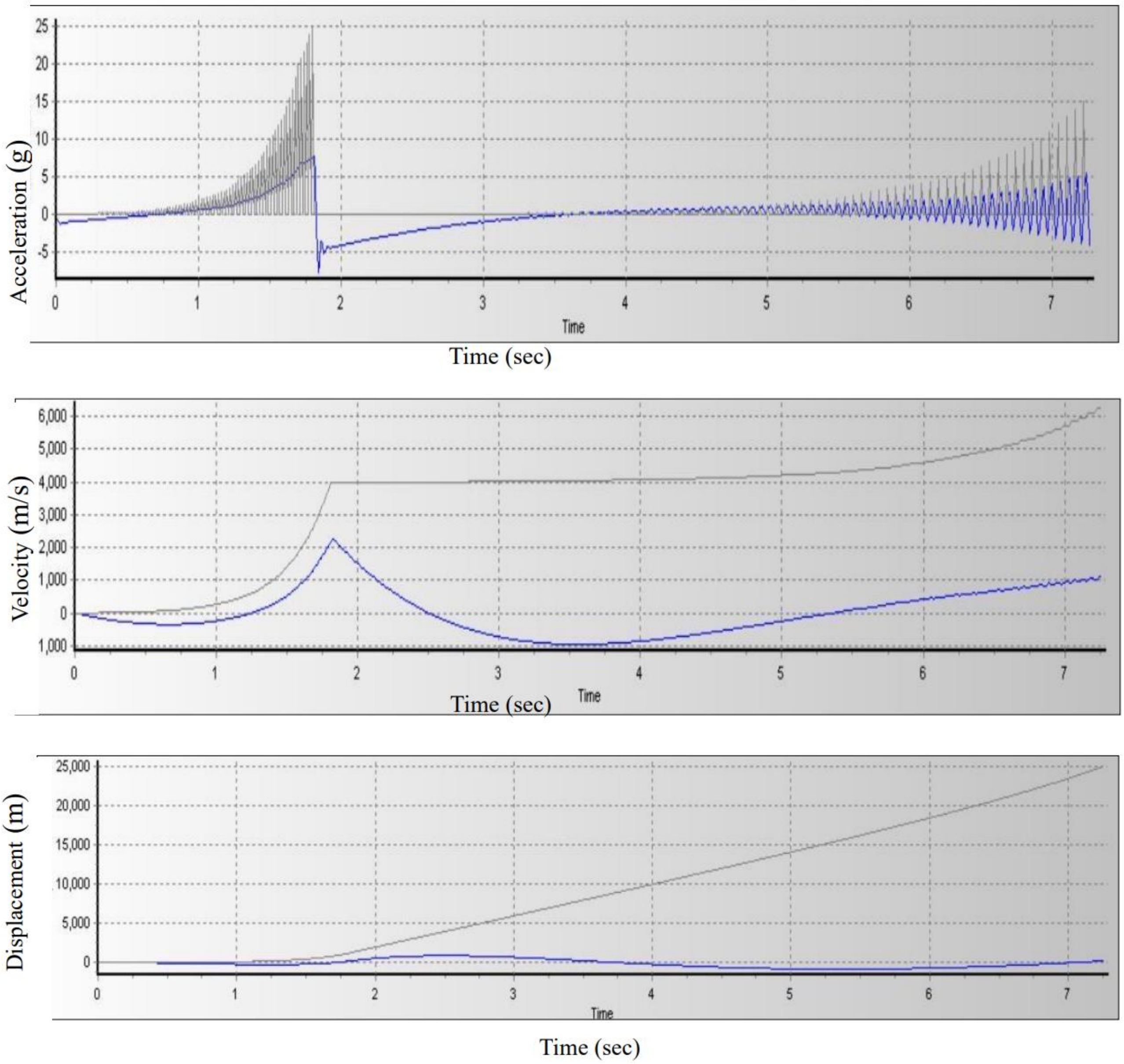

Fig. A2. Ground motion Acceleration (g), velocity (m/s^2) and displacement (m) of Chamba Earthquake, 1995.

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