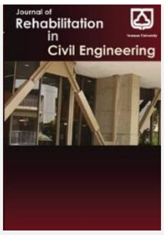
Journal of Rehabilitation in Civil Engineering 13-1 (2025) 130-150



Journal of Rehabilitation in Civil Engineering

Journal homepage: https://civiljournal.semnan.ac.ir/

Seismic Analysis of Concrete Buttress Dam Considering Intake Tower and Reservoir

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ARTICLE INFO

Article history:
Received: 08 September 2023
Revised: 01 May 2024
Accepted: 01 August 2024

Keywords:
Concrete buttress dam;
Seismic responses;
Intake tower;
Wimbleball dam;
Finite element method.

ABSTRACT

This study evaluates the intake tower's effect on the buttress dam responses, considering the access bridge and reservoir under seismic loading in ANSYS using the finite element model. Wimbleball dam in England is assigned as a case study to assess the effects of different characteristics of the system components on seismic responses. Some parameters were applied, such as the presence of the intake tower and access bridge, reservoir water level, intake tower height, and internal water level. Nine cases with and without intake towers and access bridges have been studied by raising the reservoir water level, intake tower height, and internal water level, resulting in three-dimensional seismic analyses. Circular frequencies, crest displacements, and heel stresses of the dam have been presented for current cases. The interaction between the reservoir, dam, and intake tower can alter the case's stiffness and consequently change its frequencies. The modal analysis responses presented that the case's frequencies were reduced by raising the reservoir water level by up to 40% and increasing the intake tower height by up to 19%. The seismic results show that the heel stresses of the middle buttress increase by raising the reservoir water level by up to 39%. For constant water levels in the reservoir and tower, displacements and stresses of the middle buttress increased by increasing the intake tower height by up to 3% and 43%, respectively.

E-ISSN: 2345-4423

How to cite this article: Mahdian Khalili, A., & Navayi Neya, B. (2025). Seismic Analysis of Concrete Buttress Dam Considering Intake Tower and Reservoir Interaction. Journal of Rehabilitation in Civil Engineering, 13(1), 130-150. https://doi.org/ 10.22075/jrce.2024.31734.1897

1. Introduction

Concrete structures in seismic zones can damaged by strong earthquakes [1]. Concrete hydraulic structures like dams require health monitoring [2]. In recent decades, many techniques have been developed for health monitoring and seismic improvement of concrete structures [3–6]. Intake towers are hydraulic structures whose main function is regulating the reservoir water level. Sometimes, these structures are freestanding and constructed on a concrete foundation on rock or soil in the reservoir. In contrast, they can structurally be linked to the circumambient land or the upstream surface of the concrete dams [7]. According to the buttress dam's specific geometry, the necessity for assessing dam and tower safety is increased in the case of constructing the intake tower near the concrete buttress dam. The dynamic analyses of intake towers and concrete dams were investigated with Finite Element Model (FEM), and this model had good performance in simulating water-structure interaction [8–15]. Some studies were performed separately on the dynamic analysis of intake towers and concrete buttress dams, which will be reviewed below.

Liaw and Chopra studied the effects of peripheral fluid and its hydrodynamic interactions on the intake structure's dynamic response, neglecting the influences of surface waves and fluid compressibility [16,17]. They used the added mass method to calculate the peripheral fluid interaction effect. Goyal and Chopra developed this method for linear seismic analysis of arbitrary intake towers with two axes of plan symmetry by heeding the influences of tower-reservoir-foundation interaction [18–21]. They introduced the frequency domain equations for foundation, foundation-tower, reservoir water systems, and foundation-tower-reservoir systems.

Daniell and Taylor analyzed a system including The intake tower, reservoir, and access bridge with FEM [22]. They performed ambient vibration tests on the intake to specify the vibration mode shapes. Good compatibility between tests and numerical modal results indicated that FEM could be a credible method for developing models if the analysis of complex models is required [22,23].

Millan et al. investigated the concrete gravity dam-intake tower-reservoir system under seismic loading [7]. They comprehended that a concrete gravity dam adjacent to the intake tower could lead to a resonance state under the horizontal excitation of the dam and reservoir. Alembagheri presented that the interior fluid of the intake in the gravity dam-intake tower-reservoir-foundation system has different influences on the tower dynamic responses with a rigid foundation. In contrast, it reduced the tower's displacements with a flexible foundation [24]. Aghaeipoor and Alembagheri studied the influence of seismic sequences on the intake tower of Encino dam with structure-reservoir-foundation interaction using the finite element method [25]. They presented the relative deflections and nonlinear material responses as the main dynamic responses of the tower. Khalili et al. evaluated the efficacies of sediments on the reservoir floor and the dam and tower gap on the dam and tower responses [26]. They showed that the accumulation of sediments in the reservoir floor can augment dam and tower responses. In addition, incrementing the interval between the dam and the tower may disturb the incremental trend of seismic responses in the more rigid reservoir sediments.

Teymouri and Abbasi investigated the influence of the number of vertical stiffeners on the frequency and seismic responses of a cylindrical intake tower using ANSYS [27]. They concluded that applying vertical stiffeners increases the maximum principal stresses and the abutment reaction. Also, the best reduction of the first principal stress occurs when the stiffeners are aligned with the earthquake's horizontal components or the distances of the stiffeners are shorter.

Sefidrud buttress dam in Iran is a large concrete buttress dam damaged severely by the Manjil earthquake in 1990 [28]. After the occurrence of this earthquake, many researchers studied the seismic analysis of Sefidrud dam. In one of these studies, Ghaemmaghami and Ghaemian performed a nonlinear seismic analysis on the highest monolith of the Sefidrud dam with a vacant reservoir [28]. They used a geometric scaled model of 1:30 under shaking table tests in the laboratory. The observed crack extension patterns for the condition consisting of a construction joint and a rigid foundation represented good compatibility between numerical and experimental results. Zhang et al. applied a series of shaking table tests to evaluate the seismic responses of a slender intake tower considering the dynamic interactions of hoist chamber-main tower-backfill concrete [29]. They observed that the backfill concrete height and the connection of joints can significantly affect the seismic response of the main tower.

Cracks appeared in some of the hydropower dams, for example in the Storfinnforsen hydropower buttress dam in northern Sweden [30]. The extension of a crack in the Storfinnforsen dam was studied by Malm and Ansel with FEM based on nonlinear fracture mechanics and plasticity theory [30]. The results of their study represented that the combination of thermal stresses with the loads caused by water is an important factor for concrete cracking. Case studies were carried out on the Swedish buttress dams under different values of Peak Ground Acceleration (PGA) with a return period of 10,000 years. The responses of dams indicated that for the maximum values of PGA, the concrete buttresses were severely cracked [31].

Ilinca et al. studied the dynamic analysis of the buttress dam using the direct time integration method and spectral analysis method separately [32]. They compared displacements, stresses, and sliding stability on the dam-foundation contact layer, assuming a full reservoir. Results indicated that although both methods provided close responses, the spectral analysis method obtained more conservative responses than the direct time integration method [32].

Doronin investigated the seismic persistence of a massive buttress dam with partial grouting of the intersection joints and cracks in the buttresses [33]. They presented the natural frequencies, amplitude-frequency attributes, and stress-strain conditions of the dam sections for different types of cracks in the buttress body. Enzell et al. conducted model tests with a scale of 1:15, to evaluate the failure behavior of concrete buttress dams [34]. They concluded that the shear transfer between the monoliths was large and that the failure of a single-dam monolith was improbable.

Li et al. evaluated the effect of seismic waves on the slabs of asphalt concrete-faced rockfill dams (ACFRDs) [35]. They concluded that the established oblique incident input model of SV-wave simulated the free-field half-space correctly.

Most mentioned studies, assessed case studies of damaged buttress dams after an earthquake. While the seismic behavior of the buttress dam in interaction with the reservoir and other structures would be remarkable. In this study, the concrete buttress dam is analyzed in FEM with the intake tower, access bridge, and reservoir. Nine different geometrical cases are considered to evaluate the efficacies of diverse factors on the seismic response of the dam. One case only consists of a dam-reservoir system, while in other cases, the intake tower and its internal water level and access bridge are added to the system. In cases consisting of intake towers, the influence of the reservoir is investigated on dam responses in four different reservoir water level conditions. The effect of tower height and internal water level of the tower are assessed by incrementing the tower height 1.5 and 2 times the initial state, in both full and semi-full cases with the constant reservoir water level.

2. Numerical modeling

The governing equations and boundary conditions of the system are described in this section to provide the coupled fluid-structure interaction (FSI) in FEM. Subsequently, the attributes of the elements used in the FEM and geometry of the case study considered in the present research have been described.

2.1. Governing equations

In the current study, the 3D simulation of the dam-intake tower-access bridge-reservoir system is modeled using ANSYS software by considering the Lagrangian-Lagrangian approach for FSI. In this formulation, the equilibrium dynamic motion equation is given by Eq. (1) [36,37].

$$M\ddot{u} + C\dot{u} + Ku = 0 \tag{1}$$

where M, C, and K are mass, damping, and stiffness matrixes, respectively, and $\ddot{u}$، $\dot{u}$, and u are nodal acceleration, velocity, and displacement vectors of FEM meshes, respectively, and $P(s)$ is nodal external forces vector. The total damping matrix of the system can be achieved from Eq. (2). C_I is the internal viscose damping matrix, and C_R is the damping matrix caused by wave propagation [38].

$$C = C_I + C_R \tag{2}$$

In the equilibrium dynamic equation, the internal viscous damping matrix is a combination of the system mass matrix and system stiffness matrix. C_I can be computed from Eq. (3) [38].

$$C_I = \alpha M + \beta K \tag{3}$$

where α and β are the mass and the stiffness matrix coefficients, respectively, and are obtained from Eq. (4) and Eq. (5) [38].

$$\alpha = 2\omega_1\xi_1 - \omega_1^2 \tag{4}$$

$$\beta = 2\frac{\omega_1\xi_1 - \omega_2\xi_2}{\omega_1^2 - \omega_2^2} \tag{5}$$

where the subscripts of 1 and 2 are related to the 1st and 2nd system mode shapes, respectively, and ω is the circular frequency of the system. Also, ξ is the damping ratio assumed to be equal to 0.05 for the concrete structures in this study.

2.2. Boundary conditions

In this study, equivalent dampers are used in ANSYS at the upstream face of the reservoir with the damping matrix obtained from Eq. (6). This damper applies the radiation boundary conditions upstream to ensure the waves pass without any reflection or refraction [38].

$$C_R = \rho_w . C_w \int N^T . N . ds \tag{6}$$

where N is the shape function of the element used in the reservoir boundary, and ρ_w is the density of water. C_W is the velocity of the elastic waves in the reservoir defined by Eq. (7). In this equation, K_W is the bulk modulus of the water [38].

$$C_w = \sqrt{\frac{K_w}{\rho_w}} \tag{7}$$

The Fluid80 element is used in ANSYS to simulate the reservoir. Fluid80 is a suitable 3D Lagrangian element for water to ensure FSI and has eight nodes with 3 degrees of freedom at any node defined in X, Y, and Z directions. The Solid65 element is applied in ANSYS to model the concrete dam, intake tower, and access bridge. This element has 8 nodes with 3 degrees of freedom at any node and can consider reinforced bars in three directions: X, Y, and Z.

2.3. Geometry of case study

In this study, the 3D geometrical model of a Wimbleball buttress dam and its connected intake tower is assigned as a case study (Fig. 1). This dam is about 49 m high and had impounded the river Haddeo on Exmoor in Somerset, England at 51°04′N 3°28′W to provide a water storage capacity of some 21 million m^3 over an area of 1.51 km^2. Fig. 2 shows a 3D overview of the dam, intake, and access bridge in the FEM. Fig. 3 represents the 2D geometry of the dam, intake tower, access bridge, and reservoir in X-Z coordination. The dam and intake tower heights are 48.625 m. The dam crest and the top of the intake tower have an 18.73 m distance (Fig. 3). The dam length is 268 m on the dam axis, and the dam width is 5 m at the top, and 51 m at the bottom (Fig. 3). The normal water level of the reservoir is 37.5 m, and 150 m reservoir length are assumed in the FEM (Fig. 3).

Fig. 4 (a) and Fig. 4 (b) show the 2D geometry of the buttress and intake tower in X-Y coordination, respectively. The boundary face between the structure and reservoir is coupled in a direction perpendicular to its surface, which creates movement constraints in this direction. Still, in the two other directions, the nodes can move freely. Dampers with features obtained from Eq. (6) and Eq. (7) have been used in the reservoir upstream face, and joints have been applied perpendicular to the dam and intake tower bottom surface.

Fig. 1. Wimbleball dam [39].

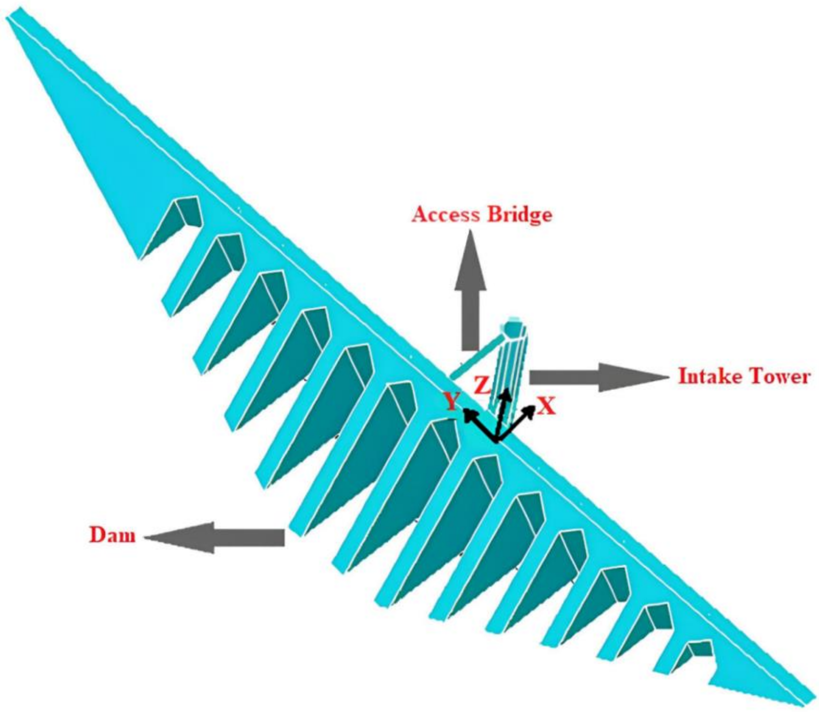

Fig. 2. 3D Overview of the dam, intake tower, and access bridge.

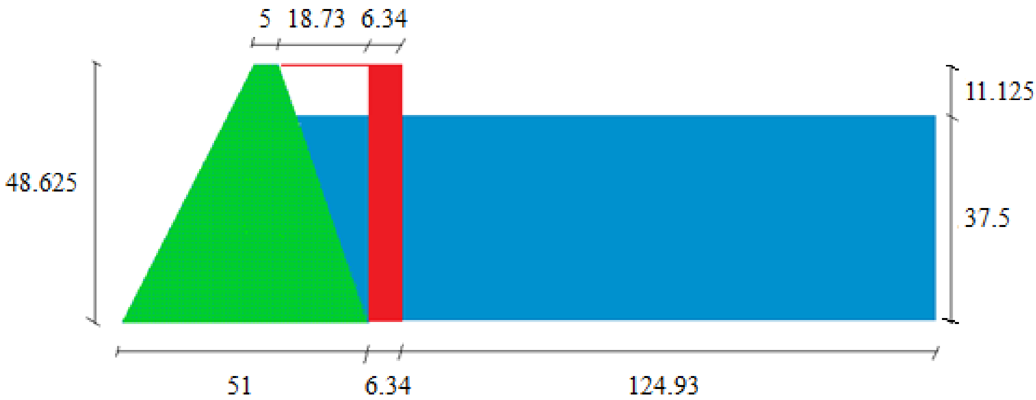

Fig. 3. 2D Geometry of dam, intake tower, access bridge, and reservoir in X-Z coordination (all dimensions are in a meter).

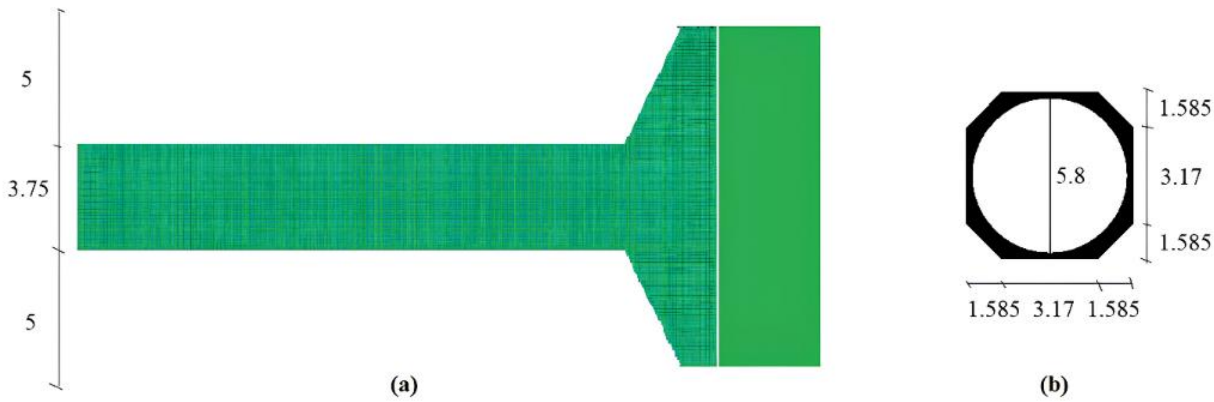

Fig. 4. 2D Geometry of (a) buttress section in X-Y coordination and (b) intake tower section in X-Y coordination (all dimensions are in a meter).

The slimming coefficient is the ratio of the intake tower height to its radius. When this coefficient is greater than 10, the tower is slender, and otherwise, it is thick. The slimming coefficient for the Wimbleball intake tower is 15.34; hence, it is a slender intake tower. Table 1 indicates the sizes and types of elements and static materials parameters used in the FEM of the dam- intake tower- access bridge- reservoir system for the present study.

Table 1. The elements characteristics and static materials parameters applied in the FEM.

Component	Material	Element Type	Element Size (m)	Bulk Modulus ($N.m^{-2}$)	Poisson's Ratio	Density ($kg.m^{-3}$)
Dam	Concrete	Solid65	2.00	1.56×10^{10}	0.20	2500
Intake tower	Concrete	Solid65	1.00	1.56×10^{10}	0.20	2500
Bridge	Concrete	Solid65	1.00	1.56×10^{10}	0.20	2500
Reservoir	Water	Fluid80	1.00	2.00×10^{9}	-	1000

As mentioned before, nine different cases are considered to study the efficacies of diverse parameters on the dam responses. Table 2 defined the ratios of the heights of the intake, reservoir water level, and the interior water level of the intake to dam height in the cases. Fig. 5 represents a 2D schematic view of the parameters in the X-Z coordination used in Table 2. In Fig. 5 and Table 2, the terms H_D, H_T, H_R, and H_W are the dam, intake, reservoir, and interior water of intake heights, respectively.

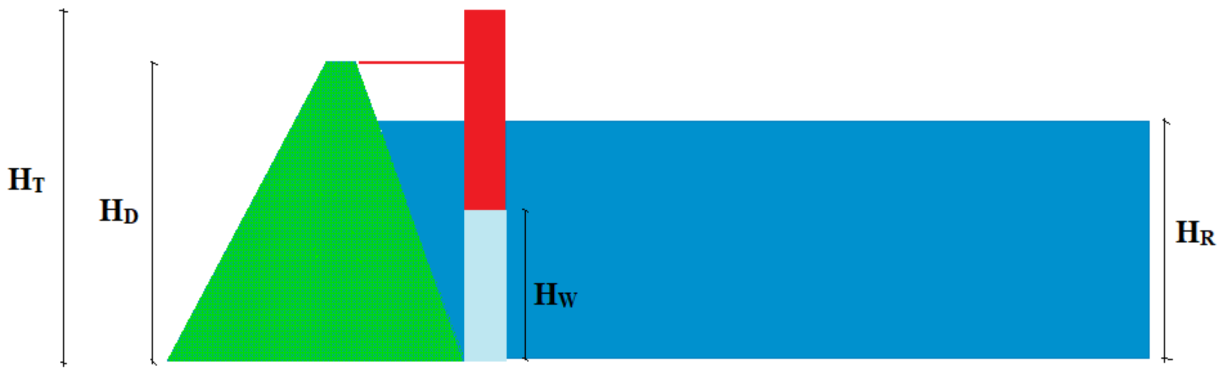

Fig. 5. 2D schematic view of the heights of the model components in the X-Z coordination.

Table 2. Ratios of the heights of the components to dam height for each case modeled and analyzed in this study.

Case	System	H_T/H_D	H_R/H_D	H_W/H_D
1	dam + reservoir	-	1.00	-
2	dam + reservoir + tower + access bridge + internal water of tower	1.00	0.25	1.00
3	dam + reservoir + tower + access bridge + internal water of tower	1.00	0.50	1.00
4	dam + reservoir + tower + access bridge + internal water of tower	1.00	0.75	1.00
5	dam + reservoir + tower + access bridge + internal water of tower	1.00	1.00	1.00
6	dam + reservoir + tower + access bridge + internal water of tower	1.00	1.00	1.50
7	dam + reservoir + tower + access bridge + internal water of tower	1.50	1.00	1.50
8	dam + reservoir + tower + access bridge + internal water of tower	1.00	1.00	2.00
9	dam + reservoir + tower + access bridge + internal water of tower	2.00	1.00	2.00

3. Results and discussion

In this section, first, the modal analysis is performed on the Wimbleball intake tower, and the obtained data are compared with the results from the Daniell and Taylor (1994) study to confirm the validity of the FEM model. Then, modal and seismic analyses were performed on current cases to evaluate the effects of the intake tower, access bridge, water level in the reservoir and tower, and intake tower height on responses of the buttress dam. The results of modal and time-history seismic analyses are discussed separately in the following subdivisions.

3.1. Validation

Fig. 6 (a) and Fig. 6 (b) present the comparison between the first and second structural mode shapes of the intake tower obtained from the present study and Daniell and Taylor (1994), respectively. Fig. 6 (a) and Fig. 6 (b) indicate that the first and second mode shapes of the intake tower obtained from Daniell and Taylor (1994) and the present study are consistent.

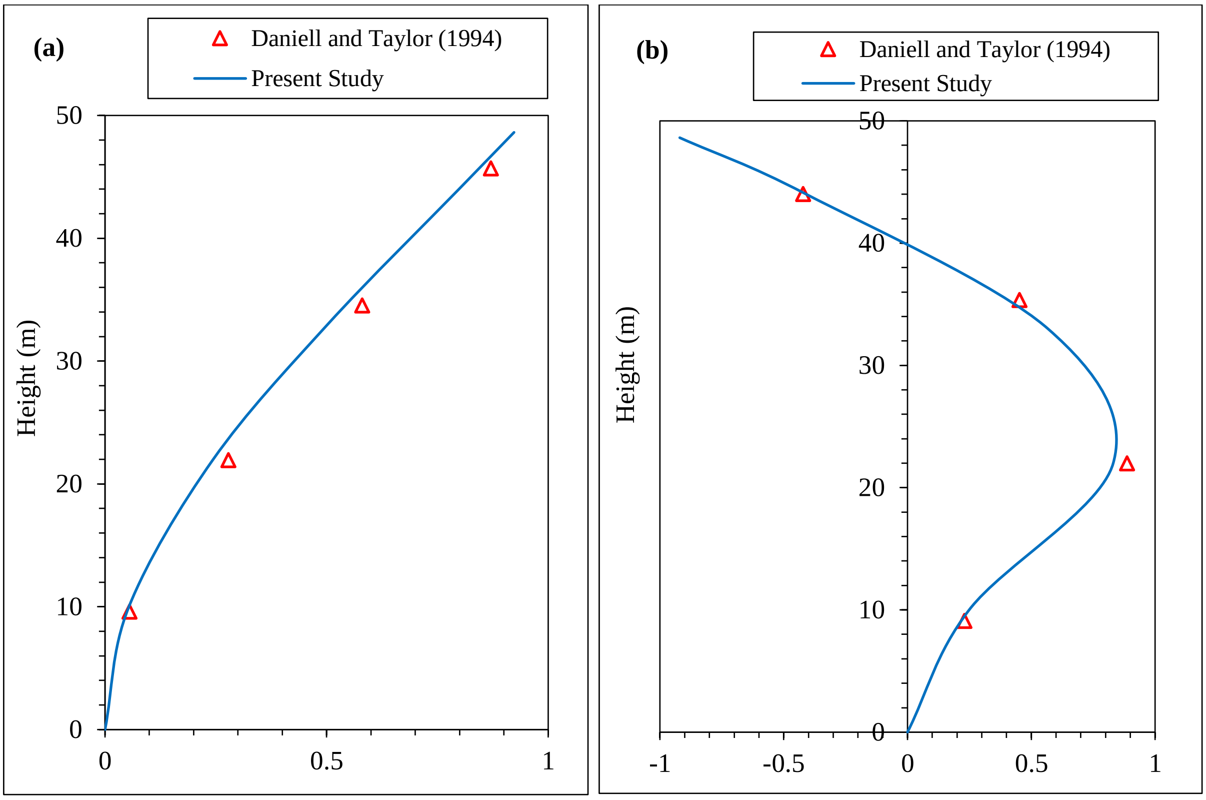

Fig. 6. Mode shape of the intake tower in Daniell and Taylor (1994), and the present study (a) first mode shape (b) second mode shape.

Fig. 7 (a) and Fig. 7 (b) represent the comparison between the modal hydrodynamic pressure profile of first and second-mode shapes of the intake tower obtained from this study and Daniell and Taylor (1994), respectively. Excellent compatibility between the modal hydrodynamic pressure profile for the first and second mode shapes of the intake tower resulted from this study, and Daniell and Taylor (1994), confirm the reliability of the FEM used in this study.

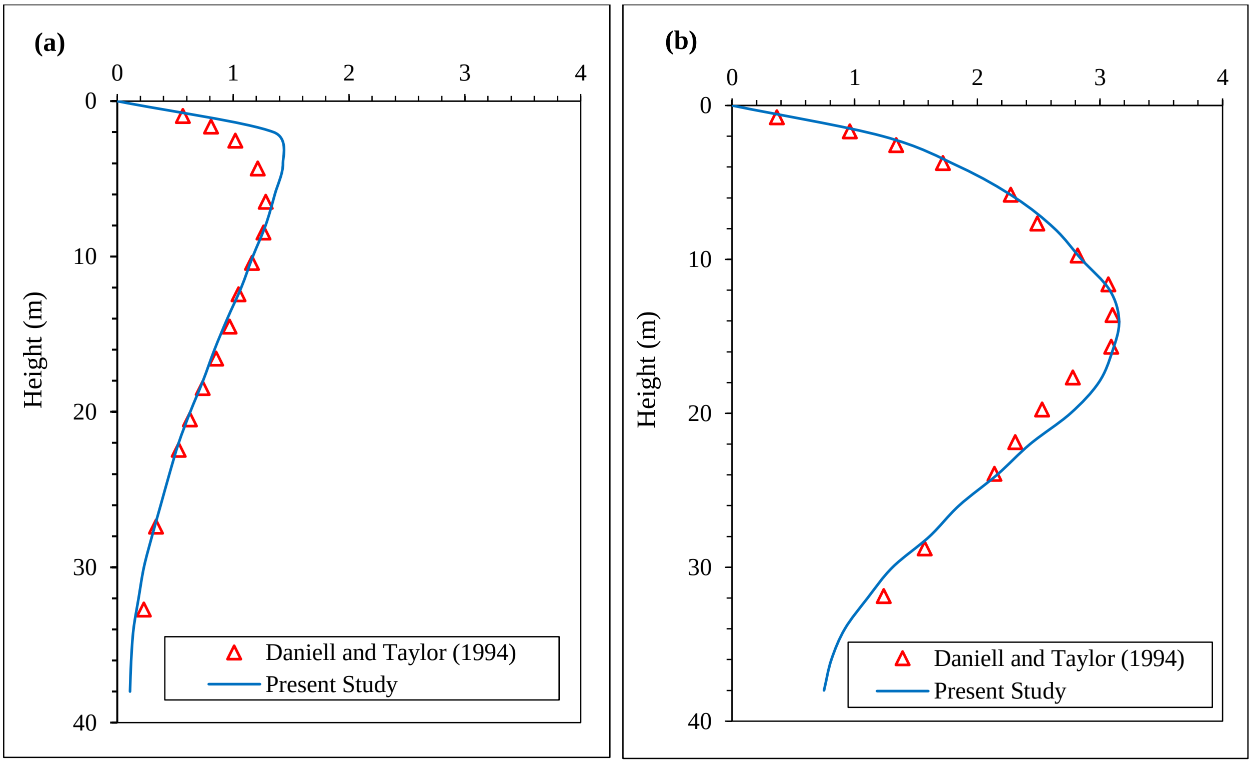

Fig. 7. Hydrodynamic pressure profile of the intake tower in Daniell and Taylor (1994), and the present study (a) first mode shape (b) second mode shape.

Table 3 compares the first two natural frequencies (*f*) obtained from the present numerical model and Daniell and Taylor's (1994) FE model, as well as test data. In all cases of Fig. 6, Fig. 7, and Table 3, the reservoir is about 0.75 full (H_R/H_D=0.75).

Table 3. Natural frequencies in Hz obtained from the present numerical model and Daniell and Taylor (1994).

Mode number	Present Study	Daniell and Taylor (1994)	
		FE model	Test
1	1.75	1.68	1.72
2	4.14	3.56	Not Measured

3.2. Modal analysis

Modal analysis is applied to nine various geometry cases of the system to determine their circular frequencies (ω). The effect of different parameters on modal responses is presented in the following subdivisions.

3.2.1. Influence of presence of intake tower and access bridge

The effect of the intake tower and access bridge on the circular frequencies (ω=2πf) of the cases is indicated in Fig. 8 for cases 1 and 5. As shown in Fig. 8, the presence of the intake tower and access bridge reduces the case's frequencies by about 67.5%.

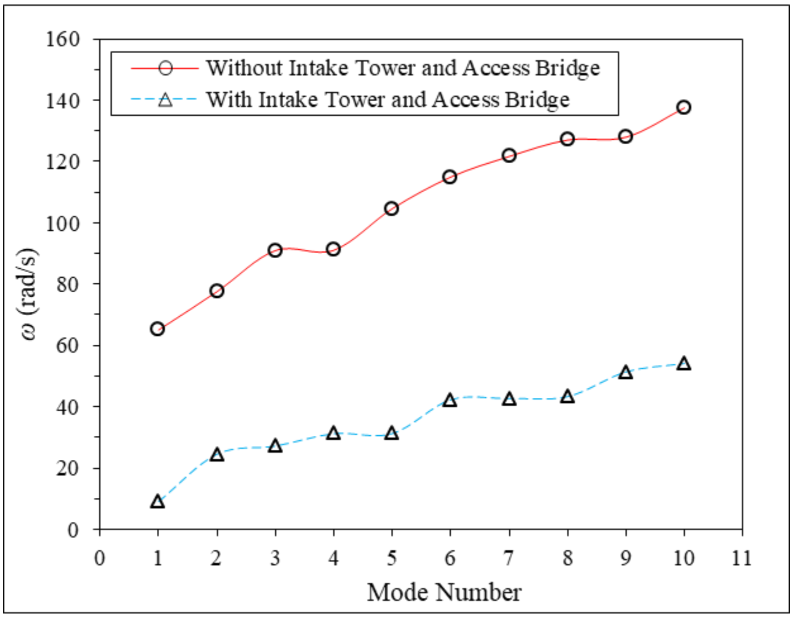

Fig. 8. Effect of the presence of intake tower and access bridge on the case's frequencies.

3.2.2. Influence of reservoir water level

The effect of reservoir water level on frequencies is illustrated in Fig. 9 for cases 2 to 5, including the dam, intake tower, access bridge, reservoir, and internal water. Results show that the frequencies reduced by about 15%, 29%, and 40%, by raising the reservoir water level from 25% to 50%, 75%, and 100% of full reservoir cases, respectively. Additionally, the system frequency reduces, when the reservoir water level increases. This result is due to the stiffness decrease as a consequence of the FSI effect.

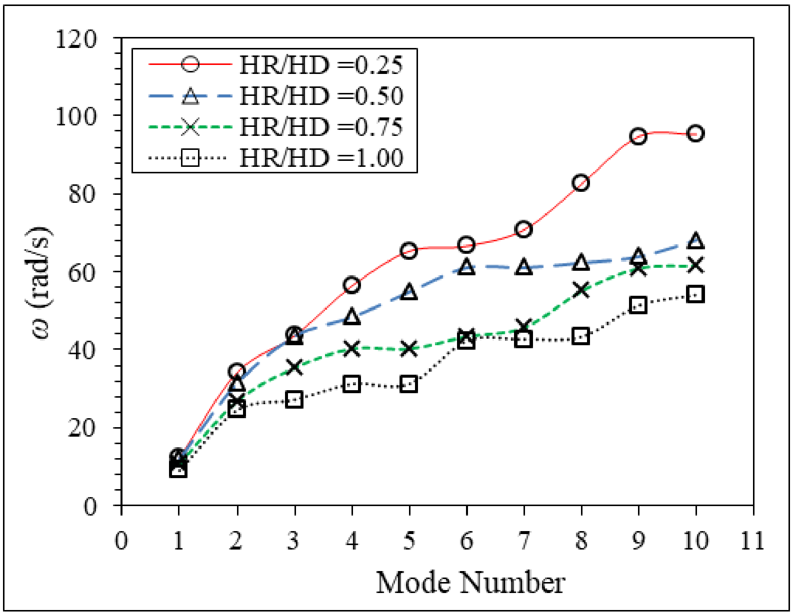

Fig. 9. Effect of reservoir water level on the case's frequencies.

3.2.3. Influence of intake tower height and its internal water level

Fig. 10 shows the frequencies of the case with H_T/H_D = 1, 1.5, and 2 to investigate the effect of increment in the intake tower height. Fig. 11 presents the system frequencies for cases with H_T/H_D and H_W/H_D = 1, 1.5, and 2 to assess the impact of raising both the intake tower height and its internal water level on modal analysis responses.

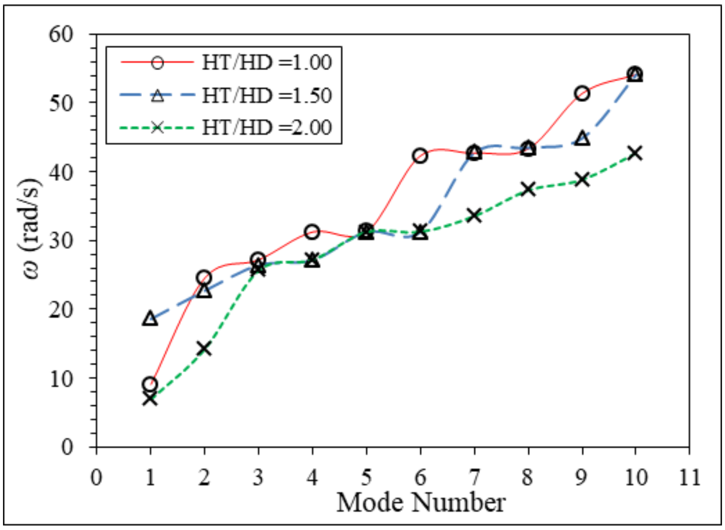

Fig. 10. Effect of increase in intake tower height on the case's frequencies.

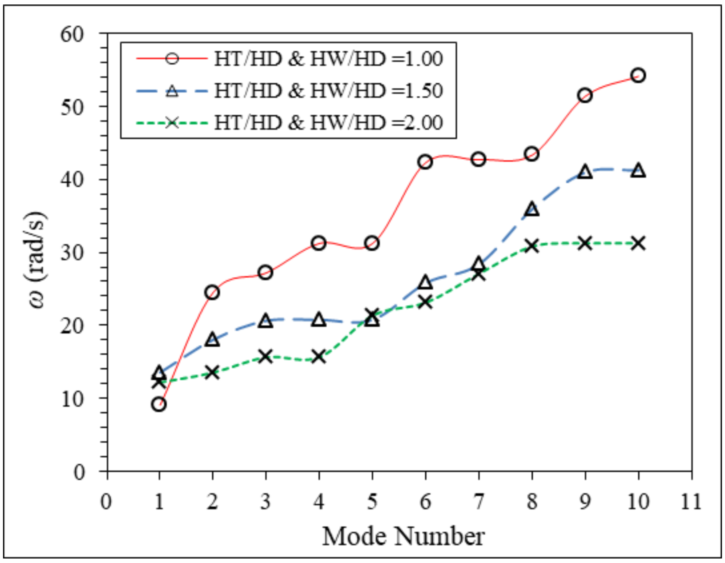

Fig. 11. Effect of increase in both intake tower height and its internal water level on the case's frequencies.

Comparison between the results of Fig. 10 and Fig. 11 show that the case's frequencies are reduced by raising the intake tower height. It means when the height of the tower increases the slimming coefficient increases, then tower frequencies increase. The frequencies of the case were reduced by about 5% and 19% by keeping the internal water level constant and raising the tower height 1.5 and 2 times the initial state, respectively. Also, the case's frequencies were reduced by about 20% and 33% when both the tower height and its internal water level increased 1.5 and 2 times the initial case, respectively. Hence, the reduction of the frequencies in cases with a 100% full intake tower is greater than in cases in which the tower is 50% full.

3.3. Time-history seismic responses

The seismic analysis is conducted on the system cases under the Tabas earthquake acceleration in three horizontal, lateral, and vertical directions. It happened on 1978/9/16 at 19:05:55 in Iran in the central region near Tabas city. The shock moment with a magnitude scale of 7.4 was apperceived about 55–85 km of ground deformation, with about 1.7 meters of maximum slip. The dam crest displacements and dam body stresses in current cases are extracted and compared, and their conclusions will be discussed in the following sections.

3.3.1. Distribution of dam crest displacements in dam axis

Fig. 12 provides the distribution of the maximum horizontal displacement in the crest of buttresses versus distance from the dam axis to distinguish the vulnerable points of the dam buttresses. It can be observed that the buttresses' responses increase by moving from the dam abutments to the center of the dam, which means the middle buttress is more vulnerable than other buttresses. Hence, the seismic responses of the middle buttress of the dam are investigated in the following sections of this study.

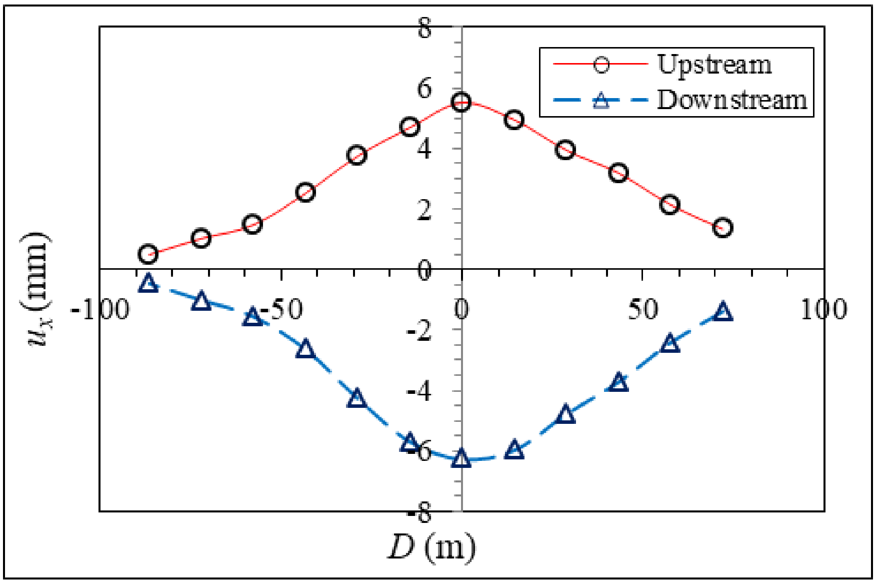

Fig. 12. Distribution of maximum horizontal displacement in dam crest to distance (D) from the dam axis.

3.3.2. Influence of presence of intake tower and access bridge on dam responses

Seismic responses of the dam under the Tabas earthquake are extracted for case 1 and case 5 to study the effect of the attendance of an intake tower and access bridge on dam responses. The maximum values of the displacements in the crest of the middle buttress and the maximum stress values at the heel of the middle buttress are represented in Table 4.

Table 4. Effect of presence of intake tower and access bridge on maximum seismic responses of dam.

Case	1	5
System	dam + reservoir	dam + reservoir + intake tower + access bridge + internal water of tower
H_T/H_D	-	1.00
H_R/H_D	1.00	1.00
H_W/H_D	-	1.00
u_x (mm)	7.68 -7.59	5.51 -6.28
u_y (mm)	2.53 -2.74	1.76 -2.13
u_z (mm)	1.36 -1.18	0.87 -0.93
σ_1 (MPa)	2.91 -0.13	13.01 -
σ_2 (MPa)	0.60 -0.61	3.01 -3.11
σ_3 (MPa)	0.19 -2.92	2.27 -13.62

As shown in Table 4, the major displacement of the dam is in the X direction, which is perpendicular to the dam axis. Fig. 13 and Fig. 14 present the time history diagrams of the crest horizontal displacement and stresses in the heel of the middle buttress (σ_1) for cases 1 and 5, respectively, to precise the influence of the presence of the intake tower and access bridge on dam responses. It can be comprehended from Fig. 13 and Fig. 14 that the presence of the intake tower and access bridge has fewer effects on the displacements. In contrast, the dam stresses increase through the recursive waves from the dam and tower to the reservoir.

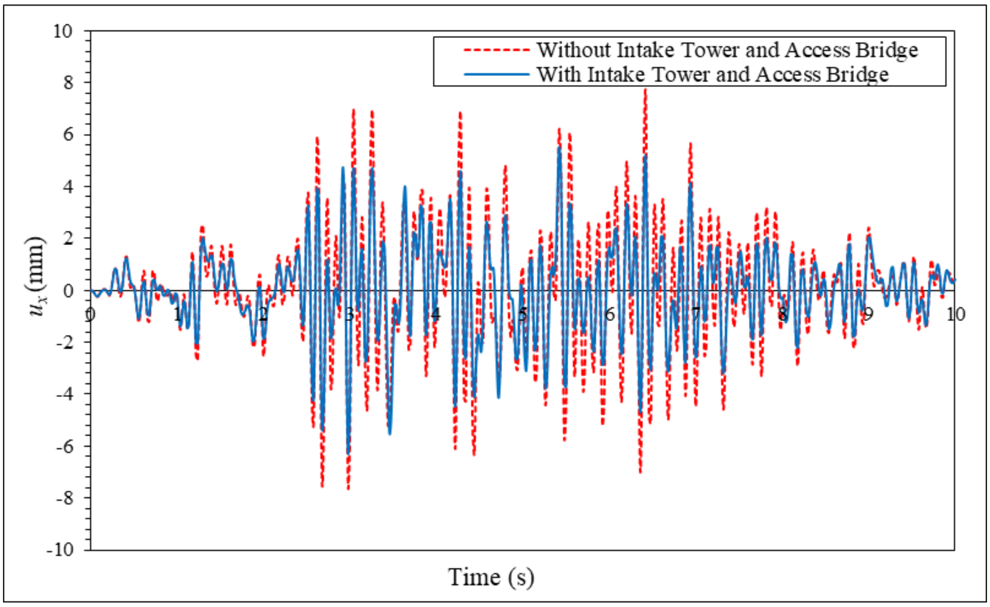

Fig. 13. Effect of the presence of intake tower and access bridge on horizontal displacements in the crest of the middle buttress.

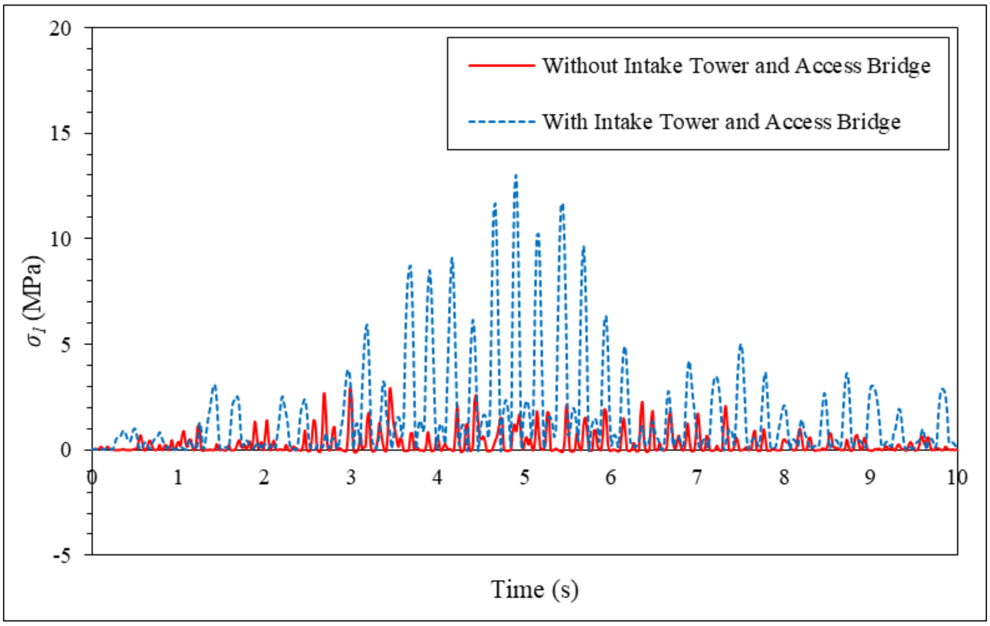

Fig. 14. Effect of the presence of intake tower and access bridge on stresses of the middle buttress.

3.3.3. Influence of reservoir water level on dam responses

Seismic responses of the dam are extracted in the dam-intake tower-access bridge-reservoir system of cases 2 to 5 with four reservoir water level conditions. Table 5 presents the effect of reservoir water level on the maximum values of the crest displacements, u_x, u_y, and u_z, in X, Y, and Z directions, respectively, and heel principal stresses, σ_1, σ_2, and σ_3 of the middle buttress. It can be observed from Table 5 that the crest displacements of the middle buttress reduced slightly, and the stresses at the heel of the middle buttress increased by enhancing the reservoir water level. Also, the maximum stress values occur in case 4, in which the reservoir is 75% full, while this level is a normal water level of the reservoir. The maximum reduction for the horizontal displacement in the crest of the middle buttress is about 20% and the maximum increase for the stress of the middle buttress is about 39% by raising the reservoir water level.

Table 5. Effect of reservoir water level on maximum seismic responses of the dam.

Case	2	3	4	5
System	dam + reservoir + intake tower + access bridge + internal water of tower			
H_T/H_D	1.00	1.00	1.00	1.00
H_R/H_D	0.25	0.50	0.75	1.00
H_W/H_D	1.00	1.00	1.00	1.00
u_x (mm)	6.89 -5.37	6.79 -5.07	5.02 -6.54	5.51 -6.28
u_y (mm)	2.16 -1.84	2.14 -1.71	1.62 -2.09	1.76 -2.13
u_z (mm)	0.88 -0.90	0.86 -0.91	0.81 -0.89	0.87 -0.93
σ_1 (MPa)	9.33 -0.62	11.37 -1.33	15.36 -2.54	13.01 -
σ_2 (MPa)	1.89 -1.63	2.48 -2.14	3.45 -3.80	3.01 -3.11
σ_3 (MPa)	0.68 -7.87	1.54 -9.55	2.31 -16.91	2.27 -13.62

Fig. 15 and Fig. 16 present the time-history diagrams of the crest horizontal displacement and stress at the bottom of the middle buttress for cases 2 and 5, respectively, to investigate the effect of reservoir water level on dam responses. It can be observed from Fig. 15 and Fig. 16 that the reservoir influences the responses slightly, and alters their content and quality. This fact has resulted from the changes in the case's stiffness and frequency due to FSI.

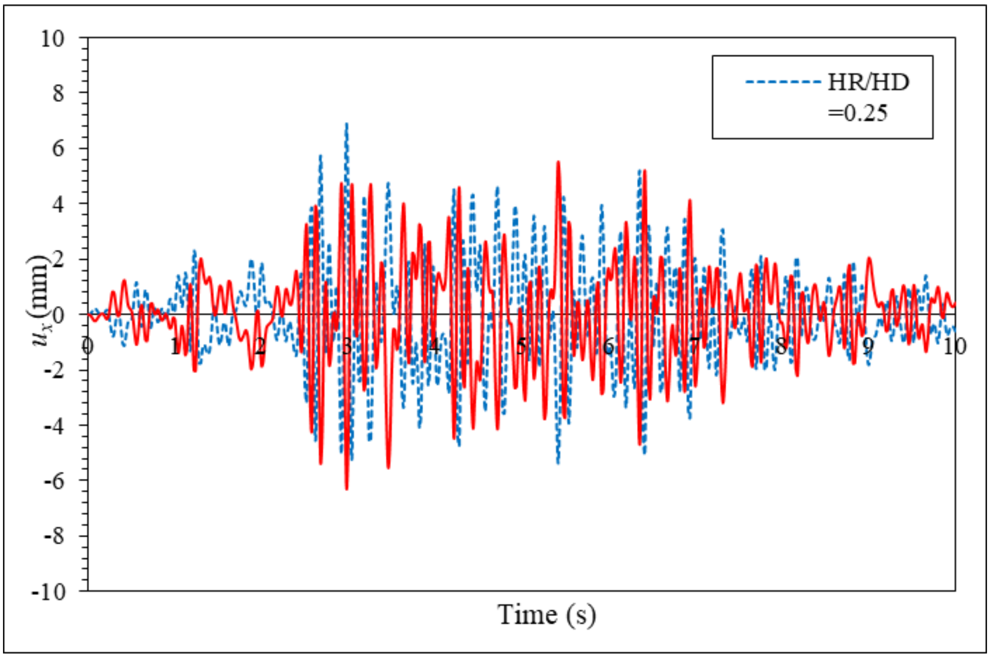

Fig. 15. Effect of reservoir water level on horizontal displacements in the crest of the middle buttress.

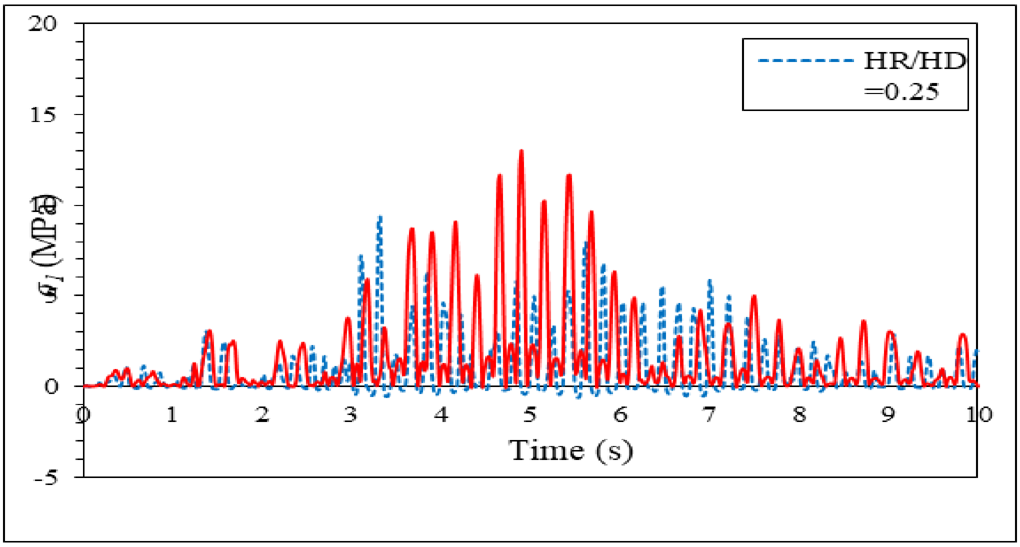

Fig. 16. Effect of reservoir water level on stresses of the middle buttress.

3.3.4. Influences of intake tower height and its internal water level on dam responses

The effects of the intake tower height and its internal water level are investigated on seismic responses of the dam by considering two different heights of intake towers with two various internal water levels. Table 6 indicates the maximum values of the crest displacements and stresses of the heel of the middle buttress obtained from seismic analysis of the cases with an increment in intake tower height and its internal water level. Displacements and stresses for case 7 averagely decreased by about 7% and 1%, respectively, and for case 9 averagely increased by about 7% and decreased by about 40%, respectively, by comparing case 7 responses with case 6 and case 9 responses with case 8. The fundamental concept of this analogy is remaining tower height and reservoir water level constant and raising the internal water level. Also, comparing the results of Table 5 and Table 6, it was figured out that the displacements and stresses averagely increased by about 3% and 43% for case 6, respectively, and decreased by about 5% and increased by about 14% for case 8, in analogy with case 5 responses, respectively. This comparison was formed based on considering a constant reservoir water level and the interior water of the intake and increasing the intake tower height. Fig. 17 and Fig. 18 show the time history diagrams of the crest horizontal displacement and stress at the heel of the middle buttress, respectively, for cases 6 and 8 to investigate the effect of intake tower height on dam responses accurately.

Table 6. Effects of tower height and internal water level on maximum seismic responses of the dam.

Case	6	7	8	9
System	dam + reservoir + intake tower + access bridge + internal water of tower			
H_T/H_D	1.50	1.50	2.00	2.00
H_R/H_D	1.00	1.00	1.00	1.00
H_W/H_D	1.00	1.50	1.00	2.00
u_x (mm)	5.24 -6.39	4.92 -5.96	5.37 -4.54	5.47 -5.31
u_y (mm)	1.91 -2.21	1.72 -2.11	2.35 -2.03	2.01 -1.73
u_z (mm)	0.89 -1.01	0.86 -0.92	0.87 -0.68	0.94 -0.97
σ_1 (MPa)	17.91 -3.75	17.62 -3.60	14.78 -2.67	10.68 -1.55
σ_2 (MPa)	4.28 -4.41	4.26 -4.30	3.39 -3.59	2.33 -2.25
σ_3 (MPa)	3.58 -18.38	3.83 -17.73	2.55 -15.66	1.64 -10.69

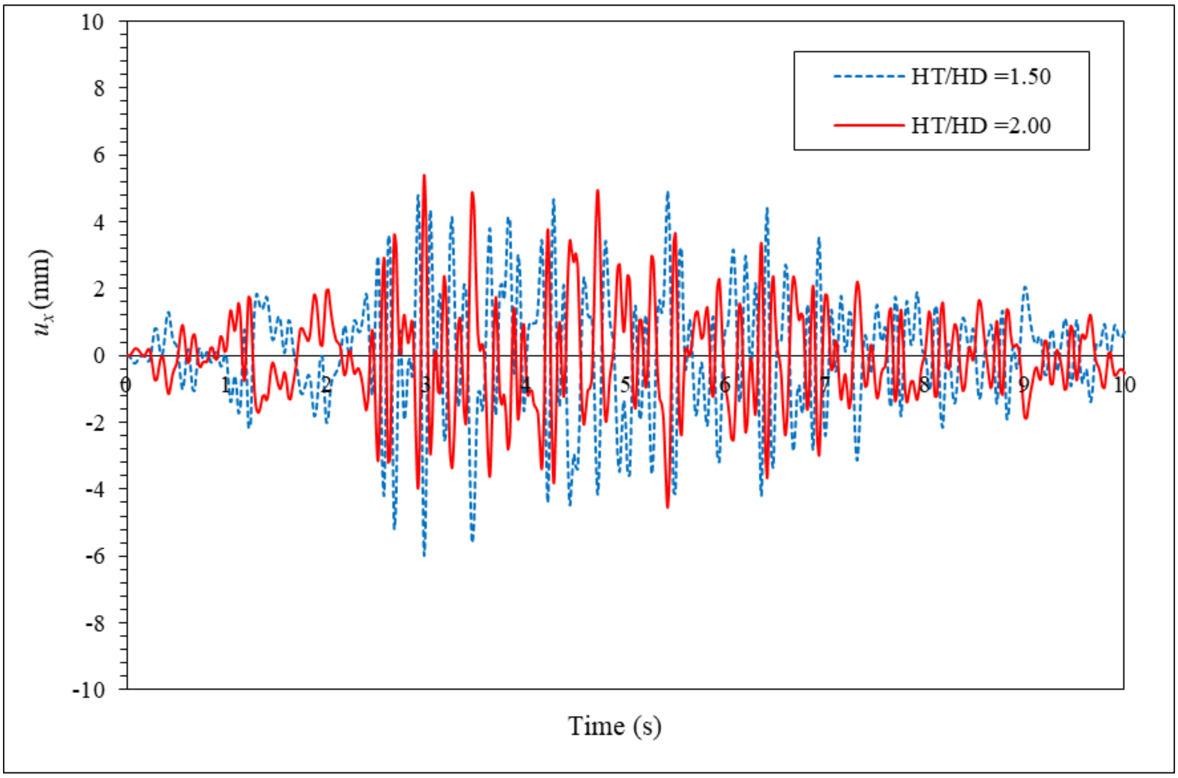

Fig. 17. Effect of intake tower height on horizontal displacements in the crest of the middle buttress.

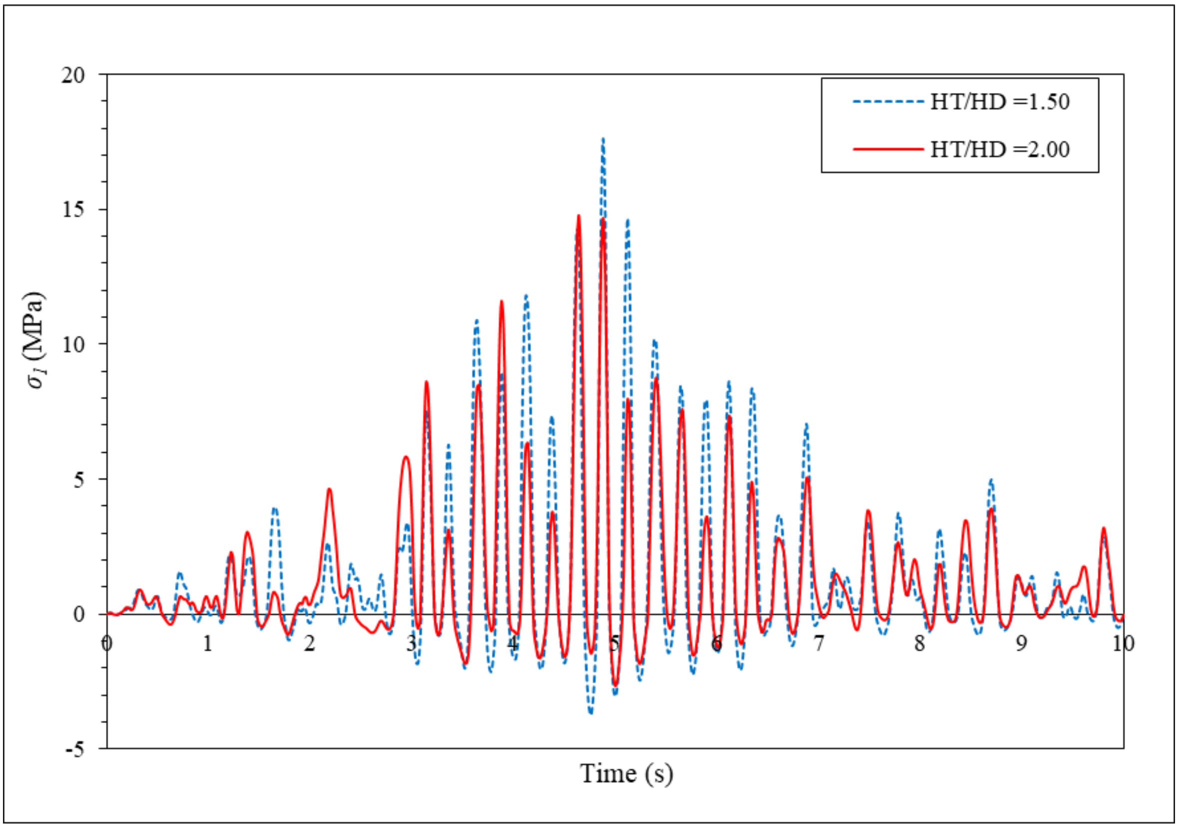

Fig. 18. Effect of intake tower height on stresses of the middle buttress.

As observed in Fig. 17 and Fig. 18, although the tower in case 8 is higher than in case 6, it has less influence on the dam responses. Raising the tower height means increasing the slimming coefficient of the tower and decreasing the frequency. In addition, the response values change by raising the intake tower height, which may be due to the changes in frequency contents.

4. Conclusions

In this study, 3D modal and seismic analysis were conducted on the dam-intake tower-access bridge-reservoir system using ANSYS software. The geometrical model of the Wimbleball buttress dam and its intake tower in England is considered a case study. Nine various geometric cases are analyzed to investigate the effect of parameters including reservoir water level, intake tower height, and internal water level on dam responses. The maximum values of the crest displacements and stresses of the heel of the middle buttress are obtained from dynamic analysis under the Tabas earthquake acceleration in three horizontal, lateral, and vertical directions. In summary, the results of this study can be explained as follows:

Seismic analysis results represent that the dam stresses are reduced by increasing the internal water level of the tower when the tower height and the reservoir water level remain constant. Also, the dam displacements increased when the intake tower height increased 1.5 and 2 times the initial case without changing the water level in the reservoir and tower.

- Seismic analysis results represent that the dam stresses are reduced by increasing the internal water level of the tower when the tower height and the reservoir water level remain constant. Also, the dam displacements increased when the intake tower height increased 1.5 and 2 times the initial case without changing the water level in the reservoir and tower.
- Raising the tower height means increasing the slimming coefficient of the tower, which decreases the case's frequency. In addition, changing the intake tower height alters the responses qualitatively. Raising the water level of the reservoir has little influence on the crest displacements but increases the stresses of the middle buttress. It was figured out that raising the reservoir water level not only affects the responses quantitatively but also alters them qualitatively, which can be due to the case's frequency changes as a result of the FSI effect.
- Modal analysis responses show that the system frequencies were reduced by up to 40%, by raising the reservoir water level. Furthermore, the system frequencies decreased by 5% and 19%, by raising the intake tower height 1.5 and 2 times the initial state, respectively. It was concluded the frequency values in cases with a full intake tower were reduced more than in cases with semi-full intake tower.
- Seismic responses present that the maximum reduction for the horizontal displacement in the crest of the middle buttress is about 20% and the maximum increase for the stress of the middle buttress is about 39% by raising the reservoir water level. Additionally, the displacements and stresses averagely increased by about 3% and 43% for raising the tower height 1.5 times the initial state, respectively, and decreased by about 5% and increased by about 14%, respectively, for raising the tower height 2 times the initial state.
- The dynamic analysis responses under the Tabas earthquake represent that the major displacement of the dam is perpendicular to the dam axis. Also, the effect of the intake tower and access bridge on dam stresses is noticeable, and the dam stresses increase through the FSI effect under recursive waves from the structure to the reservoir.
- The crest displacements and heel stresses of the dam have been analyzed under seismic components, and the long-term structural behavior of dams had not been evaluated definitely. Although the operating conditions of the dam and water tower have been simulated and analyzed at different levels, however, it cannot be declared that the capability of the model is strong during the dam's long-term behavior.
- This research used a novel case study of the buttress dam with the intake tower to evaluate dynamic behavior in seismic zones and its consequences. In model analyses, only some

parametric variations were considered and evaluated based on theoretical samples. Results have presented the importance of this subject and can be a benchmark for future research on this topic. Investigating the mechanical behavior of dam materials over a long time and rehabilitation techniques in case of damage are highly recommended for future studies.

List of symbols

The following symbols are utilized in this study:

C = damping matrix (-)

C_I = internal viscous damping matrix (-)

C_R = damping matrix caused by wave propagation (-)

C_W = velocity of the elastic waves in the reservoir ($m.s^{-1}$)

f = natural frequency of the system (Hz)

H_D = dam height (m)

H_R = reservoir height (m)

H_T = intake tower height (m)

H_W = internal water of intake tower height (m)

K = stiffness matrix (-)

K_W = bulk modulus of the water ($kg.m^{-3}$)

M = mass matrix (-)

N = shape function of the component of the reservoir in boundary (-)

$P(s)$ = nodal external forces vector (N)

u = nodal dynamic displacement vectors of FEM meshing (m)

$\dot{u}$ = nodal dynamic velocity vectors of FEM meshing ($m.s^{-1}$)

$\ddot{u}$ = nodal dynamic acceleration vectors of FEM meshing ($m.s^{-2}$)

u_x = displacement in the X direction (mm)

u_y = displacement in the Y direction (mm)

u_z = displacement in the Z direction (mm)

α = mass matrix coefficient (-)

β = stiffness matrix coefficient (-)

ξ = damping ratio (-)

ρ_w = water density ($kg.m^{-3}$)

σ_1 = first principal stress (MPa)

σ_2 = second principal stress (MPa)

σ_3 = third principal stress (MPa)

ω = circular frequency of the system ($rad.\ s^{-1}$)

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contribution statement

Ali Mahdian Khalili: Conceptualization; Data curation; Formal analysis; Methodology; Project administration; Resources; Software; Validation; Visualization; Writing – original draft; Writing – review & editing.

Bahram Navayi Neya: Investigation; Supervision; Validation; Writing – review & editing.

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