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Investigation of water length effects on the modal behavior of a prototype arch dam using operational and analytical modal analyses

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Abstract. This study determines the water length effects on the modal behavior of a prototype arch dam using Operational and Analytical Modal Analyses. Achievement of this purpose involves construction of a prototype arch dam-reservoir-foundation model under laboratory conditions. In the model, reservoir length was taken to be as much as three times the dam height. To determine the experimental dynamic characteristics of the arch dam using Operational Modal Analysis, ambient vibration tests were implemented for empty reservoir and three different reservoir water lengths. In the ambient vibration tests, the dam was vibrated by natural excitations provided from small impact effects and the response signals were measured using sensitive accelerometers. Operational Modal Analysis software process signals collected from the ambient vibration tests, and Enhanced Frequency Domain Decomposition and Stochastic Subspace Identification techniques estimated modal parameters of the dams. To validate the experimental results, 3D finite element model of the prototype arch dam was modeled by ANSYS software for empty reservoir and three different reservoir water lengths, and dynamic characteristics of each model were determined analytically. At the end of the study, experimentally and analytically identified dynamic characteristics compared to each other. Also, changes on the natural frequencies along to water length are plotted as graphs. Results suggest that reservoir water complicates the modal behavior of the arch dam significantly.

Keywords: ambient vibration test; dynamic characteristic; prototype arch dam-reservoir-foundation model; water length effect.

1. Introduction

Arch dams are required sophisticated engineering knowledge to design and construct. In fact, failure of the dams retaining large quantities of water presents a hazard for life and property during earthquakes. In addition, the structural damage to these structures can be a considerable economic loss for the governments. During the earthquakes, reservoir water affects the dynamic behavior of arch dams significantly. Earthquake behavior of the dams was incomprehensible until 1960s. After 1960, Finite Element Method (FEM) has been developed and studies have been enhanced

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considering subjects such as earthquake behavior, dam-reservoir and dam-foundation interactions (Akköse *et al.* 2007, Lotfi 2006, 2007, Akköse 2004, Lotfi and Espander 2004, Nasserzarea *et al.* 2000, Guan and Moore 1997, Fok and Chopra 1986, Wilson and Khalvati 1983, Porter and Chopra 1981, Dungar 1978, Chopra 1968). In the present, three approaches are used to consider reservoir water effects in the dynamic analyses: Westergaard (Westergaard 1933), Euler (Dungar 1978) and Lagrangian (Wilson and Khalvati 1983) approaches. From theses approaches in Lagrangian, the displacements are the variables in both the fluid and the structure. So there is no need any extra interface equations to solve the coupled system in this approach. For that reason, compatibility and equilibrium are automatically satisfied at the nodes along the interfaces between fluid and structure.

Beside these studies, it is stated that modal behavior of the arch dams must be determined experimentally. The modal behavior of an arch dam is related to its dynamic characteristics such as natural frequencies, mode shapes and damping ratios. One of the important inspections is to apply vibration tests to existing dams to determine their dynamic characteristics. In the literature, there are two experimental modal procedure called as Ambient Vibration Testing-AVT (Operational Modal Analysis-OMA), and Forced Vibration Testing-FVT (Experimental Modal Analysis-EMA). In AVT, the structure is excited using natural excitations such as earthquake, wind etc. effects which are exactly unknown. This method is also called as Only-Output Modal Identification. On the other hand in FVT, the structure is vibrated using known inputs as impact hammer or shaker. So this method is called as Input-Output Modal Identification. In OMA, the structure is excited by unknown input force and responses of the structure are measured. Some heavy forced excitations become very expensive and sometimes may cause the possible damage to the structure. However, ambient vibrations such as traffic, waves, winds, and their combination are environmental excitations. In OMA, dynamic characteristics of a structure are extracted using techniques such as Peak Picking (PP), Enhanced Frequency Domain Decomposition (EFDD), Stochastic Subspace Identification (SSI), etc. From these techniques EFDD modes are simply picked locating the peaks in Singular Value Decomposition plots (SVD) calculated from the spectral density spectra of the responses.

Recently years, modal behavior of large dams are started to investigate using OMA method (Alves and Hall 2006, Mendes *et al.* 2004, Darbre and Proulx 2002, Proulx *et al.* 2001, Ghanaat *et al.* 2000, Zhou *et al.* 2000, Daniel and Taylor 1999). In these studies it is highlighted that although the physical conditions are hard as difficulties to excite of large dams, and test become too expensive; results obtained OMA is very attractive and useful. Such kind of conditions made to researchers to construct prototype dam models to study experimentally (Mendes and Oliveira 2007, Wang and He 2007, Wang and Li 2007, Oliveira and Faria 2006, Wang and Li 2006).

In this study, the water length effects on the modal behavior of a prototype arch dam model were investigated using OMA and FEM. For this purpose, a prototype model of Type-1 arch dam-reservoir-foundation system presented in the literature was constructed in the laboratory conditions. Ambient vibration tests were conducted to the arch dam to identify dynamic characteristics for different water lengths. On the other hand, 3D finite element model of the prototype arch dam was modeled for empty and three different water lengths and dynamic characteristic of each model were determined analytically. The reservoir water was modeled using Lagrangian approach. The experimental and analytical results were compared to each other. Schematic view of the study plan appears in Fig. 1.

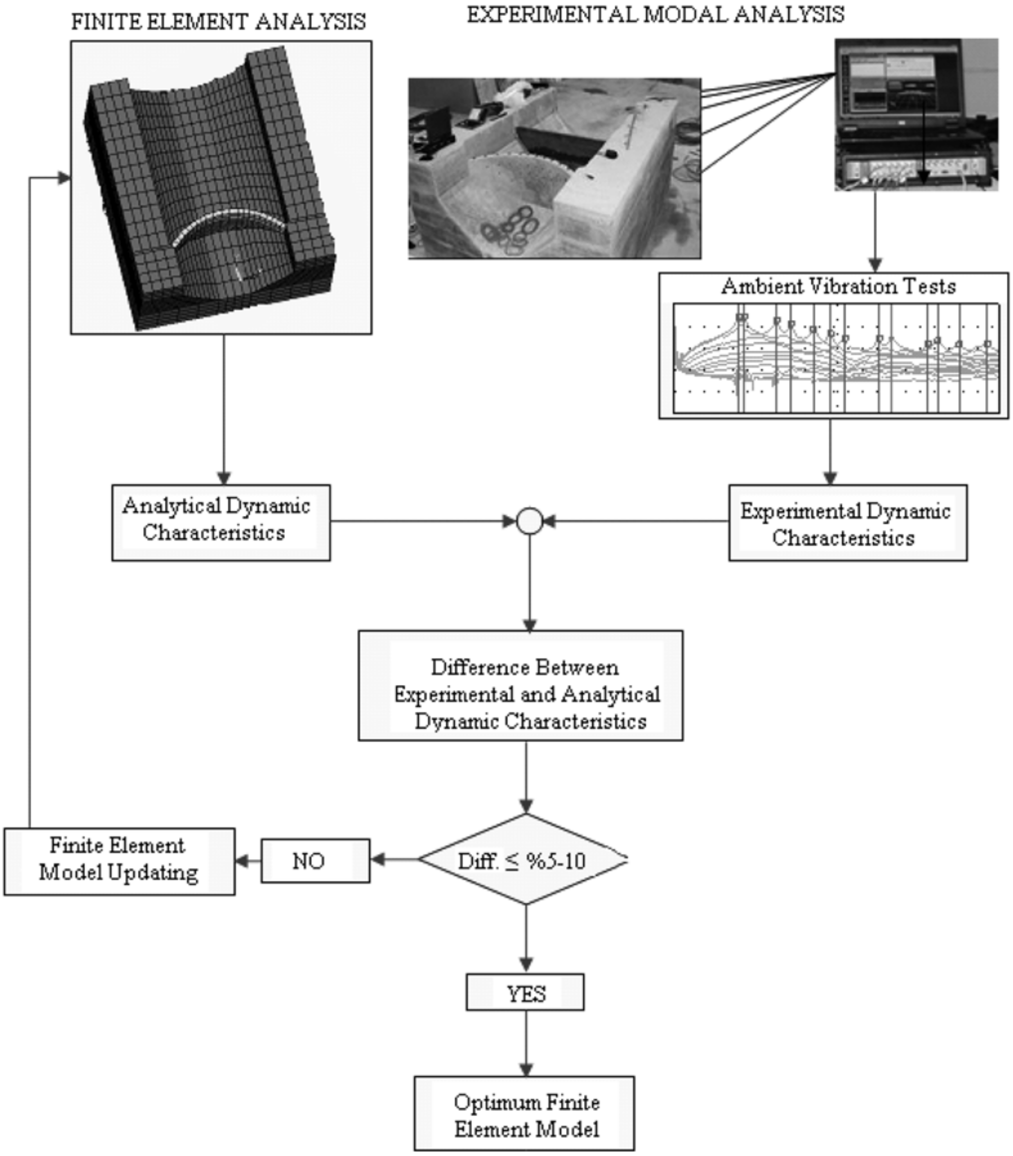


Fig. 1 Schematic view of the study plan

2. Formulation

In this study, experimental dynamic characteristics are extracted using EFDD technique. Also, reservoir water is represented by Lagrangian approach in finite element analysis of Type-1 arch dam. This approach is important for the purpose of giving fluid-structure interaction or dam-reservoir water interaction. So, the basic formulations of EFDD technique and Lagrangian approach are given in below to support the readers who are interested in such kind of studies.

2.1 Enhanced Frequency Domain Decomposition (EFDD) technique

In Operational Modal Analysis method, ambient excitation does not lend itself to Frequency Response Function (FRFs) or Impulse Response Function (IRFs) calculations because the input force is not measured in an ambient vibration test. Therefore, a modal identification procedure will need to base itself on output-only data (Ren *et al.* 2004). In OMA method, there are several modal parameter identification techniques available such as Peak Picking (PP), Stochastic Subspace Identification (SSI), and Frequency Domain Decomposition techniques (FDD). These techniques are developed by improvements in computing capacity and signal processing procedures. In this study, Enhanced Frequency Domain Decomposition (EFDD) technique is used to extract dynamic characteristics of the arch dam.

EFDD technique is an extension to FDD technique. FDD is a basic technique that is extremely easy to use. In the technique, modes are simply picked locating the peaks in Singular Value Decomposition plots (SVD) calculated from the spectral density spectra of the responses. Animation is performed immediately. As FDD technique is based on using a single frequency line from the Fast Fourier Transform analysis (FFT), the accuracy of the estimated natural frequency depends on the FFT resolution and no modal damping is calculated. Compared to FDD, EFDD gives an improved estimate of both the natural frequencies and the mode shapes and also includes damping (Jacobsen *et al.* 2006).

In EFDD, the SDOF Power Spectral Density function, identified around a peak of resonance, is taken back to the time domain using the Inverse Discrete Fourier Transform (IDFT). The natural frequency is obtained by determining the number of zero-crossing as a function of time, and the damping by the logarithmic decrement of the corresponding SDOF normalized auto correlation function. The SDOF function is estimated using the shape determined by the previous FDD peak picking-the latter being used as a reference vector in a correlation analysis based on the Modal Assurance Criterion (MAC). A MAC value is computed between the reference FDD vector and a singular vector for each particular frequency line. If the MAC value of this vector is above a user-specified MAC rejection level, the corresponding singular value is included in the description of the SDOF function. For example, the number of singular values included in the identification of the SDOF function will be larger for the lower MAC rejection levels (Jacobsen *et al.* 2006).

In FDD technique, the relationship between the unknown input and the measured responses has the expression (Bendat and Piersol 2004, Ewins 1984)

$$[G_{yy}(j\omega)] = [H(j\omega)]^*[G_{xx}(j\omega)][H(j\omega)]^T \tag{1}$$

where $G_{xx}(j\omega)$ is the *rxr* Power Spectral Density (PSD) matrix of the input, r is the number of inputs, $G_{yy}(j\omega)$ is the *mxm* PSD matrix of the responses, m is the number of responses, $H(j\omega)$ is the *mxr* Frequency Response Function (FRF) matrix, and * and superscript T denote complex conjugate and transpose, respectively. Solution of the Eq. (1) appears in detail in the literature (Brincker *et al.* 2000).

2.2 Fluid and fluid-structure systems by lagrangian approach

The formulation of the fluid system based on Lagrangian approach is given according to references (Calayır 1994, Wilson and Khalvati 1983). In this approach, fluid is assumed to be linearly elastic, inviscid and irrotational. For a general three-dimensional fluid, stress-strain relationships can be written in matrix form as follows

$$\begin{Bmatrix} P \\ P_x \\ P_y \\ P_z \end{Bmatrix} = \begin{bmatrix} C_{11} & 0 & 0 & 0 \\ 0 & C_{22} & 0 & 0 \\ 0 & 0 & C_{33} & 0 \\ 0 & 0 & 0 & C_{44} \end{bmatrix} \begin{Bmatrix} \varepsilon_v \\ w_x \\ w_y \\ w_z \end{Bmatrix} \tag{2}$$

where P, C_{11}, and ε_v are the pressures, which are equal to mean stresses, the bulk modulus and the volumetric strains of the fluid, respectively. Since irrotationality of the fluid is considered like penalty methods (Bathe 1996, Zienkiewicz and Taylor 1989), rotations and constraint parameters are included in the stress-strain equation (Eq. (1)) of the fluid. In this equation, P_x, P_y, P_z are the rotational stresses; C_{22}, C_{33}, C_{44} are the constraint parameters and w_x, w_y and w_z are the rotations about the cartesian axis x, y and z, respectively.

In this study, the equations of motion of the fluid system were obtained using energy principles. Using the finite element approximation, the total strain energy of the fluid system may be written as

$$\pi_e = \frac{1}{2}\mathbf{U}_f^T\mathbf{K}_f\mathbf{U}_f \tag{3}$$

where $\mathbf{U}_f$ and $\mathbf{K}_f$ are the nodal displacement vector and the stiffness matrix of the fluid system, respectively. $\mathbf{K}_f$ is obtained by the sum of the stiffness matrices of the fluid elements in the following

$$\left.\begin{aligned} \mathbf{K}_f &= \sum \mathbf{K}_f^e \\ \mathbf{K}_f^e &= \int_V \mathbf{B}_f^{eT}\mathbf{C}_f\mathbf{B}_f^e dV_e \end{aligned}\right\} \tag{4}$$

where $\mathbf{C}_f$ is the elasticity matrix consisting of diagonal terms in Eq. (2). $\mathbf{B}_f^e$ is the strain-displacement matrix of the fluid element.

An important behavior of fluid systems is the ability to displace without a change in volume. For reservoir and storage tanks, this movement is known as sloshing waves in which the displacement is in the vertical direction. The increase in the potential energy of the system due to the free surface motion can be written as

$$\pi_s = \frac{1}{2}\mathbf{U}_{sf}^T\mathbf{S}_f\mathbf{U}_{sf} \tag{5}$$

where $\mathbf{U}_{sf}$ and $\mathbf{S}_f$ are the vertical nodal displacement vector and the stiffness matrix of the free surface of the fluid system, respectively. $\mathbf{S}_f$ is obtained by the sum of the stiffness matrices of the free surface fluid elements in the following

$$\left.\begin{aligned} \mathbf{S}_f &= \sum \mathbf{S}_f^e \\ \mathbf{S}_f^e &= \rho_f g \int_A \mathbf{h}_s^T\mathbf{h}_s dA^e \end{aligned}\right\} \tag{6}$$

where $\mathbf{h}_s$ is the vector consisting of interpolation functions of the free surface fluid element. ρ_f and g are the mass density of the fluid and the acceleration due to gravity, respectively. Also, kinetic energy of the system can be written as

$$T = \frac{1}{2}\dot{\mathbf{U}}_f^T \mathbf{M}_f \dot{\mathbf{U}}_f \tag{7}$$

where $\dot{\mathbf{U}}_f$ and $\mathbf{M}_f$ are the nodal velocity vector and the mass matrix of the fluid system, respectively. $\mathbf{M}_f$ is also obtained by the sum of the mass matrices of the fluid elements in the following

$$\left.\begin{aligned} \mathbf{M}_f &= \sum \mathbf{M}_f^e \\ \mathbf{M}_f^e &= \rho_f \int_V \mathbf{H}^T \mathbf{H} dV^e \end{aligned}\right\} \tag{8}$$

where $\mathbf{H}$ is the matrix consisting of interpolation functions of the fluid element. If Eqs. (3), (5) and (7) are combined using the Lagrange's equation (Clough and Penzien 1993), the following set of equations is obtained

$$\mathbf{M}_f \ddot{\mathbf{U}}_f + \mathbf{K}_f^* \mathbf{U}_f = \mathbf{R}_f \tag{9}$$

where $\mathbf{K}_f^*$, $\ddot{\mathbf{U}}_f$ and $\mathbf{R}_f$ are the system stiffness matrix including the free surface stiffness, the nodal acceleration vector and time-varying nodal force vector for the fluid system, respectively. In the formation of the fluid element matrices, reduced integration orders were utilized. For the eight-noded three-dimensional fluid element, reduced integration order is chosen as (1x1x1) (Wilson and Khalvati 1983).

The equations of motion of the fluid system (Eq. (9)), have a similar form with those of the structure system when Lagrangian approach is considered in the formulations. To obtain the coupled equations of the fluid-structure system, the determination of the interface condition is required. Because the fluid is assumed to be inviscid, only the displacement in the normal direction to the interface is continuous at the interface of the system. Assuming that the positive face is the structure and the negative face is the fluid, the boundary condition at the fluid-structure interface is

$$\mathbf{U}_n^- = \mathbf{U}_n^+ \tag{10}$$

where $\mathbf{U}$ is the normal component of the interface displacement (Akkaş *et al.* 1979). Using the interface condition, the equations of motion of the coupled system to ground motion including damping effects are given by

$$\mathbf{M}_c \ddot{\mathbf{U}}_c + \mathbf{C}_c \dot{\mathbf{U}}_c + \mathbf{K}_c \mathbf{U}_c = \mathbf{R}_c \tag{11}$$

in which $\mathbf{K}_c$, $\mathbf{C}_c$, and $\mathbf{K}_c$ are the mass, damping and stiffness matrices for the coupled system and $\mathbf{U}_c$, $\dot{\mathbf{U}}_c$, $\ddot{\mathbf{U}}_c$ and $\mathbf{R}_c$ are the vectors of the displacements, velocities, accelerations and external loads of the coupled system, respectively.

3. Operational and analytical modal analyses of prototype model of Type-1 arch dam

3.1 Description of Type-1 arch dam

A Type-1 arch dam suggested at the "Arch Dams" Symposium in England in 1968 (Arch Dams 1968) was selected for the experimental application. The geometrical properties of Type-1 arch dam appear in Fig. 2. As seen in Fig. 2, Type-1 arch dam has a single curvature, constant radius and constant central angle. In addition, it has six unit height and constant 0.6 unit widths. To construct a prototype model, one selected unit was 10 cm. Therefore, dam height (H) and crest width are designed as 60 cm and 6 cm, respectively.

Type-1 arch dam was developed considering reservoir and foundation. To investigate the water length effects, reservoir of the dam was extended as 3H (H: dam height). To obtain the rigidity abutments, foundation of the dam was extended as H in the downstream and downward directions,

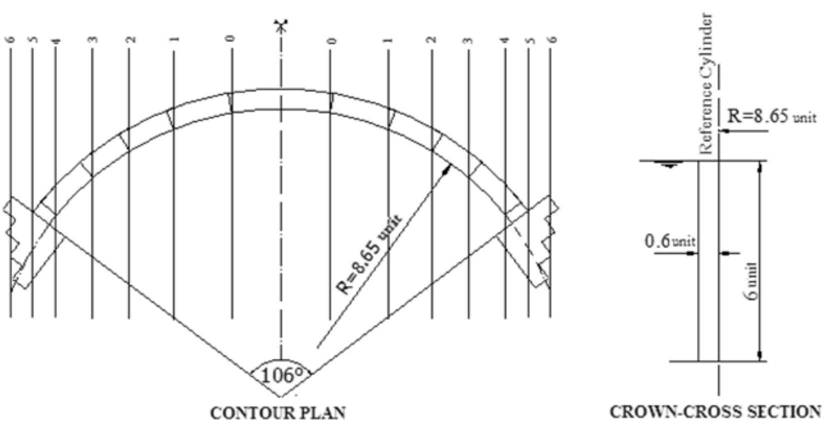


Fig. 2 Geometrical properties of Type-1 arch dam

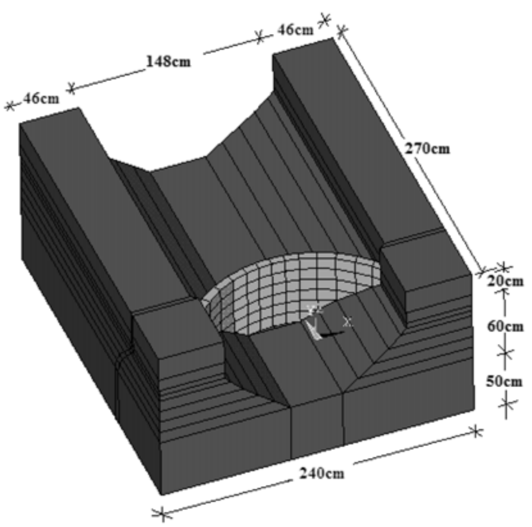


Fig. 3 3D representation of Type-1 arch dam-reservoir-foundation system and its dimensions

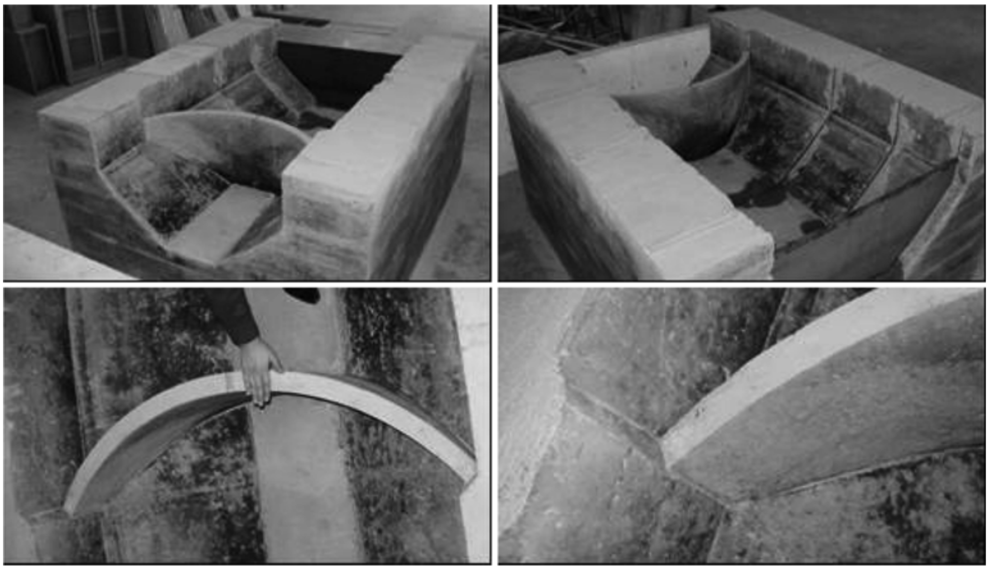


Fig. 4 Some photographs of Type-1 arch dam-reservoir-foundation system

and as reservoir length in upstream direction. Such kind of modeling is appropriate to represent the dynamic behavior of concrete dams (USACE 2003). Definitive dimensions of Type-1 arch dam-reservoir-foundation system are shown in Fig. 3.

Construction of a Type-1 arch dam-reservoir-foundation system considered the dimensions given in Fig. 3, and construction of the model system consumed approximately 6.5 m^3 concrete. Fig. 4 shows some photographs of the model.

3.2 Ambient vibration tests – operational modal analysis

Ambient vibration tests, conducted on the Type-1 arch dam model determined its natural frequencies, mode shapes and damping ratios. Measurements were performed for empty, H, 2H and 3H water lengths. In the ambient vibration tests, a B&K 3560 data acquisition system with 17 channels and a B&K 4507-B005 type uni-axial accelerometers were used. During the tests, the frequency span selected was 0-1600 Hz according to the initial finite element results. Measurements occurred during five-minute intervals, and small impact effects provided excitation. However, the excitation was natural and unknown. It means that the impact hammer was used as natural excitation. But it was not defined to the data acquisition system as a hammer. Signals obtained from

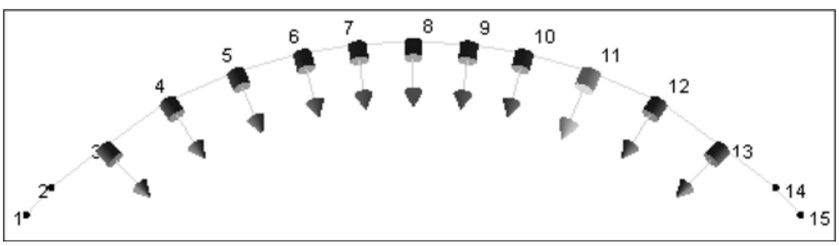


Fig. 5 Locations of accelerometers used in the ambient vibration tests

the tests were recorded and processed by the commercial software PULSE (PULSE 2006) and OMA (OMA 2006), respectively. Dynamic characteristics of Type-1 arch dam were extracted by EFDD technique. During the ambient vibration tests, eleven accelerometers were located to the normal direction of the water along to the crest (Fig. 5).

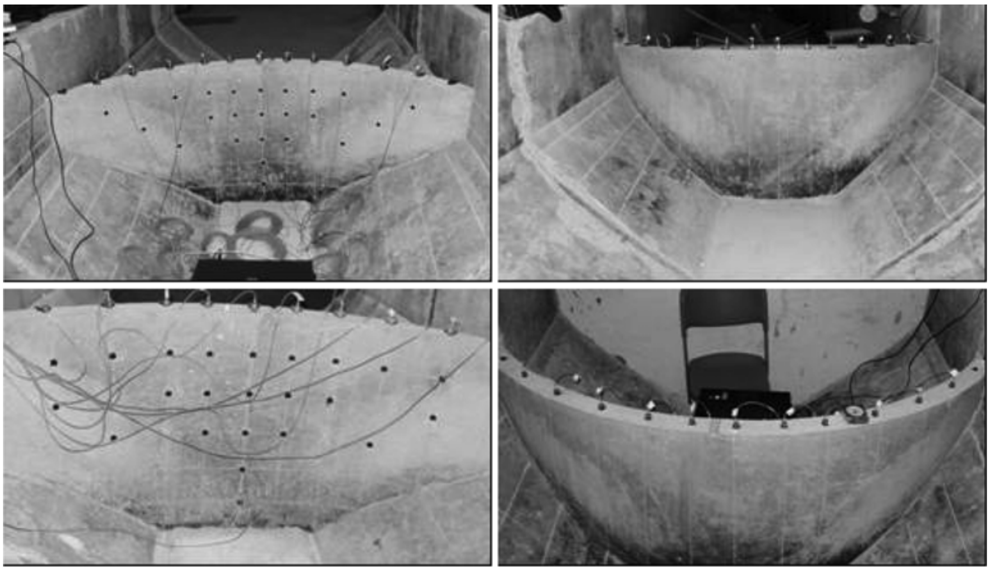
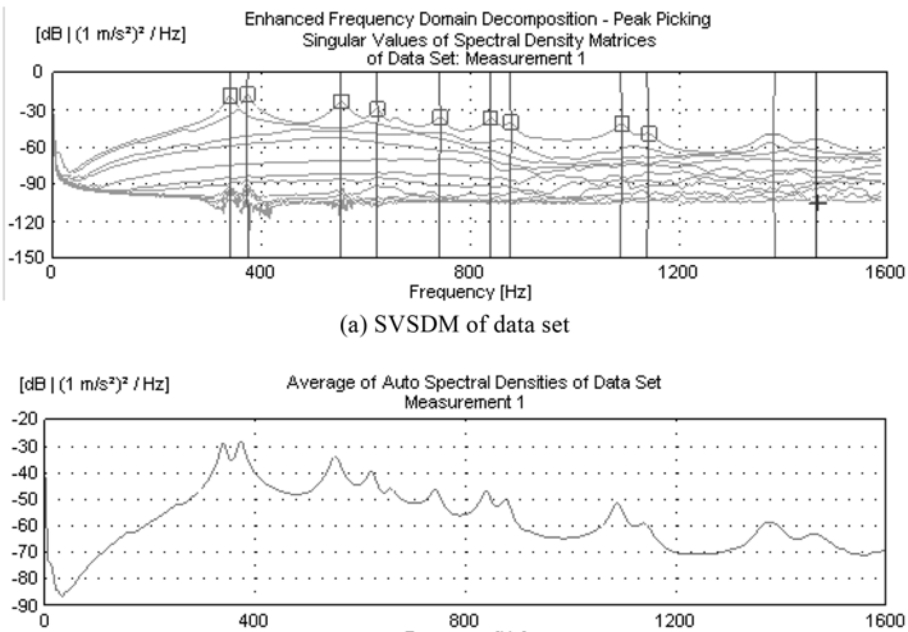


Fig. 6 Some photographs from ambient vibration tests for empty reservoir



(a) SVSDM of data set

(b) AASD of data set

Fig. 7 SVSDM and AASD of the data set for empty reservoir

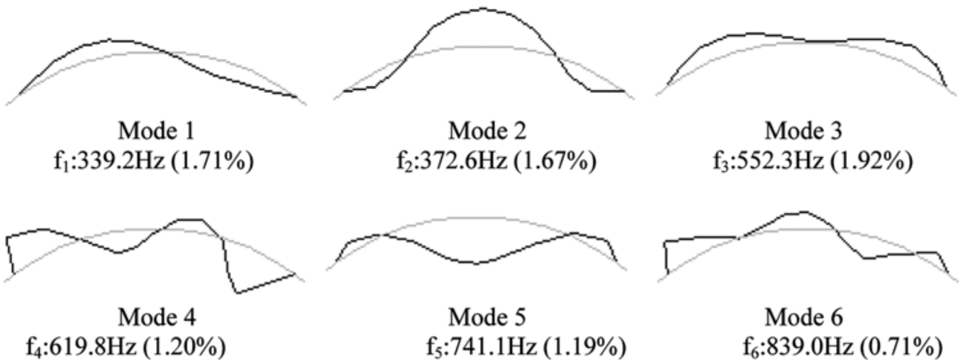


Fig. 8 Mode shapes of Type-1 arch dam for empty reservoir

3.2.1 Empty reservoir

Ambient vibration tests for empty reservoir were conducted to Type-1 arch dam after 45 days of pouring concrete. Some photographs from ambient vibration tests for empty reservoir of Type-1 arch dam model appear in Fig. 6. Singular values of spectral density matrices (SVSDM) of the data set and average of auto spectral densities (AASD) of the data set obtained from EFDD technique are shown in Fig. 7. As seen in Fig. 7, more than eight natural frequencies are obtained between 0-1600 Hz frequency span. The mode shapes, natural frequencies and damping ratios obtained from the tests appear in Fig. 8. Due to locations of the accelerometers, only symmetrical and anti-symmetrical modes were obtained.

3.2.2 H (60 cm) reservoir water length

Ambient vibration tests for H (60 cm) reservoir water length were conducted to Type-1 arch dam

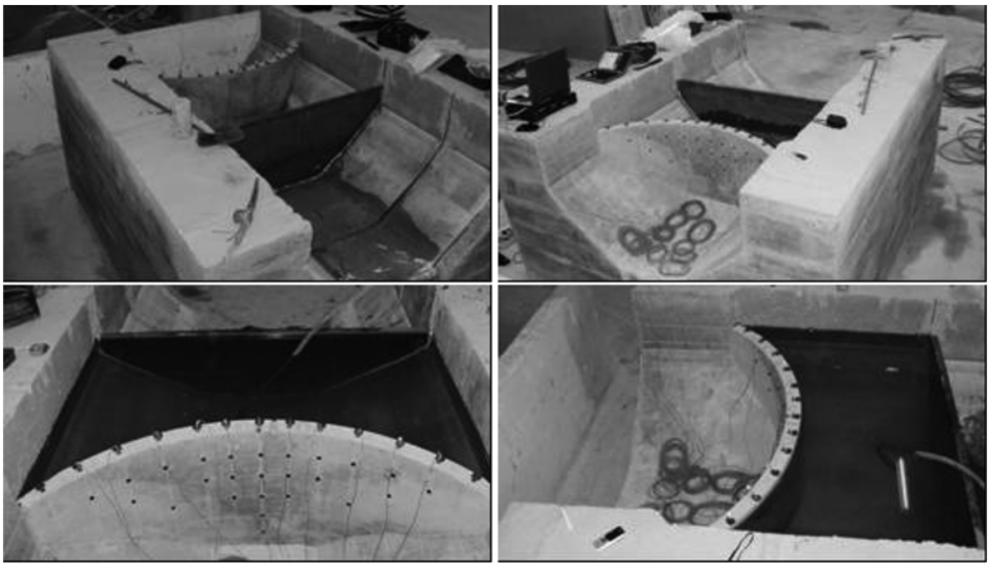
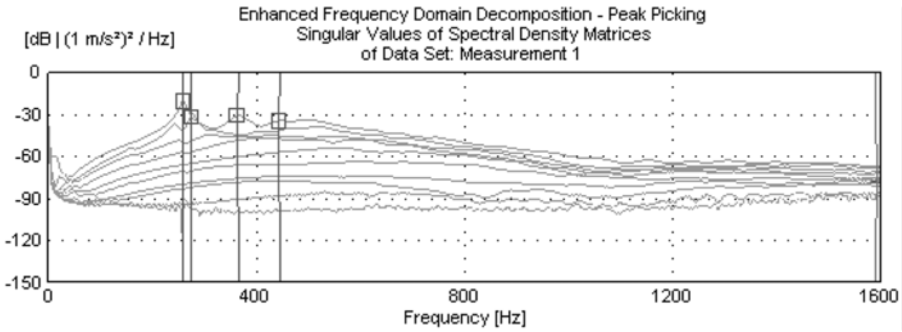
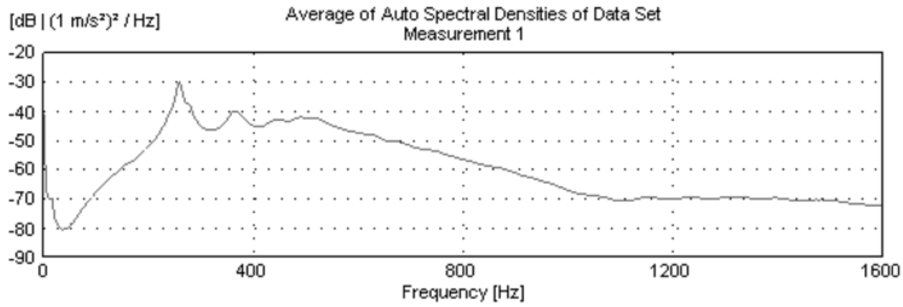


Fig. 9 Some photographs from ambient vibration tests for H water length



(a) SVSDM of data set



(b) AASD of data set

Fig. 10 SVSDM and AASD of the data set for H water length

Mode 1 f_1:259.0Hz (2.05%) | Mode 2 f_2:273.3Hz (0.41%) | Mode 3 f_3:366.8Hz (4.52%)

Fig. 11 Mode shapes of Type-1 arch dam for H water length

after 90 days of pouring concrete. Some photographs from ambient vibration tests for H water length of Type-1 arch dam model appear in Fig. 9. SVSDM of the data set and AASD of the data set obtained from EFDD technique is shown in Fig. 10. As seen in Fig. 10, only 3-4 frequencies are obtained between 0-1600 Hz frequency span. The mode shapes, natural frequencies and damping ratios obtained from the tests are shown in Fig. 11.

3.2.3 2H (120 cm) reservoir water length

Ambient vibration tests for 2H (120 cm) reservoir water length were conducted to Type-1 arch dam after 100 days of pouring concrete. Some photographs from ambient vibration tests for 2H water length of Type-1 arch dam model appear in Fig. 12. SVSDM of the data set and AASD of the data set obtained from EFDD technique is shown in Fig. 13. The mode shapes, natural frequencies and damping ratios obtained from the tests are shown in Fig. 14.

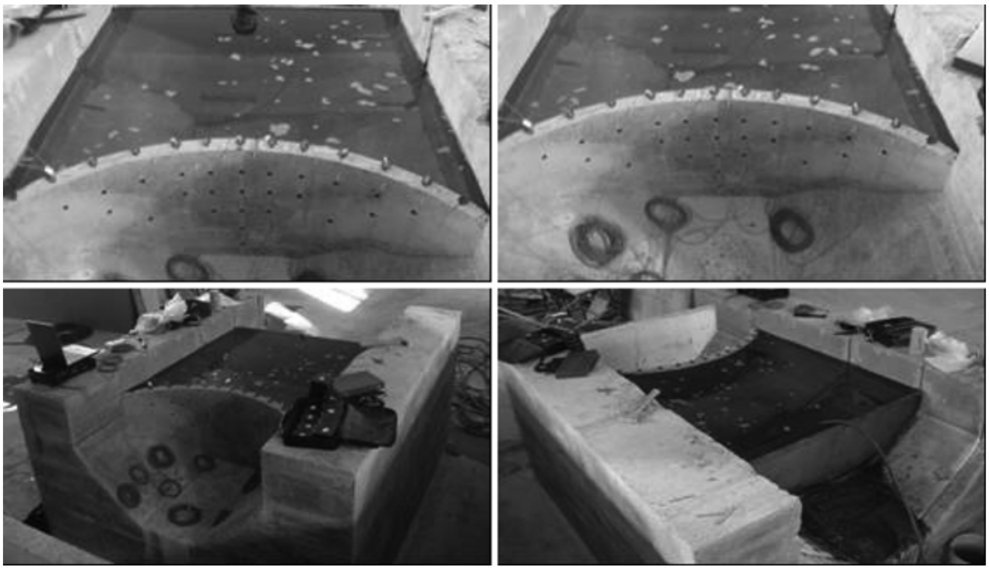


Fig. 12 Some photographs related from vibration tests for 2H water length

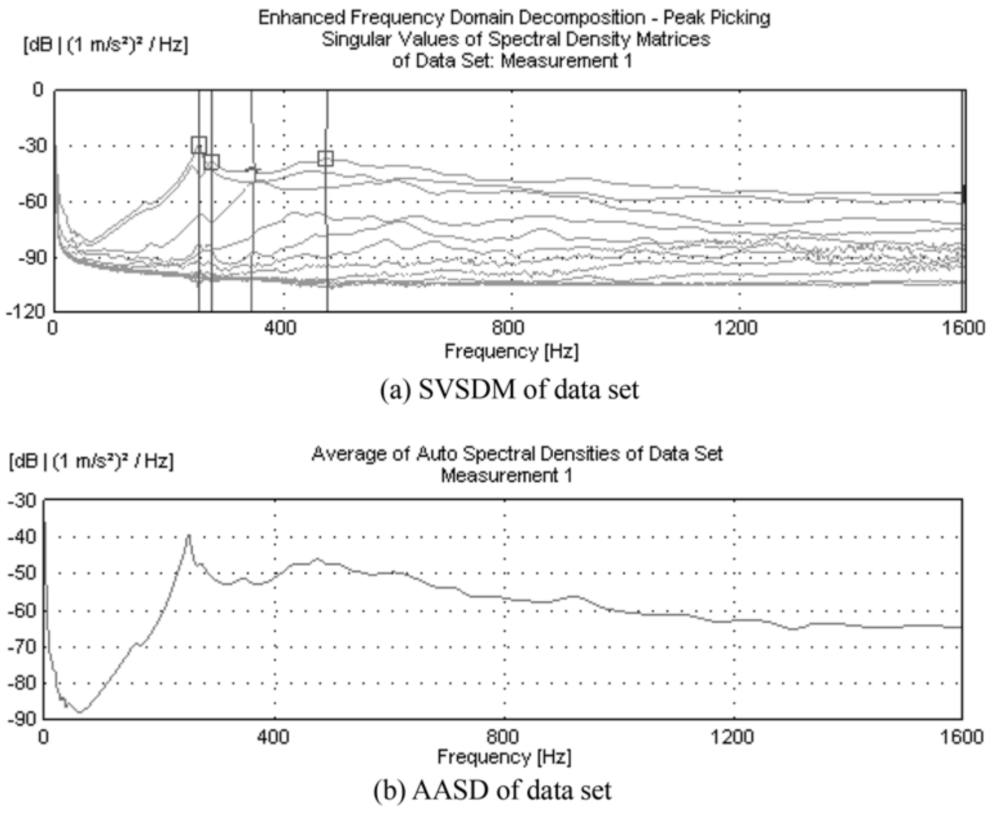


Fig. 13 SVSDM and AASD of the data set for 2H water length

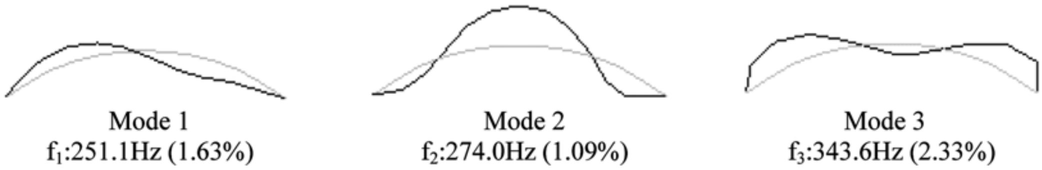


Fig. 14 Mode shapes of Type-1 arch dam for 2H water length

3.2.4 3H (180 cm) reservoir water length

Ambient vibration tests for 3H (180 cm) reservoir water length were conducted to Type-1 arch dam after 170 days of pouring concrete. Some photographs from to ambient vibration tests for 3H water length of Type-1 arch dam model appear in Fig. 15. SVSDM of the data set and AASD of the data set obtained from EFDD technique is shown in Fig. 16. The mode shapes, natural frequencies and damping ratios obtained from the tests are shown in Fig. 17.

3.3 Finite element procedure – analytical modal analysis

The ANSYS (ANSYS 2008) finite element program was used to obtain dynamic characteristics of Type-1 arch dam, analytically. To obtain realistic earthquake behavior of arch dams;

- The arch dam must be modeled as three dimensional,
- The dam-reservoir-foundation effects must be considered.

In this study, the dam-reservoir-foundation interaction effects are represented by Lagrangian approach. In this approach, the displacements are the variables in both the reservoir and the dam. So there is no need any extra interface equations in this approach. For that reason, compatibility and

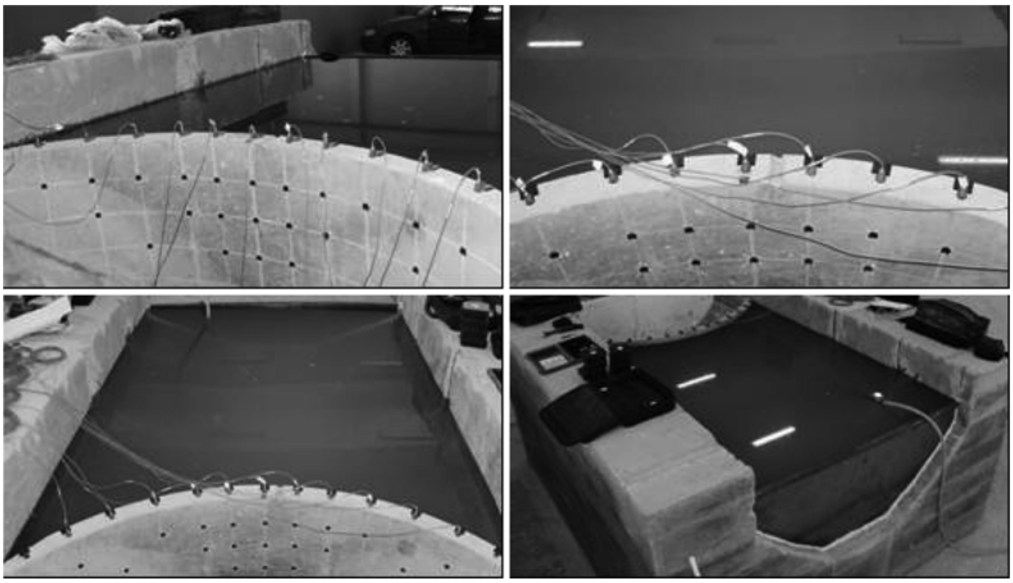
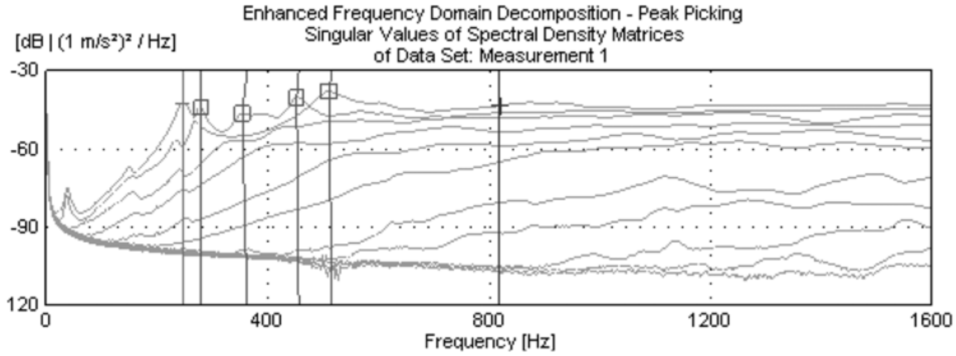
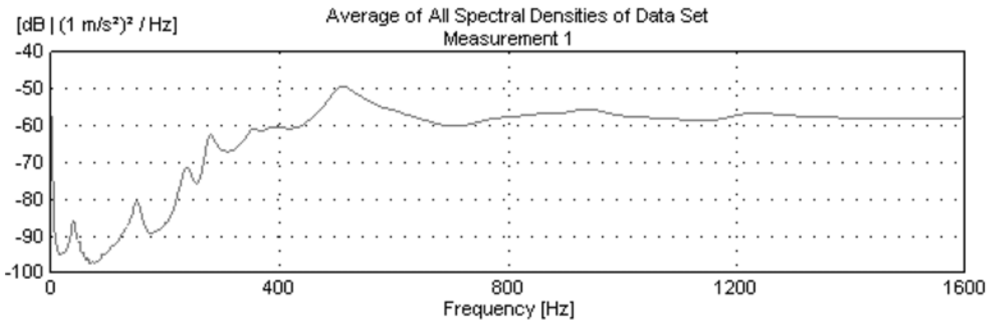


Fig. 15 Some photographs from ambient vibration tests for 3H water length



(a) SVSDM of data set



(b) AASD of data set

Fig. 16 SVSDM and AASD of the data set for 3H water length

Mode 1 f_1:248.3Hz (3.75%) Mode 2 f_2:278.0Hz (1.79%) Mode 3 f_3:362.7Hz (4.46%)

Fig. 17 Mode shapes of Type-1 arch dam for 3H water length

equilibrium are automatically satisfied at the nodes along the interfaces between dam-reservoir-foundation.

3D finite element model of the dam was constituted using geometrical properties and dimensions given in Figs. 2 and 3, respectively. The dam is modeled for empty, H, 2H, and 3H reservoir water lengths. In the finite element model, solid elements for the dam and foundation, and fluid elements for the reservoir water are used. Both solid and fluid elements have 8-nodes and each node has three degree of freedom: x, y, z translations. The element types and material properties used in the analysis are summarized in Table 1.

According to Lagrangian Approach, to obtain the coupled equations of the fluid-structure system, the determination of the interface condition is required. Because the fluid is assumed to be inviscid, only the displacement in the normal direction to the interface is continuous at the interface of the

Table 1 Material properties of dam-reservoir-foundation system

	ANSYS Element Type	Material Properties		
		Elasticity Modulus (MPa)	Poisson Ratio	Mass Density (kg/m^3)
Dam	Solid 45	15500	0.2	2300
Reservoir	Fluid 80	2070	-	1000
Foundation	Solid 45	20000	0.2	-

Table 2 Quantity of concrete components used in dam and foundation

Component	Dam	Foundation
Volume (m^3)	0.044	6.21
Aggregate (10-22 mm)	-	712 kg/m^3
Aggregate (3-9 mm)	1556 kg/m^3	874 kg/m^3
Aggregate (0-2 mm)	175 kg/m^3	175 kg/m^3
Cement (C)	360 kg/m^3	360 kg/m^3
Water (W)	210 kg/m^3	180 kg/m^3
C/W	0.58	0.50
Admixture	3.14 kg/m^3	3.24 kg/m^3
Total	101.4 kg	14309.3 kg

system. So, coupled elements are used to represent the interaction between the reservoir-dam and reservoir-foundation. They have 0.001 m length are used. Main objective of the coupled elements are hold equal the normal displacements between two reciprocal nodes according to Lagrangian Approach.

The arch dams have two main structural behaviors as arch and cantilever. They transmit water loads to abutment due to these two behaviors. So they are built using more little concrete compared to gravity dams. However, the abutments must have strength to carry loads. Therefore, the rigidity of foundation abutments is generally more than body concrete. In the construction of prototype arch dam, it is designed that the foundation must be more rigidity than the body concrete. In the construction of the system, the quantity of concrete components used in dam and foundation are given in Table 2.

On the other hand, some compressive and ultrasonic velocity tests are applied to foundation and dam samples. The results show that the elasticity modulus of the foundation is higher than the concrete of the dam. Also, the length of the foundation was taken into account as much as the dam height in the downstream, downward and cross directions. Because of the massless foundation, the analyses considered only the effects of foundation flexibility. So the foundation model extended to a distance beyond which its effects on deflections and natural frequencies of the dam become negligible (USACE 2003).

3.3.1 Empty reservoir

3D finite element model of Type-1 arch dam for empty reservoir is shown in Fig. 18. In this model, 2732 finite elements are used: 148 solid elements for the dam and 2584 solid elements for the foundation. First six natural frequencies and mode shapes of Type-1 arch dam are shown in Fig. 19. Mode shapes are obtained as symmetrical and anti-symmetrical similar to OMA results.

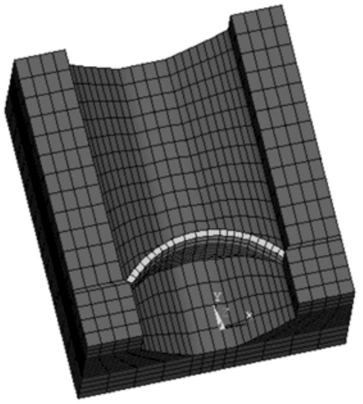


Fig. 18 3D FEM of Type-1 arch dam for empty reservoir

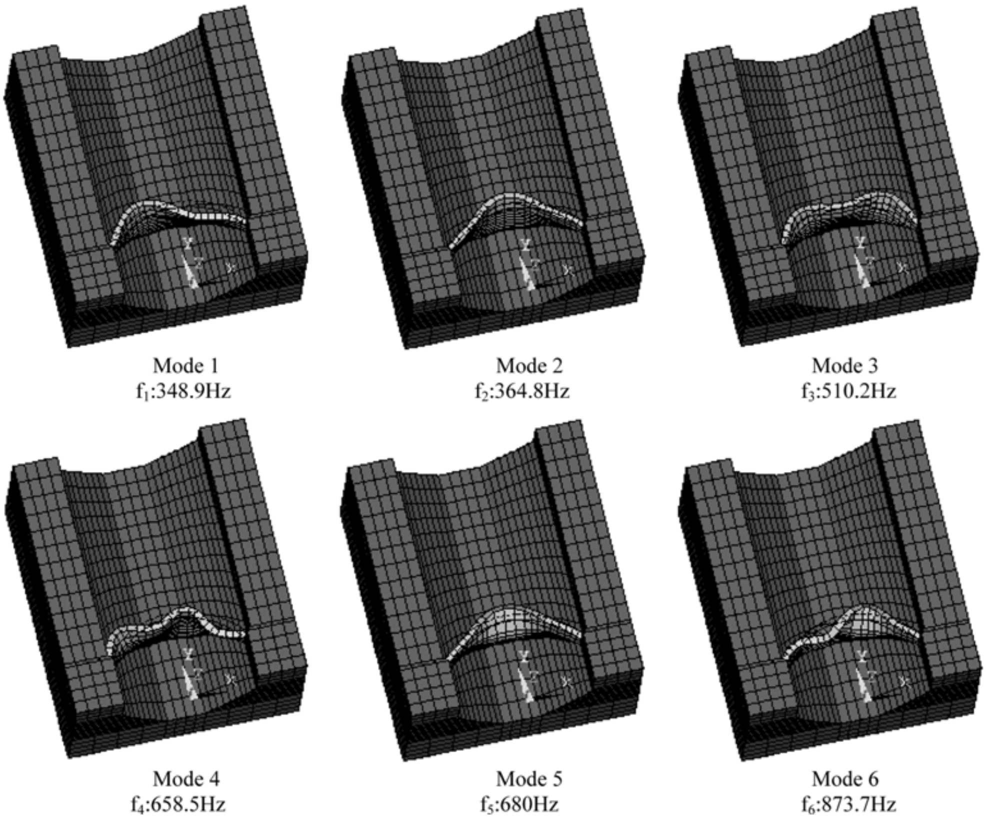


Fig. 19 Mode shapes of Type-1 arch dam for empty reservoir

3.3.2 H (60 cm) reservoir water length

3D finite element model of Type-1 arch dam for H reservoir water length is shown in Fig. 20. In this model, 3324 finite elements are used: 148 solid elements for the dam, 2584 solid elements for the foundation and 592 fluid elements for the reservoir. First three natural frequencies and mode shapes of Type-1 arch dam are shown in Fig. 21.

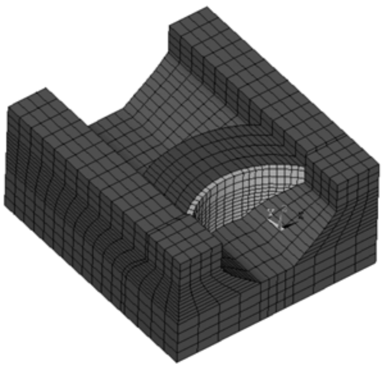
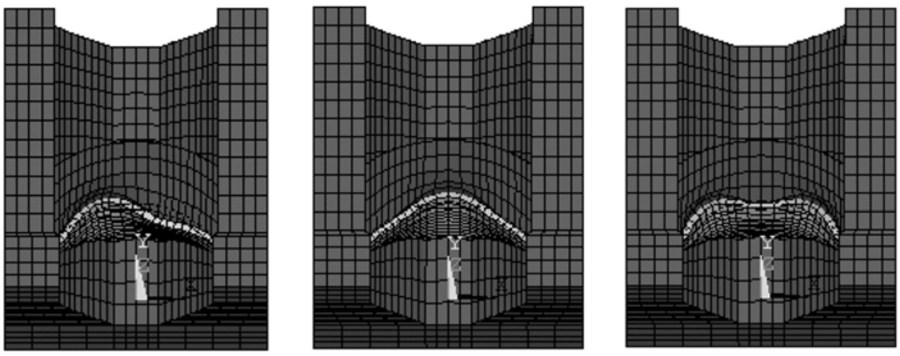


Fig. 20 3D FEM of Type-1 arch dam for H water length



Mode 1 f_1:256.7Hz | Mode 2 f_2:258.8Hz | Mode 3 f_3:380.5Hz

Fig. 21 Mode shapes of Type-1 arch dam for H water length

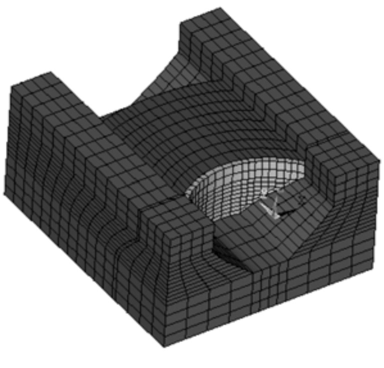
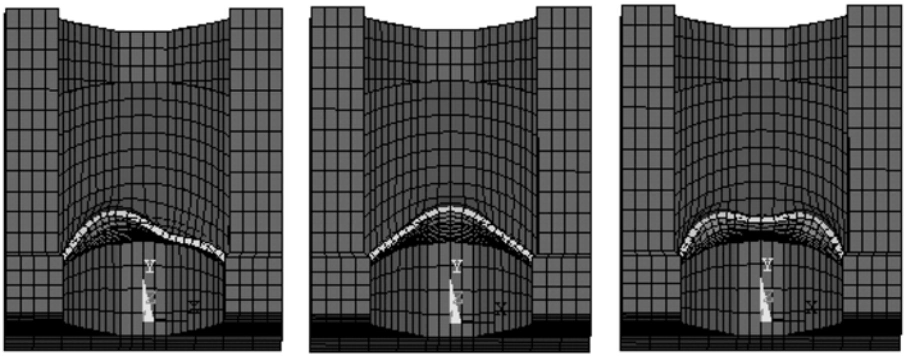


Fig. 22 3D FEM of Type-1 arch dam for 2H water length



Mode 1 f_1:252.9Hz | Mode 2 f_2:254.9Hz | Mode 3 f_3:374.6Hz

Fig. 23 Mode shapes of Type-1 arch dam for 2H water length

3.3.3 2H (120 cm) reservoir water length

3D finite element model of Type-1 arch dam for 2H reservoir water length is shown in Fig. 22. In this model, 3916 finite elements are used: 148 solid elements for the dam, 2584 solid elements for the foundation and 1184 fluid elements for the reservoir. First three natural frequencies and mode shapes of Type-1 arch dam are shown in Fig. 23.

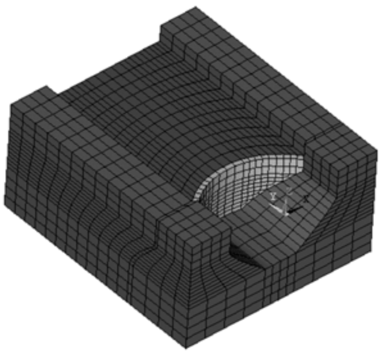
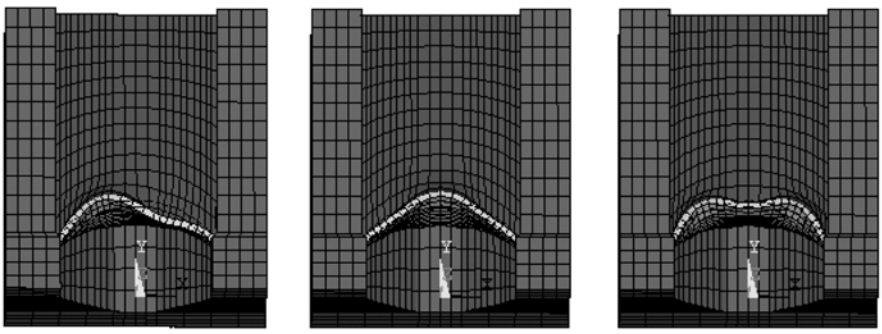


Fig. 24 Mode shapes of Type-1 arch dam for 3H water length



Mode 1 f_1:250.8Hz | Mode 2 f_2:252.9Hz | Mode 3 f_3:371.4Hz

Fig. 25 Mode shapes of Type-1 arch dam for 3H water length

3.3.4 3H (180 cm) reservoir water length

3D finite element model of Type-1 arch dam for 3H reservoir water length is shown in Fig. 24. In this model, 4508 finite elements are used: 148 solid elements for the dam, 2584 solid elements for the foundation and 1776 fluid elements for the reservoir. First three natural frequencies and mode shapes of Type-1 arch dam are shown in Fig. 25.

3.4 Comparison of OMA and FEM Results

In this study, the natural frequencies obtained from OMA and FEM for empty, H, 2H and 3H reservoir water lengths are given in Table 3. As seen in Table 3, the natural frequencies are reduced with the extending of water level. But the ratio of this reduction is decreased with the extending of water level. The variation of the natural frequencies obtained from OMA and FEM for empty, H, 2H and 3H reservoir water lengths is plotted in Fig. 26. As seen in Fig. 26, natural frequencies are reduced immediately when the reservoir is filled water. Also, frequencies obtained from OMA and FEM are nearly closed to each other.

In addition, Modal Assurance Criteria (MAC) graphics related to empty and full reservoirs are plotted in Figs. 27 and 28. As seen in Figs. 27 and 28 that the MAC values are near to 1. This

Table 3 Natural frequencies of Type-1 arch dam obtained for empty, H, 2H, and 3H reservoir water lengths

Mode	Reservoir Water Length-Frequencies							
	Empty		H = 60 cm		2H = 120 cm		3H = 180 cm	
	OMA (Hz)	FEM (Hz)	OMA (Hz)	FEM (Hz)	OMA (Hz)	FEM (Hz)	OMA (Hz)	FEM (Hz)
1	339.2	348.9	259	256.8	251.1	254.9	248.3	252.8
2	372.6	364.8	273.3	258.8	274	256.9	278.0	254.9
3	552.3	510.s2	366.8	380.5	343.6	376.6	362.7	374.4
4	619.8	658.5	-	485.0	-	477.6	-	473.7
5	741.1	680.0	-	494.1	-	486.6	-	482.0
6	839.0	873.	-	645.9	-	636.1	-	630.7
7	875.5	898.7	-	672.3	-	662.0	-	655.5
8	1088	1056	-	850.6	-	837.8	-	830.5

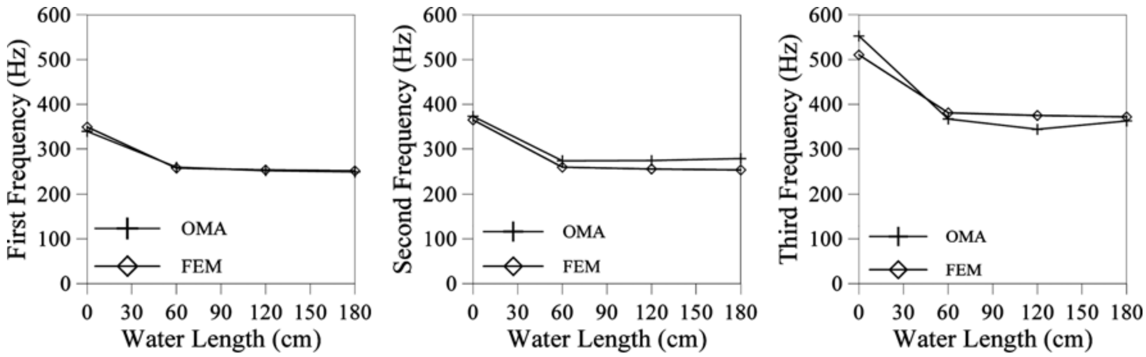


Fig. 26 The variation of frequencies of Type-1 arch dam along to water length

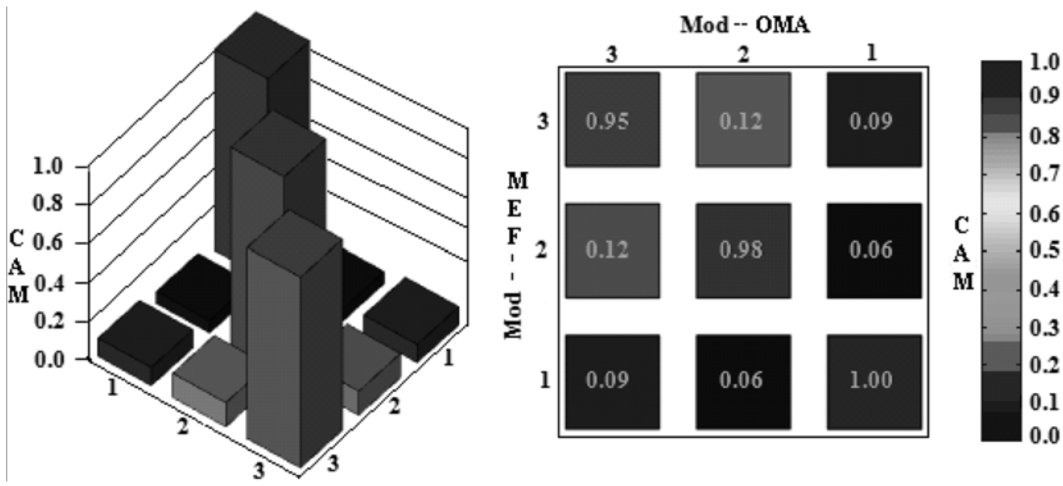


Fig. 27 MAC values related to empty reservoir case

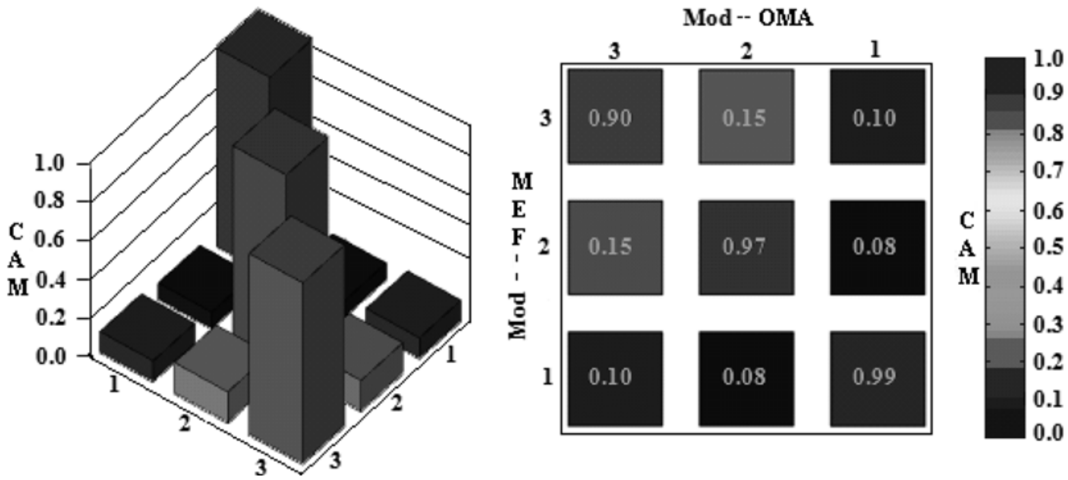


Fig. 28 MAC values related to full reservoir case

shows that experimental and analytical modes are almost overlapped. When the mode shapes related to empty and full reservoirs are examined, it can be seen that the modes shapes are near to each other. It means that reservoir water does not affect the mode shapes of the arch dam. The MAC values between modes related to empty and full reservoir are about 0.90-1.

On the other hand, in this study, more than ten modes are obtained from ambient vibration testing of empty reservoir case. However, when the reservoir is filled with water, the only 3-4 modes can be obtained. Authors think that the water is damps the vibration signals of the systems and the quality of the signal data is reduced and influence of higher modes is disappeared for full reservoir. This is true for real dams and the other fluid-structure interaction systems. In this study, many ambient vibration tests are conducted to the dam using several excitation methods. But the water always complicates the behavior of arch dams. However, there is not a similar situation for analytical results. Many modes can be obtained analytically in case of empty reservoir or full reservoir. But this is the difference between analytical and experimental studies. Experimental studies are always difficult compared to analytical studies.

4. Conclusions

This study investigated the water length effects on the natural frequencies, mode shapes and damping ratios of Type-1 arch dam using OMA and FEM procedures. For this purpose, a Type-1 arch dam constructed under laboratory conditions and its reservoir were extended as three times of its height. Ambient vibration tests were conducted to arch dam for empty, H, 2H, and 3H water lengths, and dynamic characteristics were obtained. The following observations can be made from this study:

- Natural frequencies and mode shapes obtained from OMA and FEM are almost closed to each other. So, these two methods can be used to together to compare the dynamic characteristics of prototype Type-1 arch dam.
- When comparing to the first natural frequency of Type-1 arch dam for empty reservoir and H water length, frequencies are changed 25% approximately. When comparing to the first natural frequency of Type-1 arch dam for empty reservoir and 2H water length, frequencies are changed 26.8% approximately. When comparing to the first natural frequency of Type-1 arch dam for empty reservoir and 3H water length, frequencies are changed 27.5% approximately.
- Natural frequencies are reduced immediately when the reservoir is filled water. So it can be stated that reservoir water complicates the dynamic behavior of Type-1 arch dam. However, reduction ratio is decreased along to reservoir water length. It means, dynamic behavior of Type-1 arch dam is not affected more for longer water lengths than 3H. So such a modeling is enough to represent the dynamic behavior and dam-reservoir-foundation interaction effects of Type-1 arch dam.
- Natural frequencies and damping ratios obtained for empty, H, 2H, and 3H water lengths using OMA are not distributed regularly. The reason of this is thought that the ambient vibration tests are not conducted to arch dam at the same time for each reservoir water length. So it may be some changes of physical structure of the concrete depended on the time such as shrinkage and creep.
- The mode shapes are obtained as symmetrical and anti-symmetrical for each water length, and they are closed to each other and literature. Beside, the MAC values between experimental and analytical modes are generally 90-100%.
- It is difficult to obtain modes from OMA method when reservoir is filled with water. Although 8-9 modes can be obtained for empty reservoir, only 3-4 modes can be obtained for H, 2H, and 3H reservoir water lengths. It can be stated that the full reservoir complicates the dynamic behavior of Type-1 arch dam, because of the fact that the water damps the vibration signals of the arch dam. Therefore, the quality of the signal data is reduced and influence of higher modes is disappeared for full reservoir.
- The damping ratios are generally obtained about 1-2% and 2-4% related to empty and full reservoir respectively, which are the compatible with the literature.

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