Effective Techniques for Arch Dam Ambient Vibration Test: Application on Two Iranian Dams

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ABSTRACT: *Ambient vibration test is an effective and economical means for identification of dynamic properties of structures such as dams. Mathematical models generally are developed for the design purpose. Structural and material parameters are assumed from similar projects or limited material tests. It was found desirable to verify the results obtained from mathematical model used regularly in the Iranian dam design practice by comparing with the behavior of the actual as-built structures. Indeed this was done by dynamic tests and good correlation was found. In this paper a new combination of different techniques is employed to achieve highest possible precision using the minimum available hardware.*

Keywords: Arch Dam; Ambient vibration Test; Natural frequencies; Iranian Dams

1. Introduction

Usage of vibration tests is a suitable way to determine the dynamic characteristics of structures such as large dams and specially to measure their first few natural modes of vibration. These in turn would allow verification of several properties of the structure that could not be easily found by other methods.

In 1982 Clough presented vibration tests results for Techi Dam in Taiwan. Their important results enabled an identification of first few modes and a comparison with theoretical solution [1]. In 1986 dynamic tests were carried out on the Monticellio dam. By these tests, the first six modes of the structure and their corresponding damping ratios were obtained [2]. In 1990, Severn et al conducted dynamic tests of a large arch dam along with a comparison with its mathematical model. The results were in terms of stresses and hydrodynamic pressures [3]. Furthermore in 1994, Duron et al presented a paper on different dynamic vibration tests (forced and ambient) on the Big-Creek dam. They carried out an accurate identification process on symmetric and anti-symmetric first and second modes. It is noted that in this field there are contradictory discussion with respect to the Maximum Entropy Method the results of which by no means are certain [4]. In 1996 Loh et al performed ambient vibration tests on the Fei-Tusi dam to study the decrease of frequencies of the first two modes of the structure due to raising the reservoir water level [5]. In 1999 Daniell and Taylor could precisely confirm the ambient vibration tests results with modal analysis methods [6]. This paper is a summary of tremendous experimental works carried out on two Iranian newly-built arch dams using a multi-stage measurement of ambient responses with corresponding techniques for the data processing. The method is demanding and effective once the number of facilities to monitor the huge structure is limited. More details of the work could be found elsewhere [7, 8].

The first arch dam under investigation is Shahid-Rajaee dam, which is a modern large dam designed and constructed mainly by Iranian engineers, and the second arch dam is Saveh dam which is designed by Romanian consulting engineers and constructed by the Iranian engineers.

Shahid-Rajaee dam is located on Tajan river approximately 35*km* South-East of Sari City, capital of Mazandaran Province (200*km* North-East of Tehran). The dam is a double curvature concrete arch dam and is situated in a seismically active zone. Its design and construction works have been carried out between 1989 and 1997.

The main reasons for choosing this dam for the tests were as follows:

- Existence of high seismic hazard (maximum credible ground acceleration of 0.51*g*) and an active fault in the dam site.
- Rather high span to height ratio of the shell structure (about 3:1).
- Adoption of an exceptional risk in the dam design in which a limited release of the reservoir was admitted after a big earthquake.
- Use of a modern concrete technology with relatively high strength.
- Existence of open vertical joints in the higher wings of the dam body.
- Extremely thin abutment on the left upper side of the dam body.

The main features of Shahid-Rajaee dam is described in Table (1), and Figure (1) [9,10]. Two set of dynamic tests (i.e., ambient and forced) were conducted on this dam although this paper deals with the ambient ones. Water level in the reservoir was at elevation 175 i.e., 18*m* below crest during both the ambient and the forced vibration tests.

Saveh dam is located on the Qara-Chai river in Vafraghan canyon, approximately 25*km* North-East

Table 1. Description of Shahid-Rajaee dam.

Volume of Reservoir	165 MCM
Crest Length	430m
Height Above Foundation	138m
Thickness of Crown	7m
Thickness of Foundation	26m
Crest Length to Maximum Dam Height Ratio	3.1
Spillway Type	Free Over-Fall Crest Spillway
Spillway Maximum Design Discharge	$2050 \frac{m^3}{sec}$

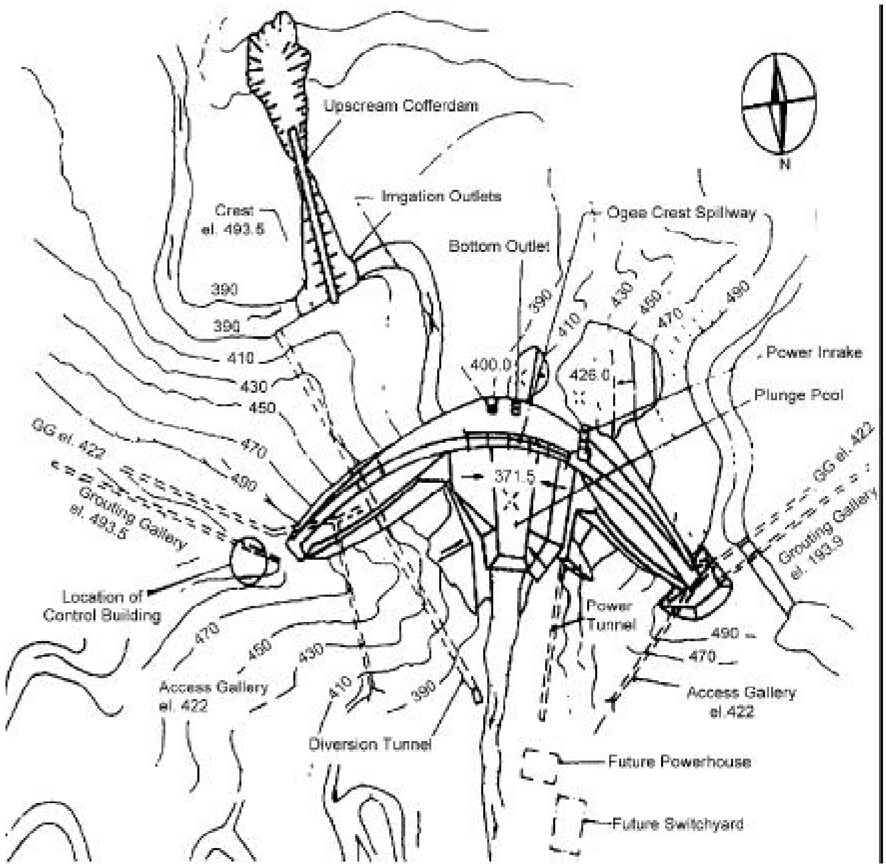


Figure 1. General view of Shahid-Rajaee dam.

of Saveh City, in Markazi Province (150*km* South-West of Tehran). The dam is a double curvature concrete arch dam and is situated in high hazard seismic zone. It was designed and construction between 1982 and 1993. Only ambient vibration tests were conducted on this dam. Water level in the reservoir was at elevation 1124.22 i.e., 47.5*m* below crest during the tests. Thus the reservoir was rather half-full. The main features of Saveh dam is described in Table (2), and Figure (2). The tests were carried out during the winter of 1999 to the autumn of 2000.

Table 2. Description of Saveh dam.

Volume of Reservoir	290 MCM
Crest Length	265m
Height Above Foundation	128m
Thickness of Crest	6m
Thickness of Foundation	25m
Crest Length to Maximum Dam Height Ratio	2.1
Spillway Type	Free Over-Fall Crest Spillway
Spillway Maximum Design Discharge	$872 \frac{m^3}{sec}$

2. Ambient Vibration Tests and Loading Classification

Ambient vibration tests were conducted on the Shahid-Rajaee and the Saveh dams using *IIEES* testing facilities in the following manner:

Five *SSR*-1 recording apparatus were used. Each of these had the ability to record the data of three different channels linked to *SS*-1 velocity-meter sensor stations. The location of sensors were based on a primary calculation of the mathematical model. Because of limited number of sensors and in order to determine different mode shapes, the tests were performed in several stages of equipment arrangements. The general layouts of these different arrangements are shown in Figures (3) and (4). In these figures each set of three sensors closely spaced are named as *A*, *B*, *C*, and *R* (as the reference set) so that for instance stations are called as *A*1, *A*2, and *A*3, or *R*1, *R*2, and *R*3.

For each station, the recording was done for 90 seconds per single hour and continued for a 30 hour period. This type of sampling was taken to enable considering all possible loading conditions for each station from statistical point of view. The ambient events (loading condition) were consisted of four groups in different time spans as explained below. To recognize the hidden modes in ambient vibration tests, artificial exciting was also generated by partial and rapid opening and closing of the bottom outlet gates of the dam body as the fifth loading

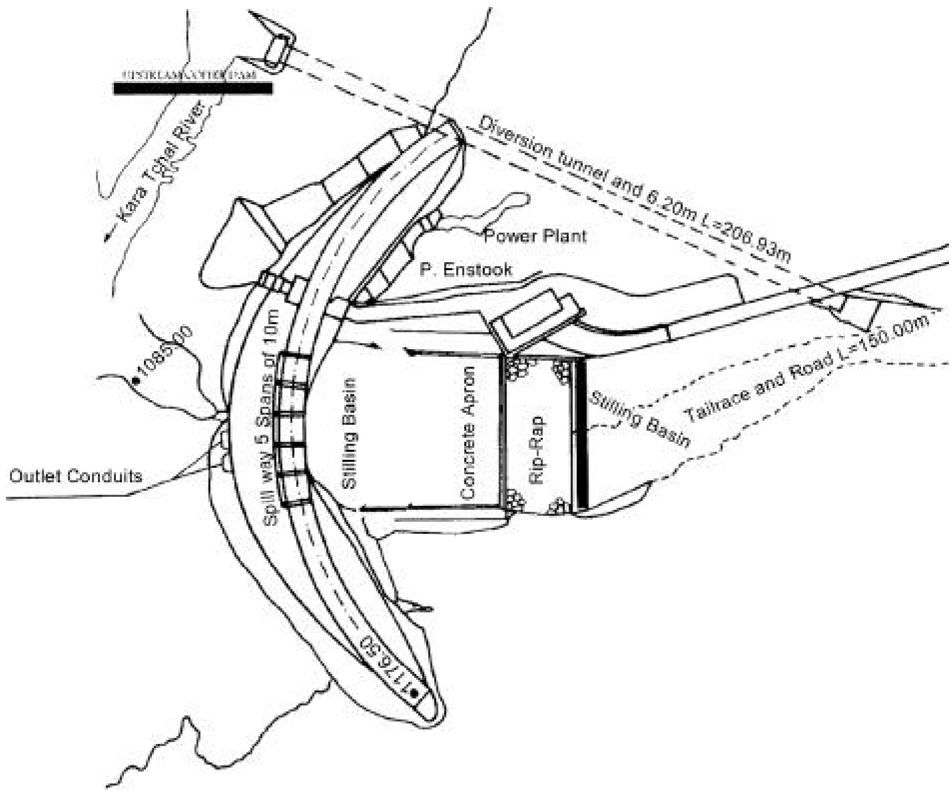


Figure 2. General view of Saveh dam.

condition. These loading conditions are;

1. Day-time condition (load due to ambient noise and wind)
2. Night-time condition corresponding to 7 *P.M.* to 7 *A.M.* (lower ambient noise level dominated by wind)
3. Gate opening shock condition (shock load with much higher amplitude than those of noise and wind)
4. Symmetric wind direction condition (prevailing the ambient noise)
5. Anti-symmetric wind direction condition (prevailing ambient noise)

The records of data were classified accordingly. The advantages of this classification are that no frequency would be omitted and all frequencies and modes would fall within the range of at least one group. Furthermore, the transient noise such as that of traffic is also noticed and could be filtered out.

3. Method of Data Processing

Due to lack of enough hardware (sensors, data acquisition apparatus, etc.) it was rather a hard task to perform such ambitious testing accurately. Therefore it was needed to select the sensors position optimally. This was done with fair success

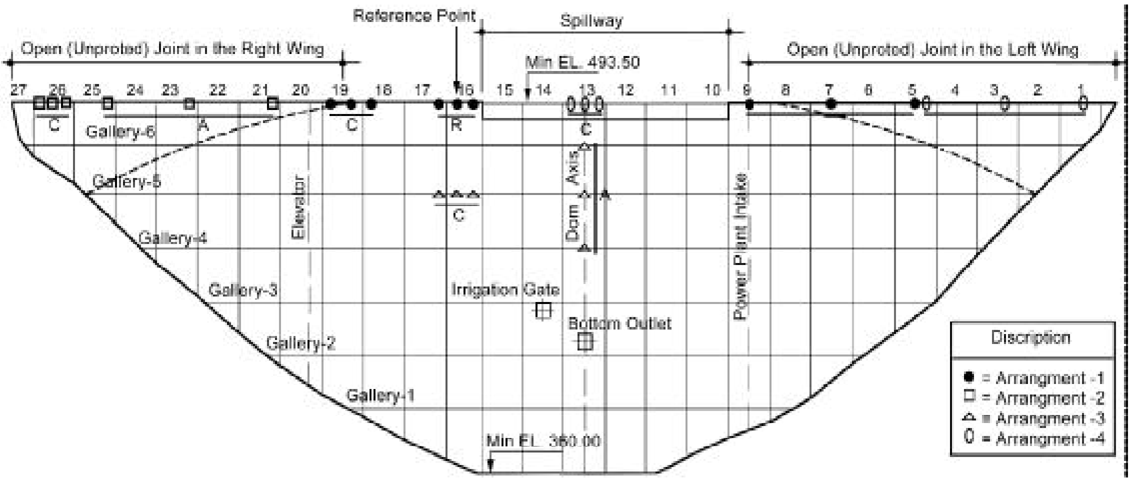


Figure 3. General layout of ambient vibration tests arrangements, and their corresponding recording stations for Shahid-Rajaee dam.

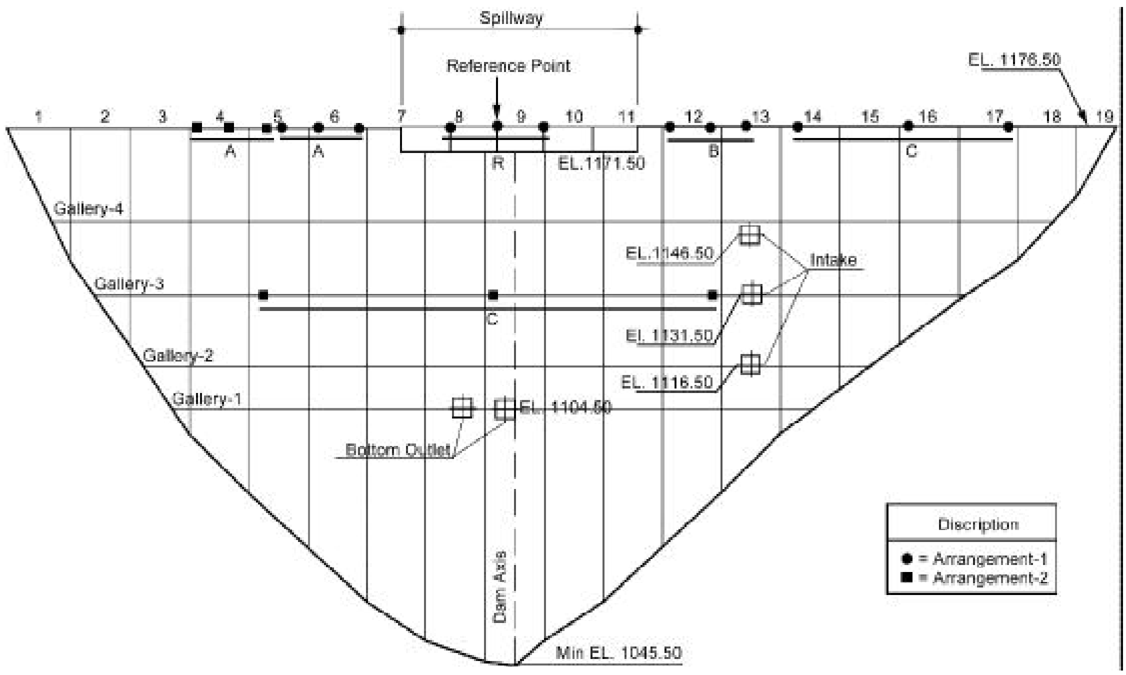


Figure 4. General layout of tests arrangements, and their corresponding recording stations for Saveh dam.

by conducting an extensive eigen-value solution of the system a priori. The stations were positioned on the maxima of modal displacements of the crest. Furthermore the data were classified according to groups described in section 2. This was so helpful to visualize many hidden modes absent in some loading conditions but present in others. To be cautious enough, a full usage of different Fourier spectra were made for several cross-checks. The method adopted and used in this research to determine the modes and corresponding frequencies are described in the flow-chart shown in Figure (5).

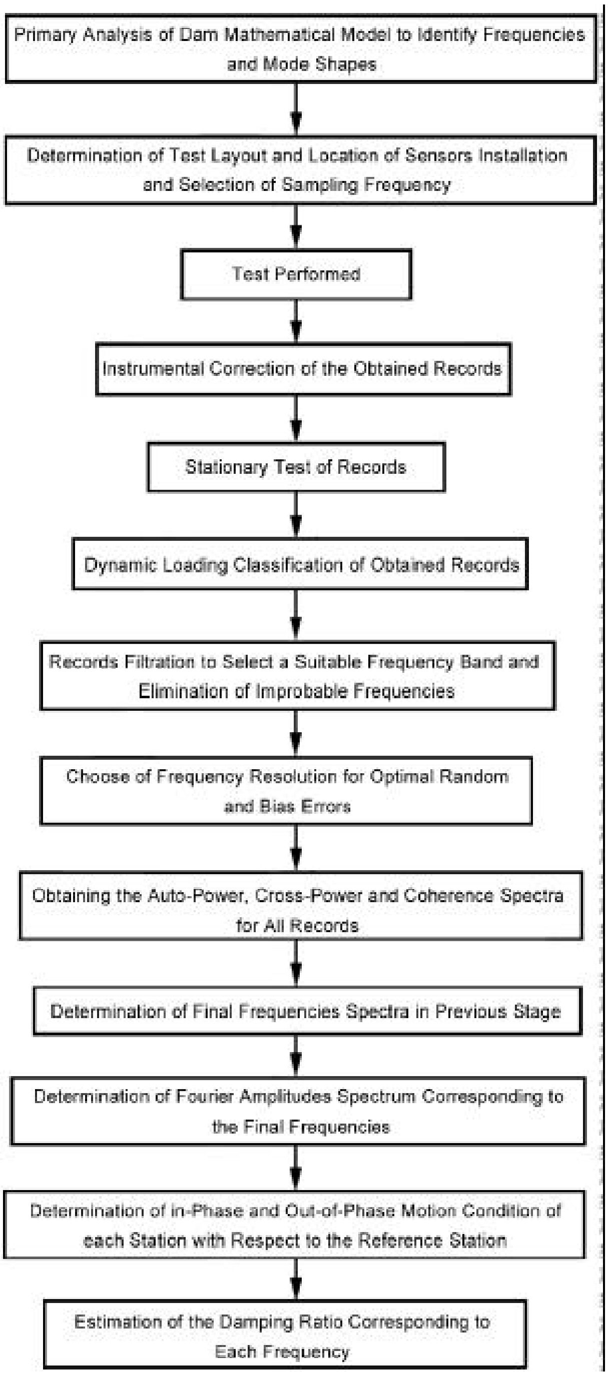


Figure 5. Algorithm of data processing in the ambient tests.

According to the above chart and to avoid any noise that may cause errors in determining the frequencies, the total duration time history has been divided into equal length windows that should not be less than twice the first period. The cross-power and the auto-power spectrum density functions (*CPS* and *APS*) have been calculated by Fourier transformation and the original frequencies have thus been detected.

To determine the mode shapes, the phase and coherency Fourier spectra have been used. Here by calculating the phase discrepancies of each point with respect to the reference station and, with observing the coherency spectrum, the modal displacement sign of each station point could be determined. There are cases in which the reference station does not enable clear phase distinction and thus other stations are examined to account for a clear and meaningful phase difference and coherency with the station concerned.

Thereafter, to determine the damping ratios at resonance frequencies, the half power method (using displacement function) have been employed satisfying the criteria bellow [11]:

$$G_{xx}(f) \sim constant;\ f - 3B_i \le f \le f_j + 3B_i \tag{1}$$

$$\xi_i \le 0.05 \tag{2}$$

$$B_e < 0.2B_i \tag{3}$$

$$f_i - f_{i-1} > 2(B_i + B_{i-1}) \tag{4}$$

Where G_{xx} is the auto-power spectrum of the excitation motion, ξ_i the modal damping, B_e the spectral resolution bandwidth, B_i the half power point of the spectral peak associated with the i^{th} mode and f is the corresponding frequency.

It is noted that the total record duration and the *FFT* sample points number (band resolution) are very important in determination of this ratio. The two types of error that may occur are [1]:

$$\varepsilon_r^2\left[G_{xx}\hat{}(f)\right] = \frac{1}{B_e.T_r} + \left(\frac{B_e^2.G_{xx}(f)}{24G_{xx}(f)}\right)^2 \tag{5}$$

$$\varepsilon_b\left[G_{xx}\hat{}(f_r)\right] = -\frac{1}{3} + \left(\frac{B_e}{B_r}\right)^2 \tag{6}$$

Where ε_r is the random error, ε_b is the bias error, $G_{xx}(f)$ is the true auto-power spectral value at frequency $f, G''_{xx}(f)$ is the true second derivative of $G_{xx}, \hat{G}_{xx}(f)$ is the estimate for $G_{xx}(f)$, and T_r is the total record length (in seconds) which is split into n_d smaller blocks of length T. f_r is the resonant frequency.

The bias error at a resonant peak will always be negative, resulting in a general underestimation of peak spectral values which in turn mean spurious higher damping ratios to be found from the half-power bandwidth method. However, bias error is negligible for the sufficiently small frequency resolution bandwidth. The total error is equal to:

$$\varepsilon_{total} = \left[(\varepsilon_b)^2 + \left(\varepsilon_r^2\right)^2 \right]^{\frac{1}{2}} \qquad (7)$$

and it can be concluded that this error whose components are proportional to $B_e^2, \frac{1}{B_e}$ respectively, shall be minimized. As both the random error and the bias error are functions of the total number of samples points for each window, the minimization could be carried out using an iterative process. In this work best solution was found using 512 points for most records of both series of dams tests.

4. Test Results

Some of test results in certain loading conditions are presented in Figures (6) and (7) for Shahid-Rajaee and Saveh dams respectively. It should be mentioned that the first and the second natural frequencies of the Shahid-Rajaee dam are not visible in these graphs as these correspond to either anti-symmetric wind, or day-time loading conditions which are not shown here.

Table (3) shows the modal frequencies and their corresponding damping. In Figures (8) and (9), the

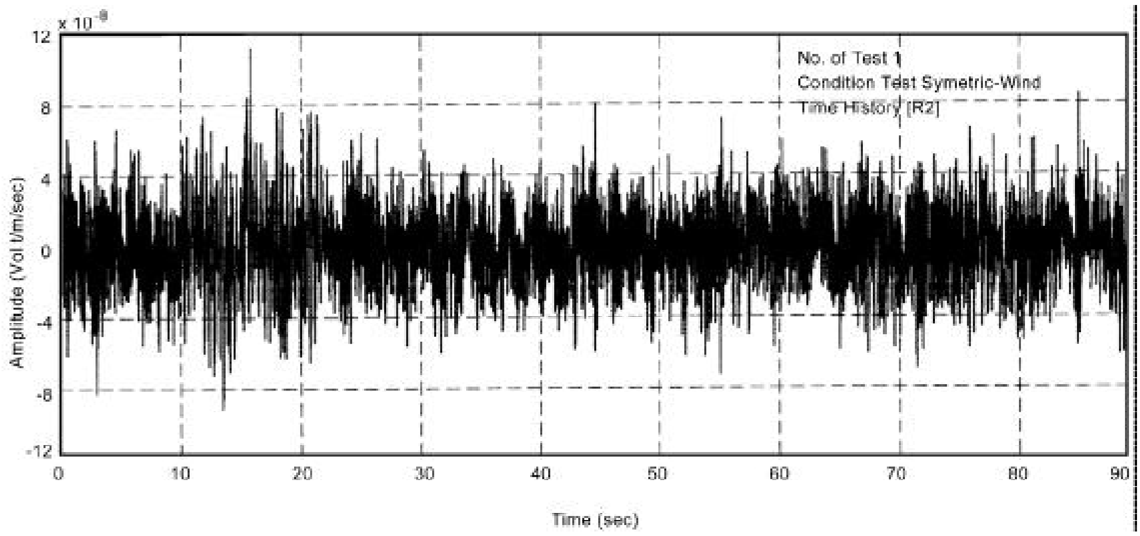


Figure 6a. Time history of station [R2] on crest midpoint (Symmetric wind condition-Shahid-Rajaee dam).

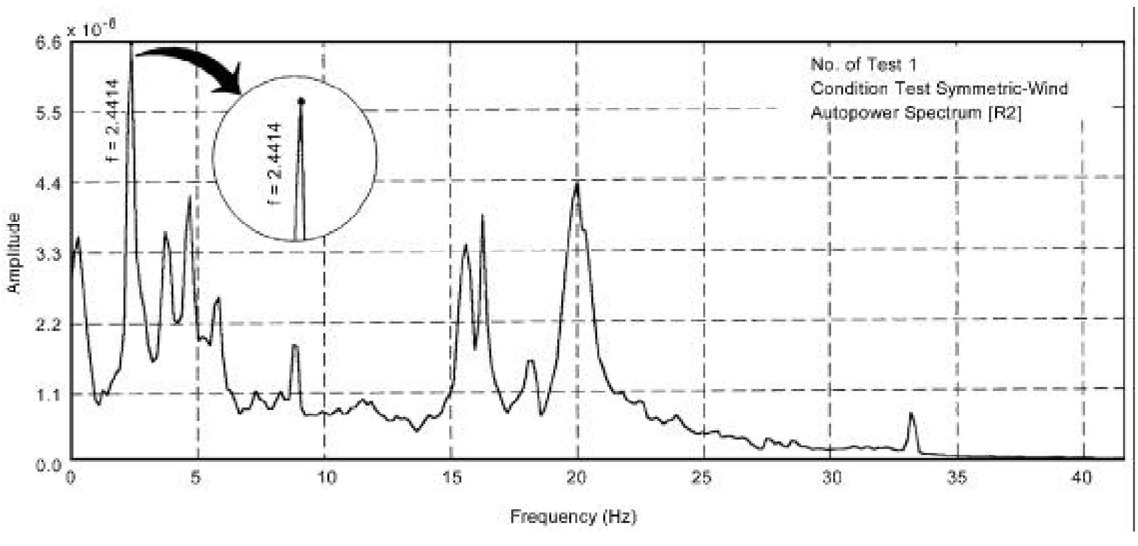


Figure 6b. Auto-power spectrum of station [R2] on crest midpoint (Symmetric wind condition-Shahid-Rajaee dam).

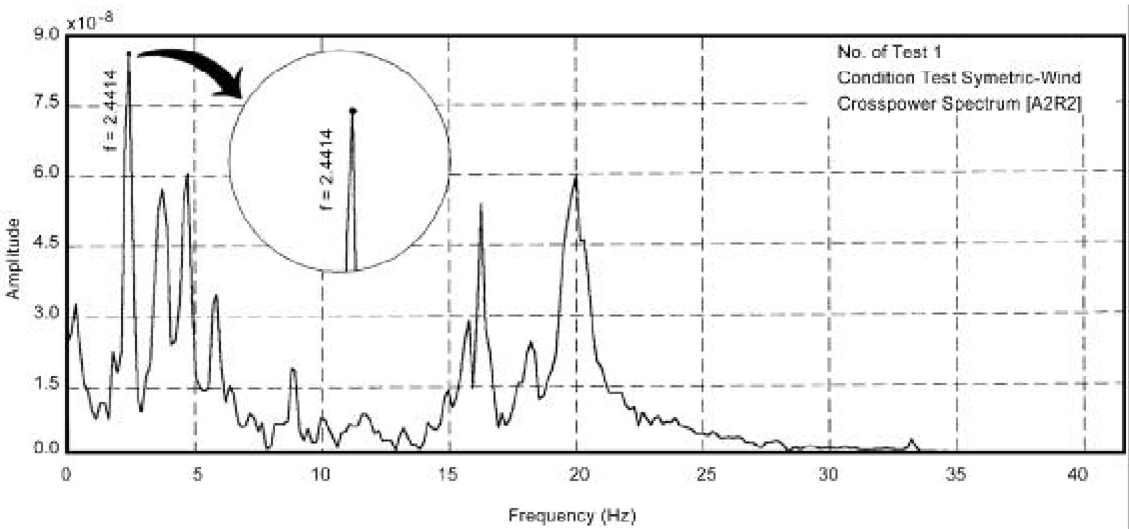


Figure6c. Cross-power spectrum between stations [A2 and R2] at crest (Symmetric wind condition-Shahid-Rajaee dam).

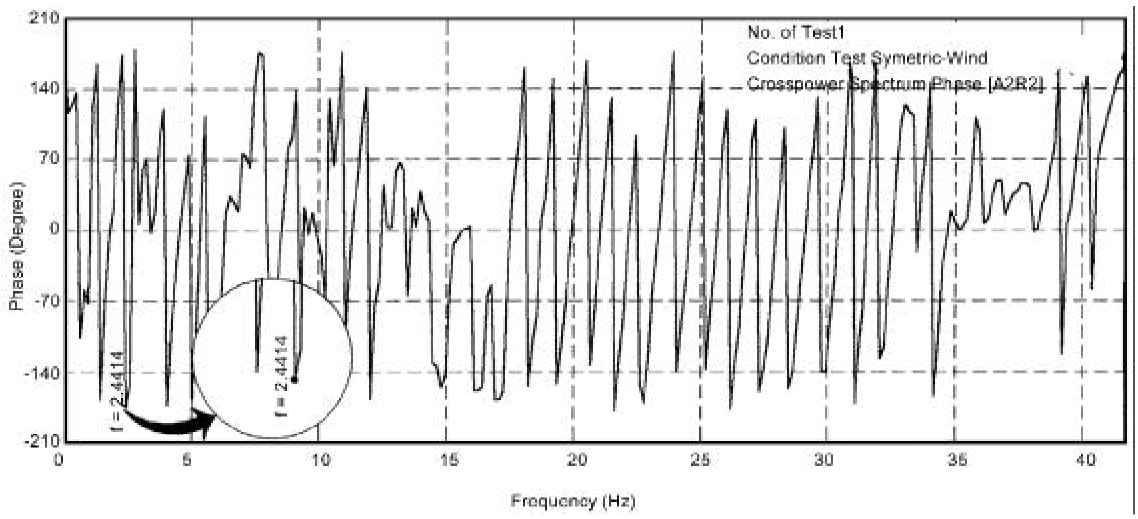


Figure 6d. Phase spectrum between stations [A2 and R2] at crest midpoint (Symmetric wind condition-Shahid-Rajaee dam).

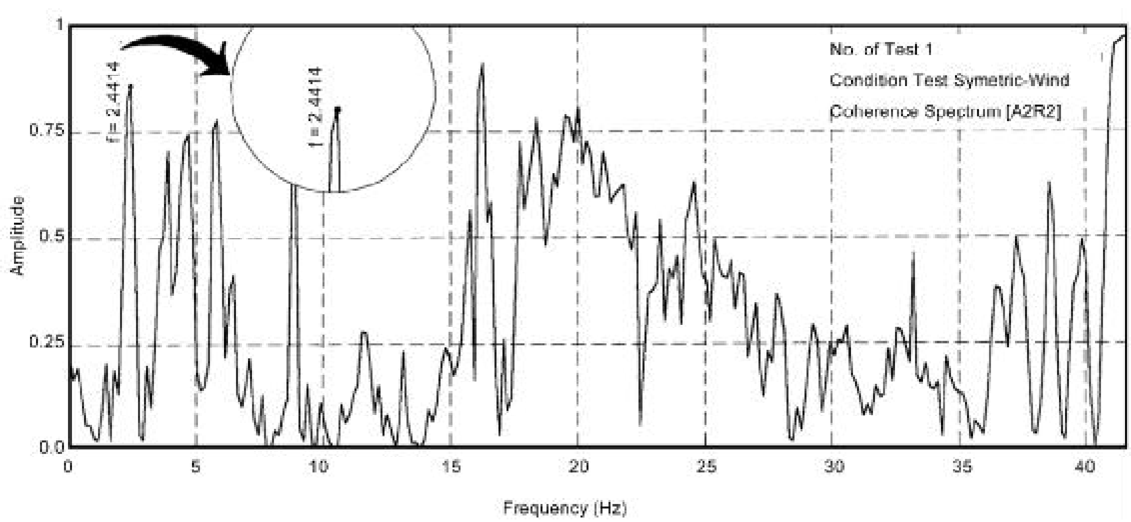


Figure 6e. Coherence spectrum between station [A2 and R2] at crest midpoint (Symmetric wind condition-Shahid-Rajaee dam).

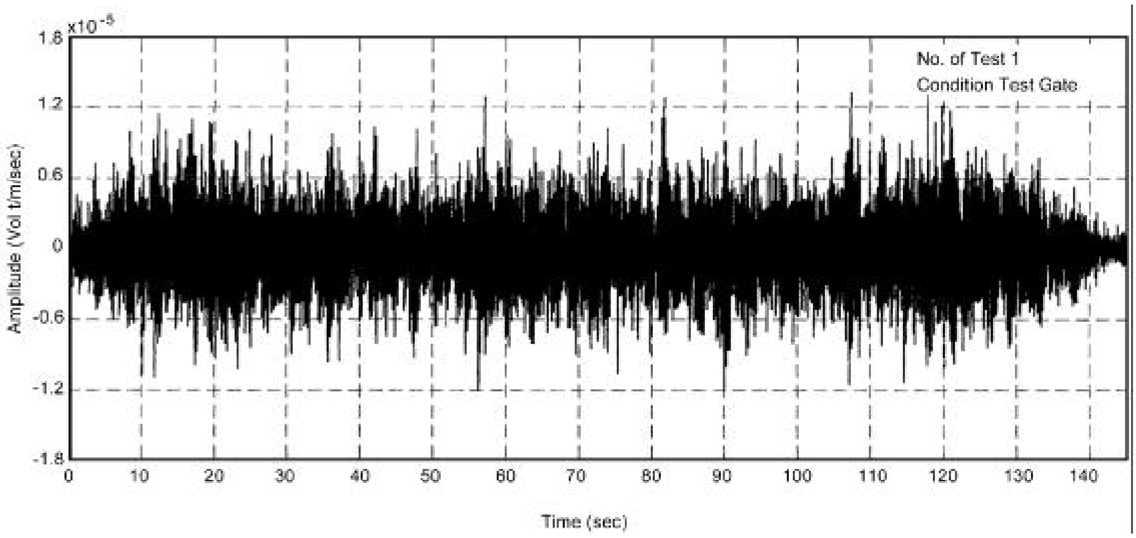


Figure 7a. Time history of station [R2] at crest midpoint (Gate condition-Saveh dam).

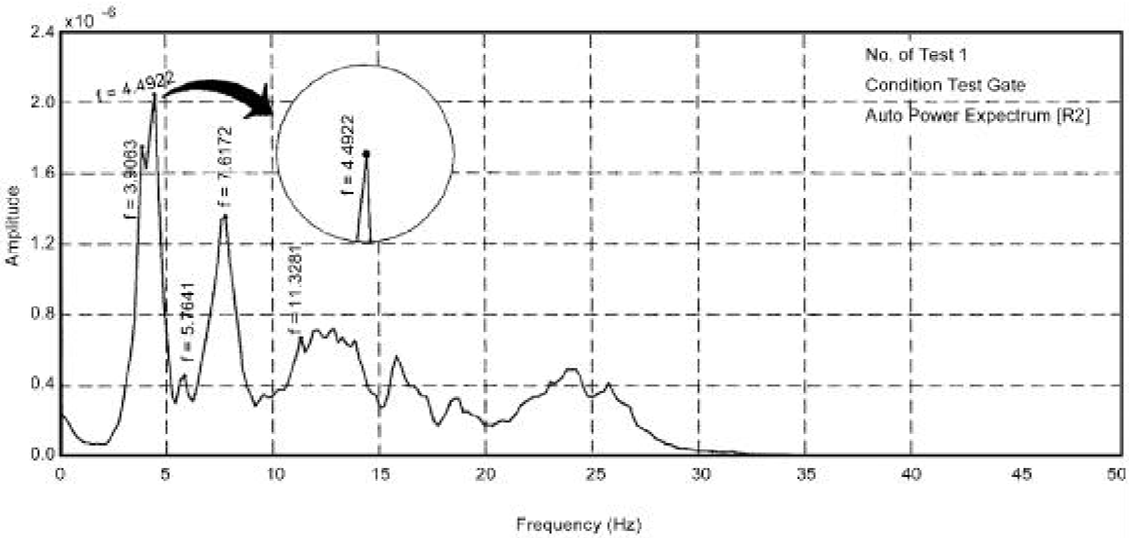


Figure 7b. Auto-power spectrum of station [R2] at crest midpoint (Gate condition-Saveh dam).

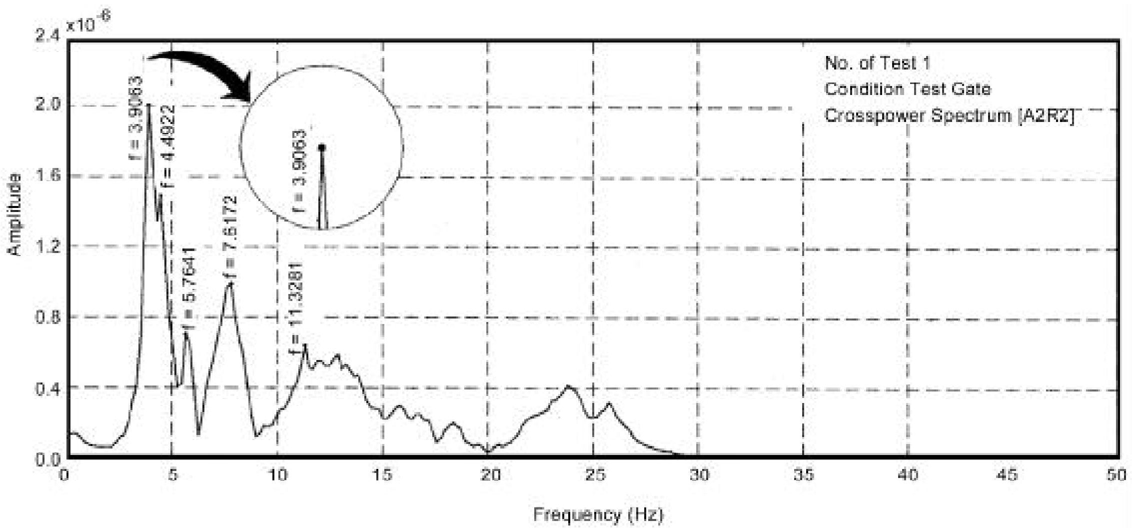


Figure 7c. Cross-spectrum between stations [A2 and R2] at crest (Gate condition-Saveh dam).

five first mode shapes and their corresponding frequencies have been presented for the two dams.

As seen in the case of Shahid-Rajaee dam, the frequencies are notably low particularly for the first two modes. This is due to the exceptional site and design conditions of this dam as mentioned earlier, i.e., thin left abutment, open vertical joints in the upper wings of the shell, and finally low modulus of deformation in most parts of the rock foundations as shown in Figure (10). Damping values are also shown in the Table (3). Of course these are corresponding to very low amplitude motion and thus not applicable to usual dynamic analyses.

Table 3. Frequencies and damping ratios obtained from tests for all modes.

Mode No.	Shahid Rajaee Dam		Saveh Dam	
	Frequency (Hz)	Damping (%)	Frequency (Hz)	Damping (%)
1	1.46	1.32	3.91	1.74
2	2.27	1.21	4.39	1.04
3	2.44	1.12	5.76	1.30
4	2.93	1.05	6.25	0.80
5	3.58	0.95	7.61	0.90

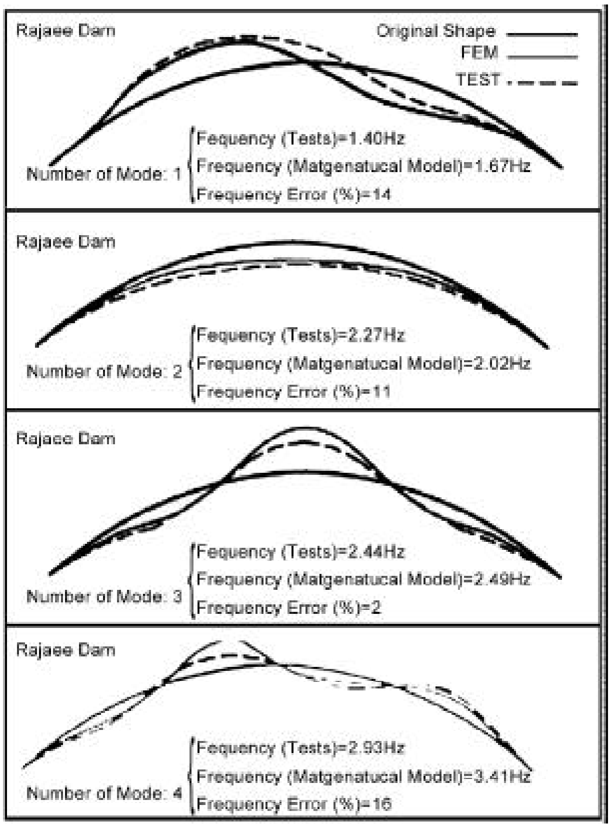


Figure 8. Undamped mode shapes and frequencies found by tests and computations for Shahid-Rajaee dam.

5. Mathematical Modeling and Its Results

5.1. System Equations

The governing system equations for the dam-reservoir-foundation are derived into two sets of ordinary differential equations after discretization by finite element techniques as,

$$M_s \ddot{U} + C_s \dot{U} + K_s U + F_o + F_I = 0 \tag{8}$$

for the dam-foundation substructure, and

$$M_f \ddot{P} + C_f \dot{P} + K_f P + F_o' + F_I' = 0 \tag{9}$$

for the reservoir. The matrices M_s and M_f are the mass, C_s and C_f are the damping, K_s and K_f are the stiffness of the dam-foundation and the reservoir substructures respectively. F_I and F_I' are the forces due to interactions between the dam and the reservoir. F_o and F_o' are external forces due to earthquake, U is the vector of nodal displacements for the dam and P is the vector of nodal hydrodynamic pressures for the reservoir.

In order to take the dynamic interaction of dam-reservoir-foundation system into consideration, it is necessary to solve the above two sets of equations simultaneously. The finite element model of the

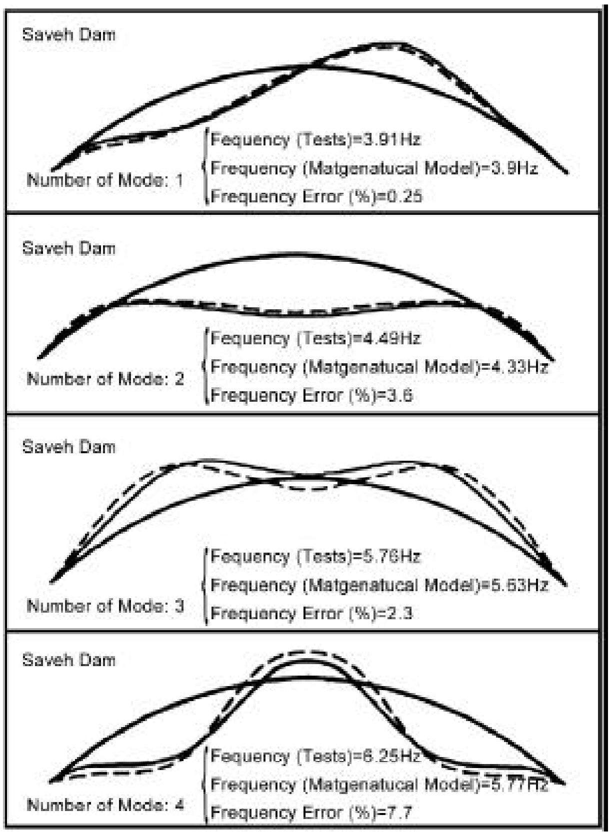
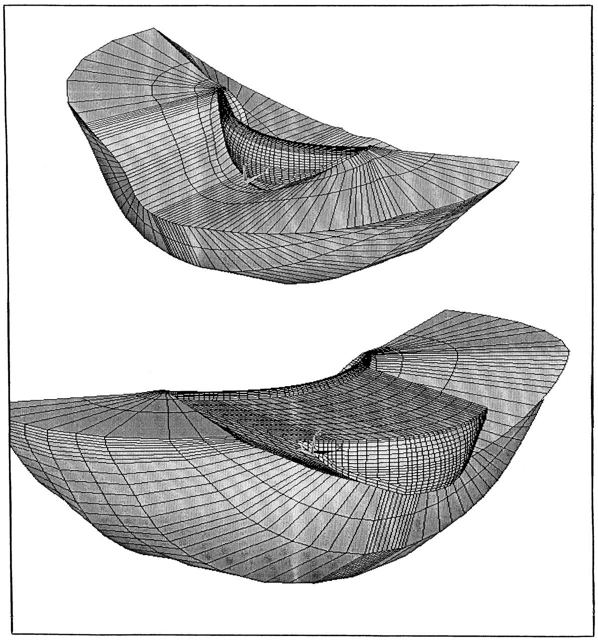
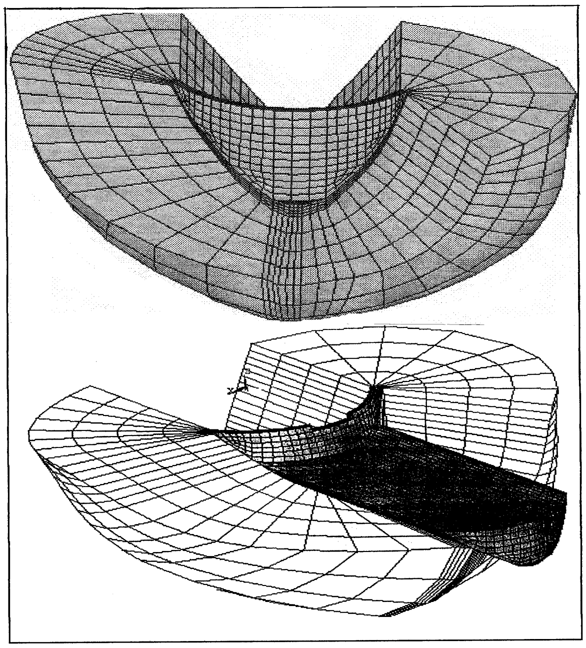


Figure 9. Undamped mode shapes and frequencies found by tests and computations for Saveh dam.



(Shahid-Rajaee Dam)

Figure 10. Mathematical model of empty and full reservoir for Shahid-Rajaee dam.



(Saveh Dam)

Figure 11. Mathematical model of empty and full reservoir for Saveh dam

system of dam-reservoir-foundation is illustrated in Figure (10) and (11) for the two dams systems.

5.2. Material and Model Properties

Features of the mathematical model for the two dams are as follows:

a. *Shahid-Rajaee Dam:*

- 983 isoparametric 20 node elements.
- Isotropic and linear elastic concrete and rock.
- Massless foundation.
- Reservoir of length equal to 300*m*.
- Radius of foundation is 1.5 times the dam height.
- Static elastic modulus of concrete: 22*GPa*
- Dynamic elastic modulus of concrete: 30*GPa*
- Poisson's ratio of concrete: 0.18
- Specific weight of concrete: 24kN/m^3
- Poisson's ratio of rock: 0.25
- Specific weight of rock: 24kN/m^3
- Static elastic modulus of rock are 20.7*GPa* in zone *I*, 16.3*GPa* in zone *II* and 7.4 in zone *III*, see Figure (12).
- The reservoir water is compressible (acoustic velocity in water $\approx$ 1440 *m/s*).

b. *Saveh dam:*

- 500 isoparametric 8 node elements
- isotropic and linear elastic concrete and rock.
- massless foundation.
- reservoir of length equal to 350*m*.
- Radius of foundation is 1.5 times the height of dam.
- Static elastic modulus of concrete: 30*GPa*
- Poisson's ratio of concrete: 0.2
- Specific weight of concrete: 24kN/m^3
- Poisson's ratio of rock: 0.25
- Specific weight of rock: 26kN/m^3
- Static elastic modulus of rock: 40*GPa*
- The reservoir water is compressible (acoustic velocity in water $\approx$ 1440*m/s*)

Natural frequencies and modes of each system have been computed for both cases of full and empty reservoir[1].

The analysis was performed by a program devised for coupled problems such as for fluid-structure interaction. The corresponding results are also presented in Figures (8) and (9) .

6. Discussion

Comparison of the results of tests versus mathematical model reveals that the error for the third mode is less than those of the first and the second modes. The first and the second modes might be so sensitive

1. Up to 18m below crest for Shahid-Rajaee dam and, up to 47.5m below crest for Saveh dam (semi full)

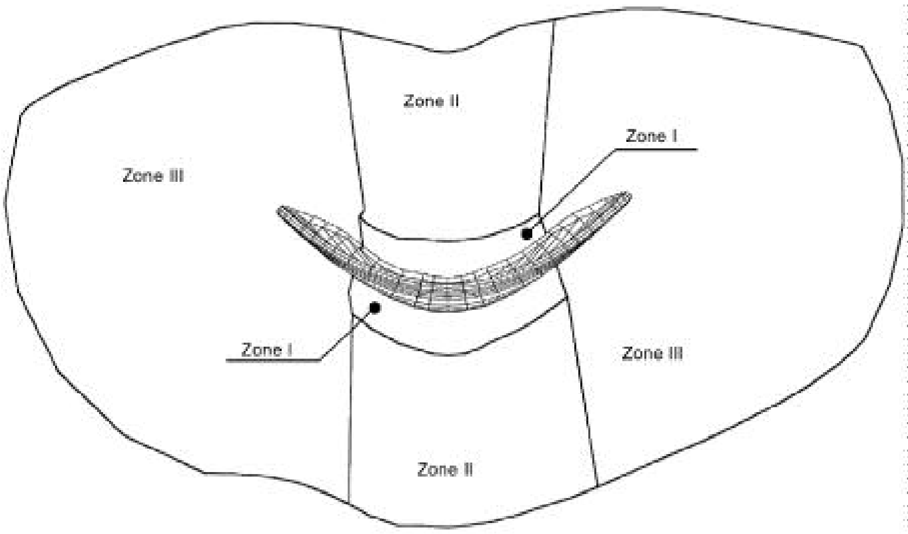


Figure 12. General view of the foundation geotechnical zones for Shahid-Rajaee dam.

to alternative arrangements of sensors that could well introduce errors in the measurements. Unfortunately the forced vibration tests which was performed afterwards could not catch these modes either as the generated forces at these frequencies were quite low. However the third mode and higher ones were sharply detected by those tests and thus verified. It is also expected that the location of sensors for the 3^{rd} mode have been more favorable.

It was also interesting that the usage of cross-power spectrum, sometimes neglected in similar studies, was indeed quite helpful for accurate determination of frequencies. It was also noted that in determining the damping ratio, longer records satisfied the error minimization requirements best. Furthermore, for determination of many hidden and important modes it was found effective to utilize artificial exciting such as opening and closing the dam outlet gates. Finally it could be said that using the ambient vibration test proves to be very useful in determination of primary modes.

With respect to the adopted method of system identification (introduced in Figure (5)), it could be stated that the method could overcome considerably the serious shortcomings caused by the low number of sensors available in monitoring large structures as these dams. However the method could be presumably much more accurate once enough sensors and facilities are available.

7. Conclusions

1. A complete algorithm of dynamic identification for large structural systems is devised in order to enable testing of dams with rather small number of testing facilities.
2. As it can be observed there are some discrepancies between the mathematical model and the test results. This problem would have certain impacts on the design assumptions taken for these dams. However these are not considerable and could be minimized when appropriate massive foundation and actual material properties (not necessarily the design values) could be employed. This was later on done through the process of uncertainty variable optimization, a subject of the forthcoming paper.
3. Finally the 1^{st} dynamic tests of two huge Iranian dams were conducted for design verification with good success using rather limited facilities. It is recommended that for future works more extensive hardware should be provided to enhance the reliability of these tests. The authors feel confident that such tests are going to be used for seismic safety evaluation of other existing dams as well as for design enhancement of new dams in Iran.

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