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EVALUATION OF DISCREPANCIES BETWEEN THE DYNAMIC CHARACTERISTICS OF MATHEMATICAL AND PROTOTYPE MODELS OF CONCRETE ARCH DAM

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SUMMARY

Conducting experimental investigations for recognition of concrete dams behavior under dynamic loads e.g. earthquakes or natural phenomena is of paramount importance. This issue may be considered as one of the most strategic goals in the branch of water industry of our nation.
In the present research characteristic and dynamic behavior of a concrete arch dam (Shahid Rajaee and Saveh Dam) have been investigated under the ambient and forced vibration tests, and the results have been compared with those of the mathematical model. Using a consistent algorithm developed in this research we processed the records obtained from the tests performed.
In analysis of the mathematical model of the whole dam-reservoir-foundation system effects of different non-deterministic parameters as equivalent (average) modulus of elasticity of concrete and rock, water compressibility, foundation mass distribution pattern, Poisson ratio of concrete and rock, etc. were studied. The target of the sensitivity study was based on natural frequencies. The important results, which were obtained, show that the assumption of water incompressibility would strongly influence the natural frequencies of the system particularly on higher modes. For better calibration of the mathematical model a frequency optimization process was performed.
As a result of this investigation the five first modes of the system were obtained from the ambient and forced vibration tests. These proved a good agreement with those of the mathematical model.

INTRODUCTION

Vibration test is one of the most suitable methods to determine the dynamic characteristics of structures such as dams and specially to measure the first modes response which could not easily be caught by other methods i.e. , forced tests.
In 1979 Wulff, presented a paper about ambient vibration in the Crystal Spring dam in U.S.A showing good results on the identification of lower mode shapes and their damping ratio [12].

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In 1982 Clough presented vibration tests results for Techi Dam in Taiwan .Their important results enabled an identification of first modes and a comparison with theoretical solution [2].
In 1990 a paper was presented by Serven et al, on dynamic tests and its comparison with mathematical model. The results were in terms of stresses and hydrodynamics pressure [3].
Further in 1994 also Duron et al presented a paper on different dynamic vibration tests (forced & ambient) on the Big-Creek dam. They carried out an accurate identification on symmetric and anti-symmetric first and second modes [4].
In 1998 Daniell and Taylor presented a paper, the main result of which was the precise confirmation of ambient vibration test results with modal analysis methods [6].
This paper is a summary of tremendous works of experiment carried out .An introduction to the works is given in reference [7].

DESCRIPTION OF DAMS TESTS

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 0.51g) 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.

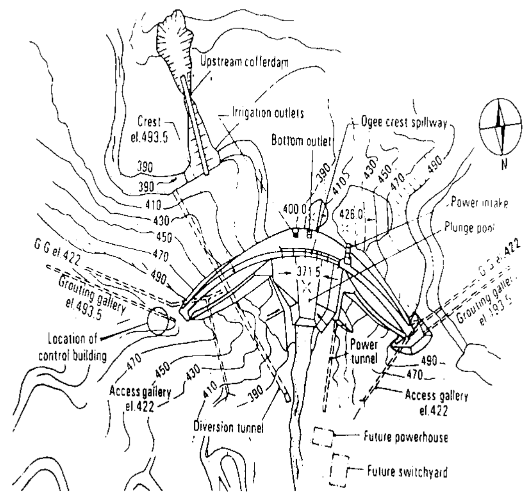


Fig. 1 : General view of Shahid Rajaee-dam

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.

Table 1. Description of Shahid-Rajaee dam

Volume of reservoir	165 MCM
Crest length	430 m
Height above foundation	138 m
Thickness of crown	7 m
Thickness of foundation	26 m
Crest length to maximum dam height ratio	3.1
Spillway type	Free over-fall crest spillway
Spillway maximum design discharge	2050 m^3/sec

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

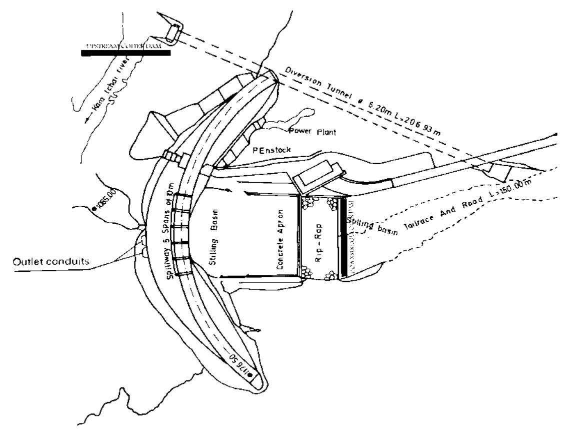


Fig. 2 : General view of Saveh dam

Table 2. Description of Saveh dam

Volume of reservoir	290 MCM
Crest length	265 m
Height above foundation	128 m
Thickness of crest	6 m
Thickness of foundation	25 m
Crest length to maximum dam height ratio	2.1
Spillway type	Free over-fall crest spillway
Spillway maximum design discharge	872 m^3/sec

AMBIENT VIBRATION TESTS AND LOADING CLASSIFICATION

Ambient vibration tests were conducted on the Shahid-Rajaee and the Saveh dams using IIEES testing facilities by the authors 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 locations 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 A1, A2, and A3, or R1, R2, and R3.

Fig. 3. General layout of tests arrangements and their corresponding recording stations for Rajaee dam

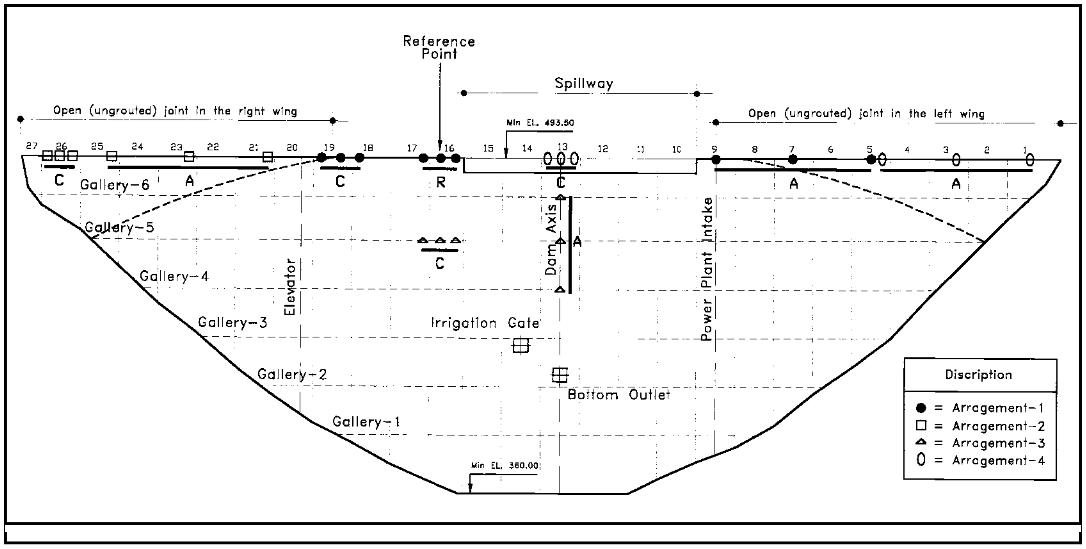


Fig. 4. General layout of tests arrangements and their corresponding recording stations for Saveh dam

METHOD OF DATA PROCESSING

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 condition. These loading conditions are shown in table 3.

Table 3 – Records grouping

No. Of Group	Name Of Group	Condition Of Record registration	Record that have been produced(minute)	
			Rajaee dam	Saveh dam
1	Day-time	load due to ambient noise and wind	49.5	58
2	Night-time	corresponding to 7 P.M. to 7 A.M(lower ambient noise level dominated	40.5	48

		by wind)		
3	Anti-symmetric wind direction	prevailing the ambient noise	10.5	15
4	Symmetric wind direction	prevailing the ambient noise	3	6
5	Gate Opening	shock load with much higher amplitude than those of noise and wind	3	3

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.
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 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 mention above. 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 reference [13].
Table 4 shows the modal frequencies and their corresponding damping. In Figure 5 the four 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. Damping values are also shown in the Table 4. Of course these are corresponding to very low amplitude motion and thus not applicable to usual dynamic analyses.

Table 4. Frequencies & 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

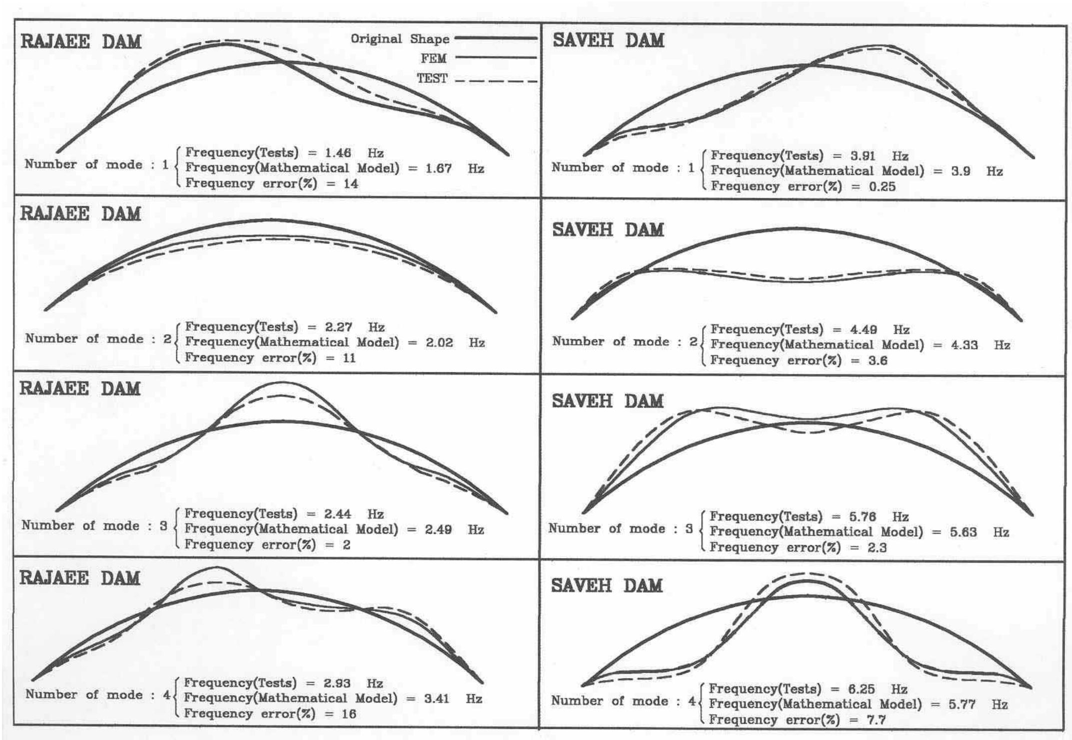


Fig. 5. Undamped mode shapes and frequencies found by tests and computations for Shahid-Rajaee and Saveh dams

MATHEMATICAL MODELING AND ITS RESULTS

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,

$$M_S \ddot{U} + C_S \dot{U} + K_S U + F_o^{'} + F_I^{'} = 0$$

for the dam-foundation substructure, and

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

for the reservoir. The matrices Ms and Mf are the mass, Cs and Cf are the damping, Ks and Kf are the stiffness of the dam-foundation and the reservoir substructures respectively. FI and F'I are the forces due to interactions between the dam and the reservoir. Fo 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.

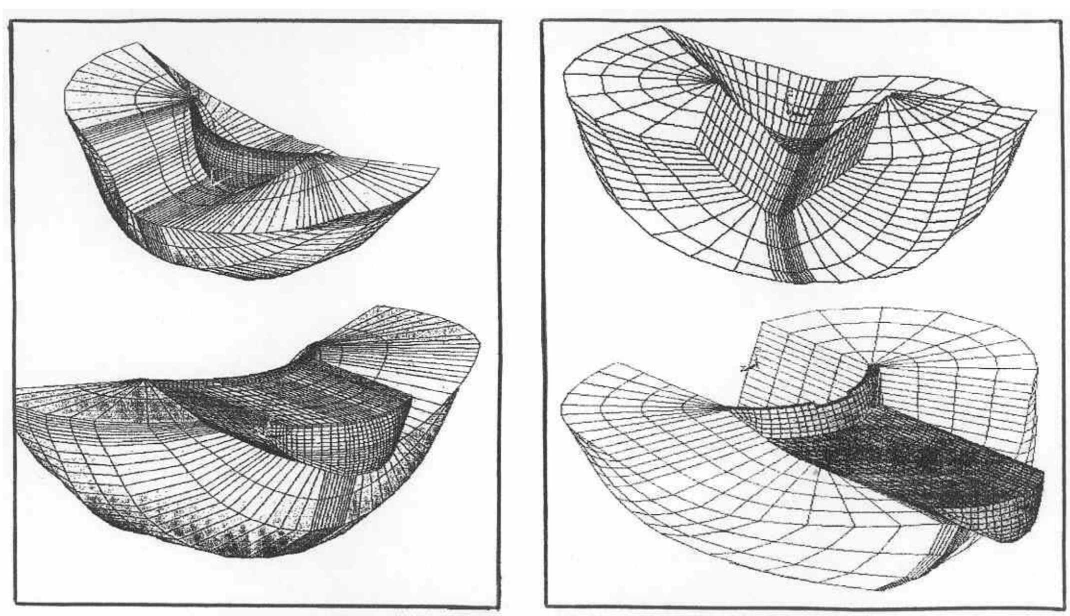
In order to take the dynamic interaction of dam-reservoir-foundation system into consideration, it is necessary to solve the above two sets of equations simultaneously. The finite element model of the system of dam-reservoir-foundation is illustrated in Figure 6.

Material and Model Properties

Features of the mathematical model for the two dams are as shown in table 5.

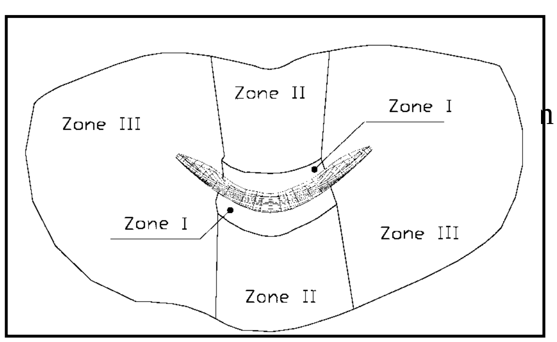
Table 5- Features of the mathematical model for Rajaee and Saveh Dams

Shahid-Rajaee dam	Saveh dam
983 isoparametric 20 node elements.	500 isoparametric 8 node elements
isotropic and linear elastic concrete and rock	isotropic and linear elastic concrete and rock
mass less foundation	mass less foundation
Reservoir of length equal to 300 m	reservoir of length equal to 350 m
Radius of foundation is 1.5 times the dam height	Radius of foundation is 1.5 times the height of dam
Static elastic modulus of concrete : 22 GPa	Static elastic modulus of concrete : 30 GPa
Dynamic elastic modulus of concrete : 30 GPa	Dynamic elastic modulus of concrete : 35 GPa
Poisson's ratio of concrete : 0.18	Poisson's ratio of concrete : 0.2
Specific weight of concrete : 24 kN/m³	Specific weight of concrete : 24 kN/m³
Poisson's ratio of rock : 0.25	Poisson's ratio of rock : 0.25
Specific weight of rock : 24 kN/m³	Specific weight of rock : 26 kN/m³
Static elastic modulus of rock are 20.7 GPa in zone I , 16.3 GPa in zone II and 7.4 in zone III (Figure 7)	Static elastic modulus of rock : 40 GPa
The reservoir water is compressible (acoustic velocity in water ≈ 1440 m/s)	The reservoir water is compressible (acoustic velocity in water ≈ 1440 m/s)



Rajaee dam Saveh dam

Fig. 6: Mathematical model of empty & full reservoir for two dam



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Natural frequencies and modes of each system have been computed for both cases of full and empty reservoir[3]. The analysis was performed by a program devised for coupled problems such as for fluid-structure interaction. The corresponding results are also presented in Figure 5.

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 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 3rd 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 [13], 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.

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 [13].

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. In the analysis of mathematical model the dam and its foundation together with the reservoir were modeled and a number of different parameters like modulus of elasticity of concrete and rock, water compressibility, the effect of foundation mass, Poisson's ratio of concrete and rock on the natural frequencies were also investigated. The most important conclusion was that, the assuming of incompressibility strongly influence on the natural frequencies of the system in higher modes.

4. To make better comparison between the mathematical model and the prototype, a frequency optimization was performed. I.e. by developing a synthetic optimized algorithm and by utilizing two important parameters of uncertainty (modulus of elasticity of concrete and rock) equivalent elasticity modulus was obtained which minimized the defined goal function. The most important achievement of

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

this part was the assumption of considering the concrete as orthotropic which has diminished the value of goal function relative to the isotropic state of concrete and in fact has minimized it.

5. Finally the first 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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