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Experimental evaluation of crack effects on the dynamic characteristics of a prototype arch dam using ambient vibration tests

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Abstract. The aim of the study is to determine the modal parameters of a prototype damaged arch dam by operational modal analysis (OMA) method for some damage scenarios. For this purpose, a prototype arch dam-reservoir-foundation model is constructed under laboratory conditions. Ambient vibration tests on the arch dam model are performed to identify the modal parameters such as natural frequency, mode shape and damping ratio. The tests are conducted for four test-case scenarios: an undamaged dam with empty reservoir, two different damaged dams with empty reservoirs, and a damaged dam with full reservoir. Loading simulating random impact effects is applied on the dam to crack. Cracks and fractures occurred at the middle of the upper part of the dams and distributed through the abutments. Sensitivity accelerometers are placed on the dams' crests to collect signals for measurements. Operational modal analysis software processes the signals collected from the ambient vibration tests, and enhanced frequency domain decomposition and stochastic subspace identification techniques are used to estimate modal parameters of the dams. The modal parameters are obtained to establish a basis for comparison of the results of two techniques for each damage case. Results show that approximately 35-40% difference exists between the natural frequencies obtained from Case 1 and Case 4. The natural frequencies of the dam considerably decrease with increasing cracks. However, observation shows that the filled reservoir slightly affected modal parameters of the dam after severe cracking. The mode shapes obtained are symmetrical and anti-symmetrical. Apparently, mode shapes in Case 1 represent the probable responses of arch dams more accurately. Also, damping ratio show an increase when cracking increases.

Keywords: arch dam; ambient vibration test; damage scenario; enhanced frequency domain decomposition; stochastic subspace identification; modal parameter identification; operational modal analysis.

1. Introduction

Arch dams have multiple benefits, however, they can also present a risk to public safety and economic infrastructure. This risk arises from the possibility of dam failure and the ensuing damage. Although dam failures are infrequent; some factors such as age, construction deficiencies, inadequate maintenance and seismic or weather events contribute to the possibility (Nic 2008). Especially, the failure of dams retaining large quantities of water poses a serious threat to life and property during earthquakes. Consequently, the safety of dams has always been of great concern because failure of these structures can cause great disasters, involving the potential for catastrophic human and

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material losses.

It is known that damages considerably affect structural safety of dams (Noriziaan 1995, Oliveira and Faria 2006, Zhong *et al.* 2009). Damages of arch dams occur when tensile stresses exceed the concrete's strength (Valliappan *et al.* 1999, JianWen *et al.* 2009), and the presence of cracks in an arch dam are evidence. The cracks may change due to the physical properties of the structure such as stiffness, damping, mass and boundary conditions. The changes in the stiffness or flexibility of the structure cause the changes in the modal properties (Sánchez 2005). Operational Modal Analysis (OMA) of vibration response signals is a popular method to determine modal parameters (Brincker *et al.* 2003, Herlufsen *et al.* 2005). Some previous researches have investigated the dynamic behaviour of large dams and prototype dam models using Operational Modal Analysis (Zhou *et al.* 2000, Darbre and Proulx 2002, Alves and Hall 2006, Wang and Li 2006, 2007, Wang and He 2007, Sevim *et al.* 2010, Sevim *et al.* 2011a, 2011b).

The purpose of this study is to investigate the effect of the cracks on the modal parameters of a prototype arch dam using Operational Modal Analysis. For this aim, a prototype concrete arch dam is constructed under the laboratory conditions and ambient vibration tests are conducted under different damage scenarios. Enhanced Frequency Decomposition Domain (EFDD) technique in the frequency domain and Stochastic Subspace Identification (SSI) technique in the time domain are used to extract natural frequencies, mode shapes and damping ratios for each damage scenario.

2. Formulation of OMA techniques

In the absence of input force measurements, ambient excitation does not lend itself to Frequency Response Function (FRFs) or Impulse Response Function (IRFs) calculations. A modal identification procedure uses solely output data. Several modal parameter identification techniques are available for extracting these modal parameters. The parameter identification techniques are the Operating Vectors Method, the Complex Exponential Method, the Polyreference Time Domain Method, the Enhanced Frequency Domain Decomposition (EFDD) and various Stochastic Subspace Identification (SSI) techniques. This study extracts modal parameters from experimental measurements using the Enhanced Frequency Domain Decomposition (EFDD) and Stochastic Subspace Identification (SSI) techniques.

2.1 Enhanced Frequency Domain Decomposition (EFDD) technique

In the EFDD technique, the relationship between the unknown input $x(t)$ and the measured responses $y(t)$ has the expression (Ewins 1984, Brincker *et al.* 2000, Bendat and Piersol 2004, Jacobsen *et al.* 2006)

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

where $G_{xx(jw)}$ is the Power Spectral Density (PSD) matrix of the input; $G_{yy(jw)}$ is the PSD matrix of the responses; $H(jw)$ is the Frequency Response Function (FRF) matrix, and * and superscript T denote complex conjugates and transpositions, respectively. The solution of Eq. (1) appears in detail in the literature (Brincker *et al.* 2000).

2.2 Stochastic Subspace Identification (SSI) method

Stochastic Subspace Identification (SSI) is an output-only method that directly works with time data without the need to convert time domain measurements to auto-correlations or to frequency spectra. The method is especially suitable for operational modal parameter identification, and the literature provides a detailed technical overview (Van Overschee and De Moor 1996, Peeters and DeRoeck 1999, Peeters 2000).

The model for vibrating structures can be defined by a set of linear, constant coefficient and second-order differential equations (Peeters and DeRoeck 1999)

$$M\ddot{U}(t) = C_*\dot{U}(t) + KU(t) = F(t) = B_*u(t) \tag{2}$$

where M, C_*, K are the mass, damping and stiffness matrices; $F(t)$ is the excitation force, and $U(t)$ is the displacement vector at continuous time (t). Notably, the force vector $F(t)$ is factorized into a matrix B_* describing the inputs in space and a vector, $u(t)$. In the SSI method, the equation of dynamic equilibrium Eq. (2) is converted to the more suitable discrete-time stochastic state-space model (Peeters and DeRoeck 1999).

3. Operational Modal Analysis of a prototype arch dam

3.1 Design and construction of type-1 arch dam

In this study, a Type-1 arch dam, which is one of five arch dam types suggested at the "Arch Dams" Symposium in England in 1968 (Arch Dams 1968), is selected for the application. The other four type dams have different geometrical properties such as double curvature, different centre angle and different radius. However, the Type-1 arch dam has a single curvature, constant radius and constant central angle which the geometrical properties are shown in Fig. 1. In addition, it has 6 unit height and constant 0.6 unit widths. So the construction of the Type-1 arch dam is more easily to construct than the other four type dams. To construct the prototype model, one selected unit is 10 cm. Therefore, the model dam's height and crest width are 60 cm and 6 cm, respectively. Development of a Type-1 arch dam considers reservoir and foundation. The reservoir of the dam is extended as 3H

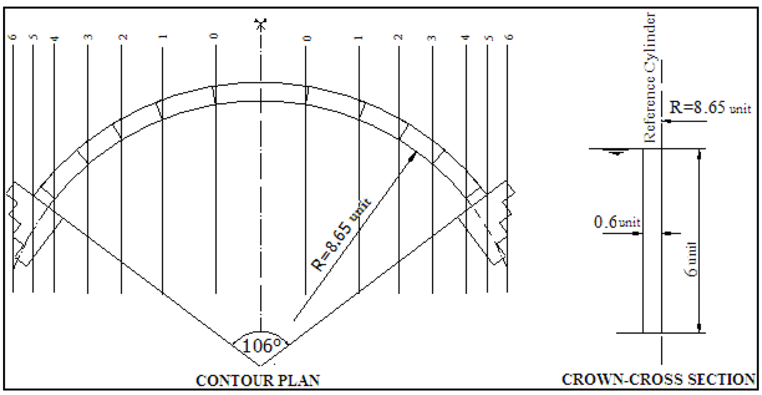


Fig. 1 Geometrical properties of Type-1 arch dam

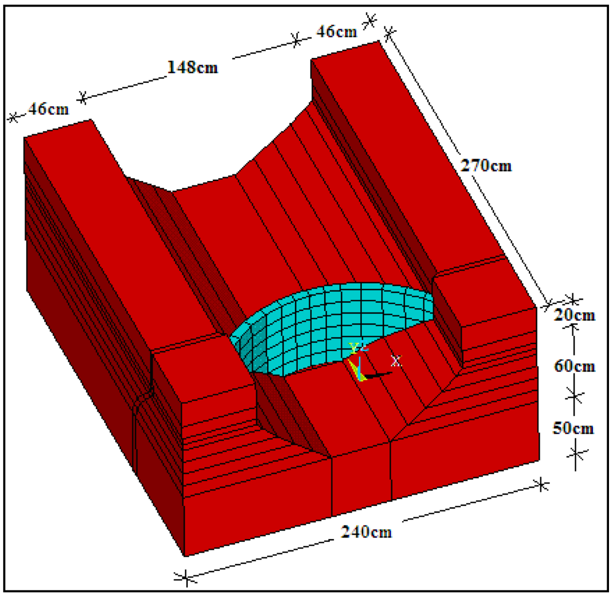


Fig. 2 3D representation of a Type-1 arch dam-reservoir-foundation model

Fig. 3 Photographs of a Type-1 arch dam-reservoir-foundation model

(H: dam height); the foundation of the dam is an extension of about H in the downstream and downward directions, and is an extension of the reservoir's length in the upstream direction. Such modelling is appropriate to represent the dynamic behaviour of concrete arch dams (USACE 2003). Definitive dimensions of Type-1 arch dam-reservoir-foundation models are shown in Fig. 2.

Some view of the construction of a Type-1 arch dam-reservoir-foundation system considering the dimensions given in Figs. 2 and 3. Construction of the model system consumes approximately 6.5 m^3 concrete. The model's construction required five days and three workers.

Fig. 4 Measurement equipment used for the ambient vibration tests

3.2 Ambient vibration tests and modal parameter identification

Ambient vibration tests are conducted on the Type-1 arch dam model to determine its modal parameters such as natural frequencies, mode shapes and damping ratios. An important aspect of the vibration tests is the selection of measurement equipment (especially accelerometer type), and appropriate measurement setup, including the best measurement time and frequency span. Since they are variable when considering structure type, measurement equipment and setup used for vibration testing of a small structure are not appropriate for vibration testing of a large structure. In the ambient vibration tests, B&K 3560 data acquisition system and B&K 4507-B005-type uni-axial accelerometers are used (Fig. 4). These accelerometers have 1000 mV/g sensitivity and 0.1-6000 Hz frequency span. During the tests, the frequency span is selected as 0-1600 Hz according to finite element results, and eleven accelerometers are located at the crest of the dam, as shown in Fig. 5. Measurements are made during five-minute intervals, and small impact effects provided as excitations. Tests occurred after the poured concrete aged for 10 months. Signals obtained from the tests are recorded and processed by the commercially software PULSE (2006) and OMA (2006), respectively. EFDD and SSI techniques are used to extract the modal parameters of the dam.

The following four cases are considered during the ambient vibration tests:

- Case 1: Undamaged dam model with empty reservoir,
- Case 2: Minor-damaged (some minor damage to dam by random impact loadings) dam model with empty reservoir,
- Case 3: Severely damaged (additional damage producing cracks in the dam's body) dam model with empty reservoir,
- Case 4: Severely damaged dam model with reservoir filled (water flowed and oozed slowly from cracks in the dam's body).

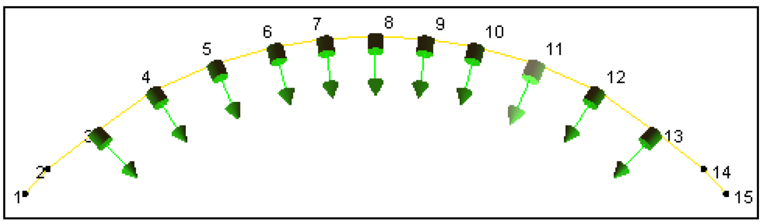


Fig. 5 Locations of accelerometers used in the ambient vibration tests

3.2.1 Case 1

Case 1 represents measurements from the undamaged dam model with an empty reservoir. Photographs from the first test are shown in Fig. 6. Singular values of spectral density matrices (SVSDM) of the data set and the average of auto spectral densities (AASD) of the data set from the EFDD technique are given in Fig. 7. A stabilization diagram of estimated state space models (SDESSM) and selection of modes (SM) from the SSI technique are presented in Fig. 8. As seen in Figs. 7 and 8, more than thirteen natural frequencies from the empty reservoir arise from the 0-1600 Hz frequency span.

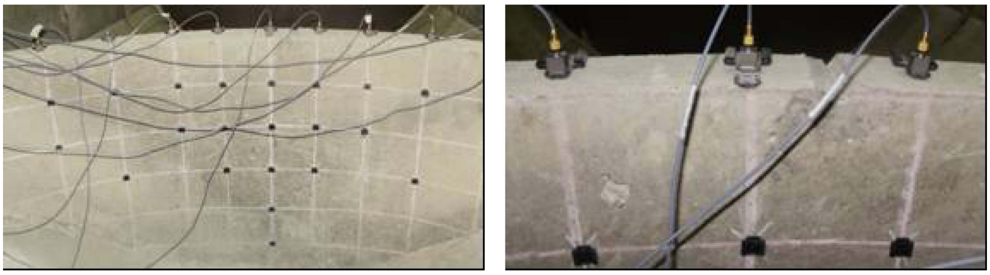
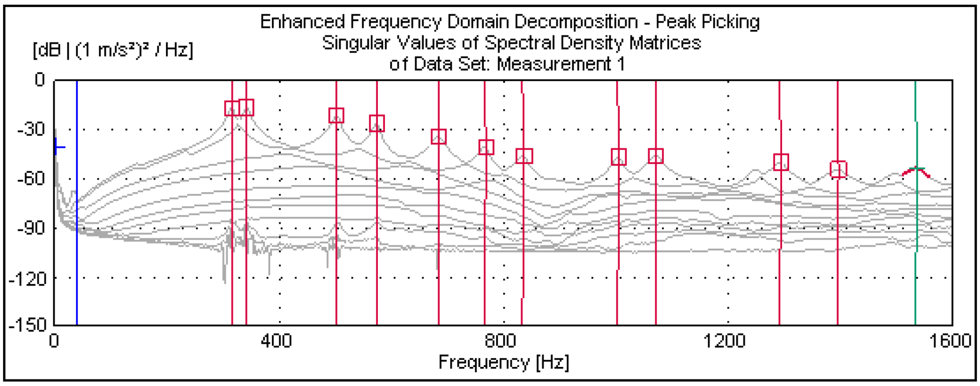
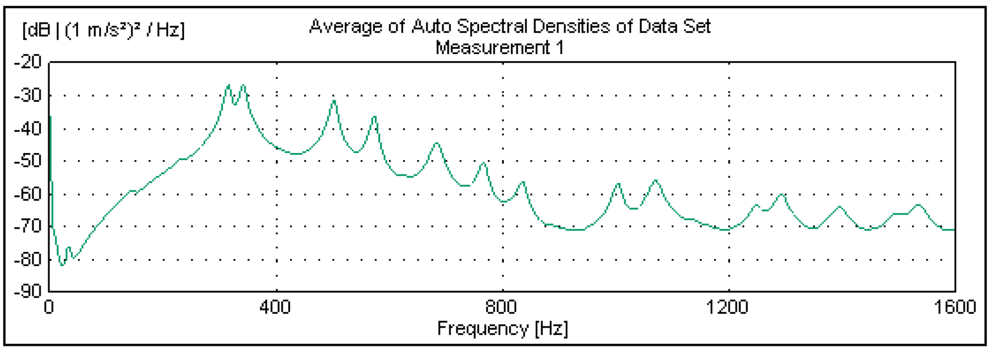


Fig. 6 Photographs from the first test

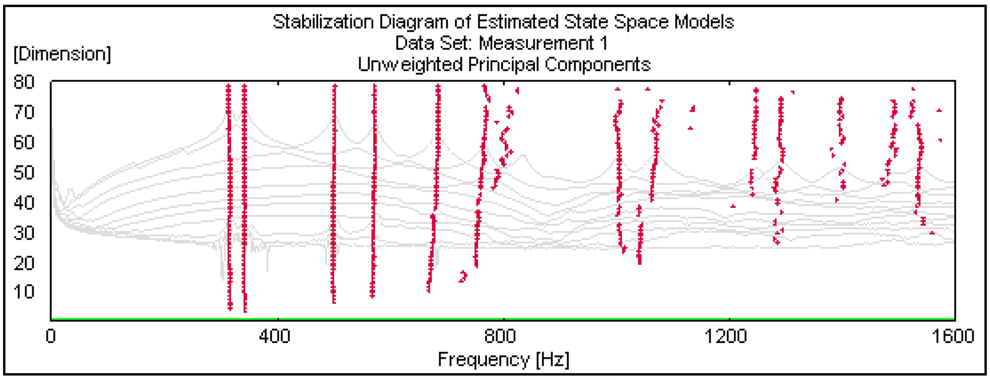


(a) SVSDM of data set

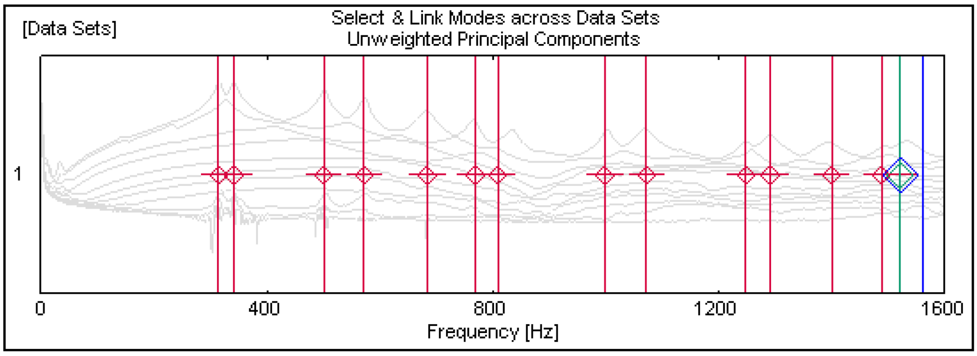


(b) AASD of data set

Fig. 7 SVSDM and AASD of the data set for Case 1



(a) SDESSM data set



(b) SM across data set

Fig. 8 SDESSM and SM across data set for Case 1

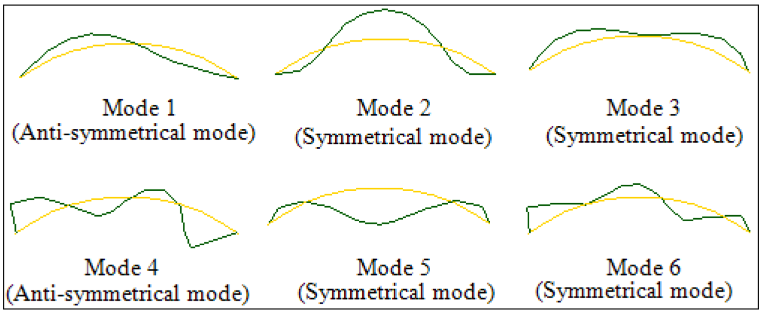


Fig. 9 Mode shapes of Type-1 arch dam obtained from the first test

Mode shapes obtained from the first test are shown in Fig. 9. Due to locations of the accelerometers along the normal direction of water, only symmetrical and anti-symmetrical modes are obtained. The natural frequencies and damping ratios of a Type-1 arch dam related to Case 1 are given in Table 1.

3.2.2 Case 2

In the second test, loading simulating random impact effects is applied the dam to crack. The minor cracks occurred at the middle of the upper part of the dam and distributed through the

Table 1 Natural frequencies and damping ratios from Case 1 of the Type-1 arch dam

Mode	EFDD		SSI	
	Frequency (Hz)	Damping ratios (%)	Frequency (Hz)	Damping ratios (%)
1	315.1	1.44	314.2	1.53
2	341.3	1.54	341.3	1.51
3	501.9	1.12	500.5	1.02
4	573.1	0.96	571.7	0.84
5	683.1	1.48	683.6	1.03
6	764.8	1.15	768.8	1.39
7	832.5	1.18	808.2	0.44
8	1002	0.73	997.9	0.91
9	1069	0.98	1072	1.66
10	1245	1.02	1247	1.18
11	1290	0.92	1290	0.44
12	1393	1.24	1399	2.27
13	1482	0.28	1487	0.15

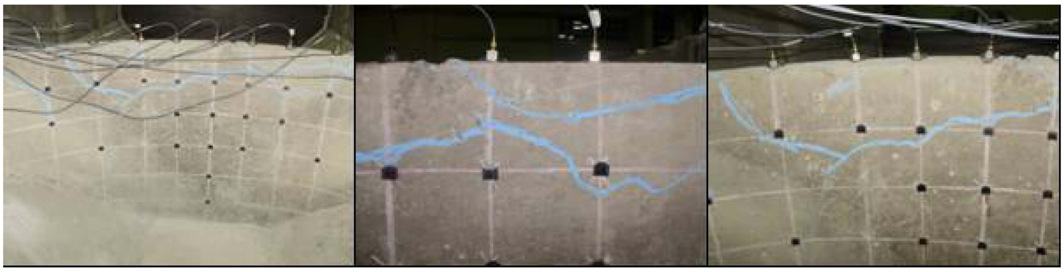


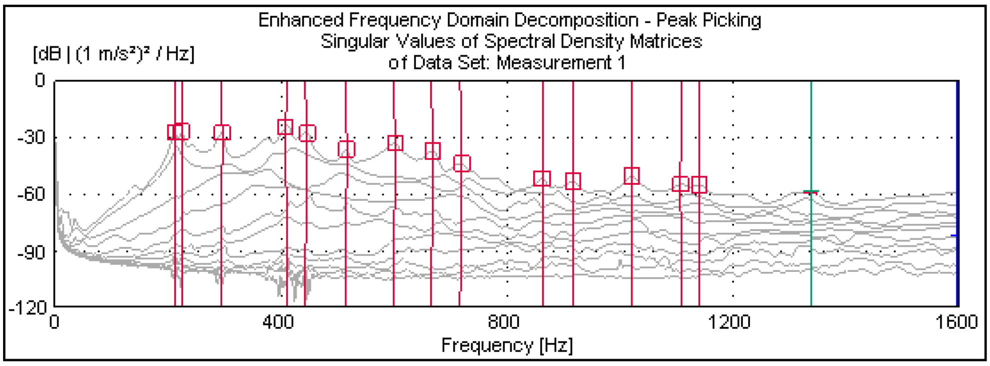
Fig. 10 Photographs from the second test

abutments as in similar studies in the literature (Oliveria and Faria 2006, JianWen *et al.* 2009, Karaton 2004). Photographs from the second test are shown in Fig. 10. Singular values of spectral density matrices (SVSDM) from the data set and the average of auto spectral densities (AASD) from the data set by the EFDD technique are given in Fig. 11. A stabilization diagram of estimated state space models (SDESSM) and selection of modes (SM) from the SSI technique are presented in Fig. 12. As seen in Figs. 11 and 12, Case 2 produced more than 13 natural frequencies in the 0-1600 Hz frequency span.

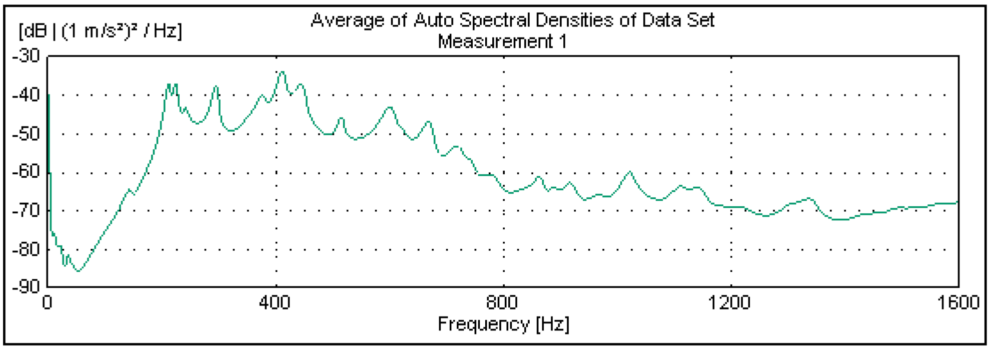
From the second test, symmetrical and anti-symmetrical mode shapes are obtained (Fig. 13). The natural frequencies and damping ratios of the Case 2, Type-1 arch dam are given in Table 2.

3.2.3 Case 3

In the third test, in addition to the cracks from Case 2, some severe cracks and fractures occurred in the dam's body. These cracks distributed below and to the sides of the first cracks. The formation of these new cracks is expected and same situations can be seen in the literature (Oliveria and Faria 2006, JianWen *et al.* 2009, USACE 2003). Photographs from the third test are given in Fig. 14.



(a) SVSDM of data set



(b) AASD of data set

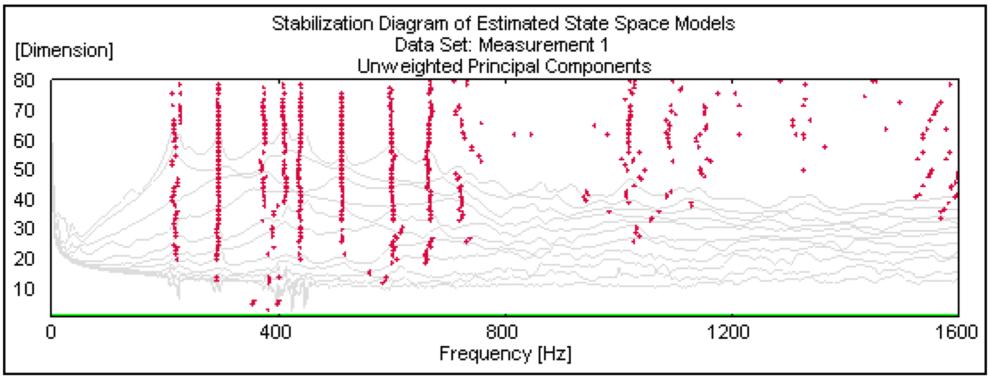
Fig. 11 SVSDM and AASD of the Case 2 data set

Singular values of spectral density matrices (SVSDM) from the data set and average auto spectral densities (AASD) from the data set by the EFDD technique are given in Fig. 15. A stabilization diagram of estimated state space models (SDESSM) and selection of modes (SM) by the SSI technique are presented in Fig. 16. As seen in Fig. 15, Case 3 produced nine natural frequencies in the 0-1600 Hz frequency span by the EFDD technique, however, almost no modes are obtained by the SSI technique.

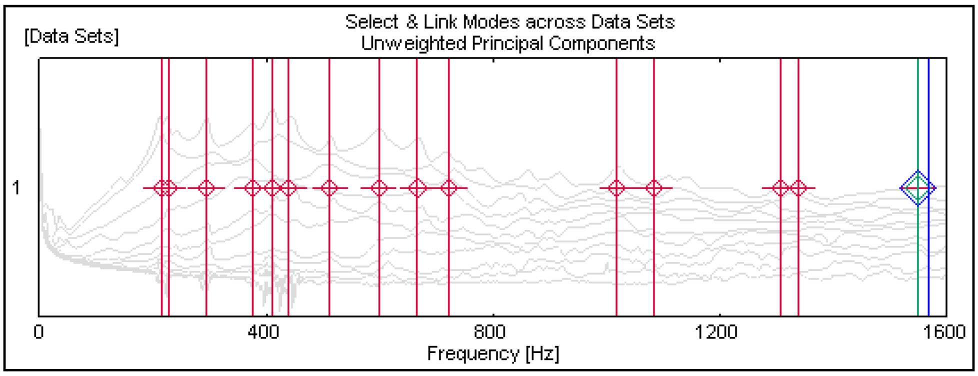
Mode shapes are obtained as symmetrical and anti-symmetrical from the third test, as shown in Fig. 17. The natural frequencies and damping ratios from the Case 3, Type-1 arch dam are given in Table 3.

3.2.4 Case 4

In the fourth test, teservoir of the model is filled with the water to see effects of water on the severe cracking. The water flowed and oozed slowly from the dam's body. Photographs from the fourth test are given in Fig. 18. Singular values of spectral density matrices (SVSDM) from the data set and the average of auto spectral densities (AASD) from the data set by the EFDD technique are given in Fig. 19. The SSI technique did not produce any modal parameters in the last test. As seen in Fig. 19, Case 4 has only six natural frequencies from the 0-1600 Hz frequency span by the EFDD technique.



(a) SDESSM data set



(b) SM across data set

Fig. 12 SDESSM and SM across the Case 2 data set

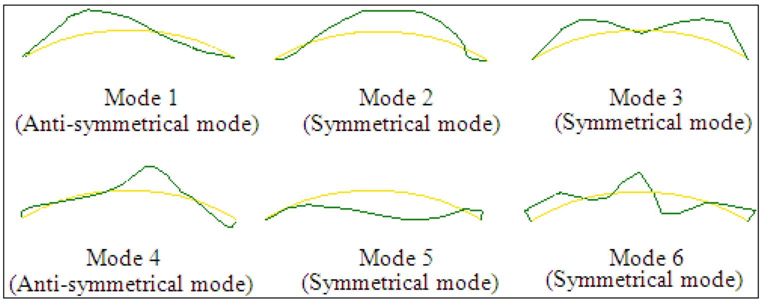


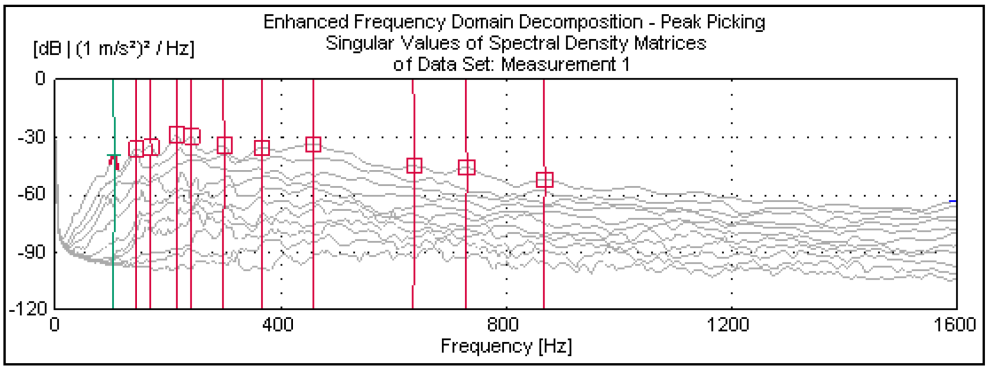
Fig. 13 Mode shapes of Type-1 arch dam obtained from the second test

Mode shapes are obtained as symmetrical and anti-symmetrical from the fourth test (Fig. 20). The natural frequencies and damping ratios of the Case 4, Type-1 arch dam are given in Table 3.

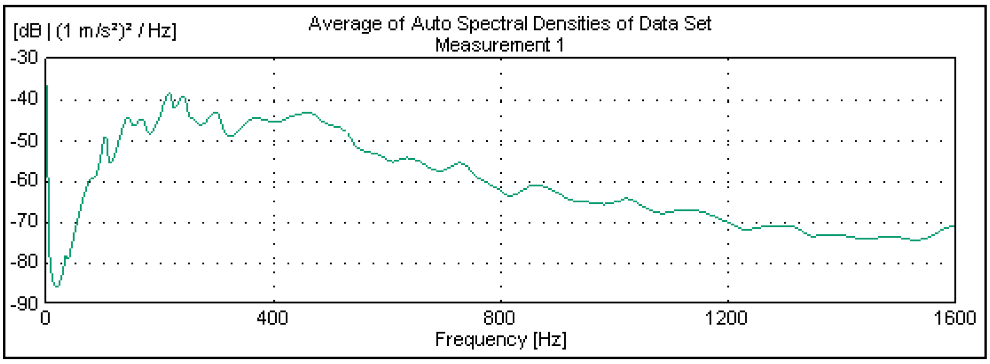
3.2.5 Comparison of test results

Table 5 summarizes the comparison of the first six natural frequencies obtained from the four cases, and Fig. 21 shows the plots of changes in frequencies extracted by the EFDD technique. It

Fig. 14 Photographs from the third test



(a) SVSDM of data set

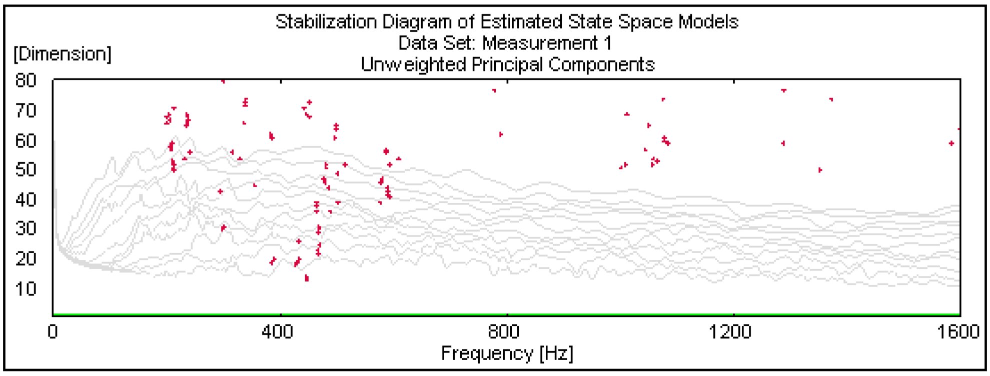


(b) AASD of data set

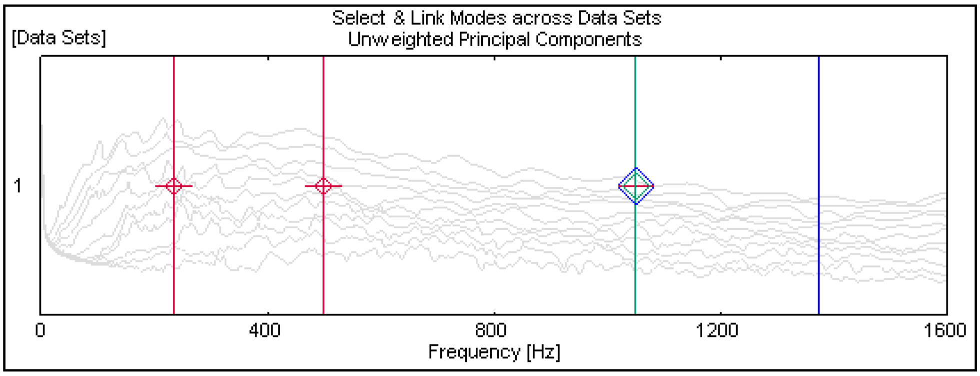
Fig. 15 SVSDM and AASD from the Case 3 data set

can be seen from the Fig. 21 that frequencies exhibit decrease from Case 1 through Case 4. A difference about 35% occurs between the Case 1 frequencies and those of Case 2. However, little difference appears among the frequencies obtained from Case 2, Case 3 and Case 4 compared to Case 1. In addition, the change is only about 5% between frequencies obtained from Case 3 and Case 4. The reservoir effect on the structural behaviour can be seen from the literature (Sevim *et al.* 2011c).

In the experimental measurements of the engineering structures (such as bridges, dams, buildings etc.) by Operational Modal Analyses method, some assumptions are made:



(a) SDESSM data set



(b) SM across data set

Fig. 16 SDESSM and SM across the Case 3 data set

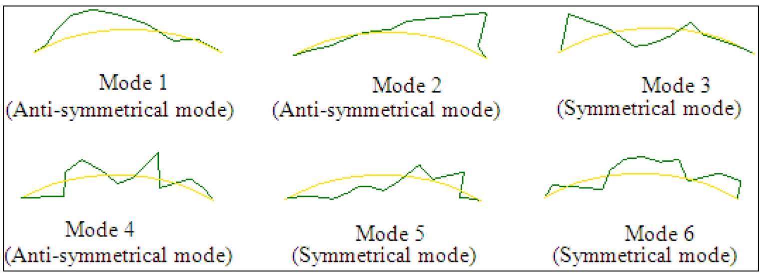


Fig. 17 Mode shapes of Type-1 arch dam obtained from the third test

- The measured response at each point represent the all of the structural behaviour,
- Boundary conditions do not change during experimental measurements,
- The measured structure has linear elastic response.

The arch dam model is located within the elastic limits in Case 1. But, the model is not located within the elastic limits in Case 2-4. When the damage is introduced, the system switches the non-linear region. So, the reservoir loosed the real effect. Also, since rigidity of the dam decreases after cracks and fractures appeared and some oozing occurs from the dam's body, small change in the

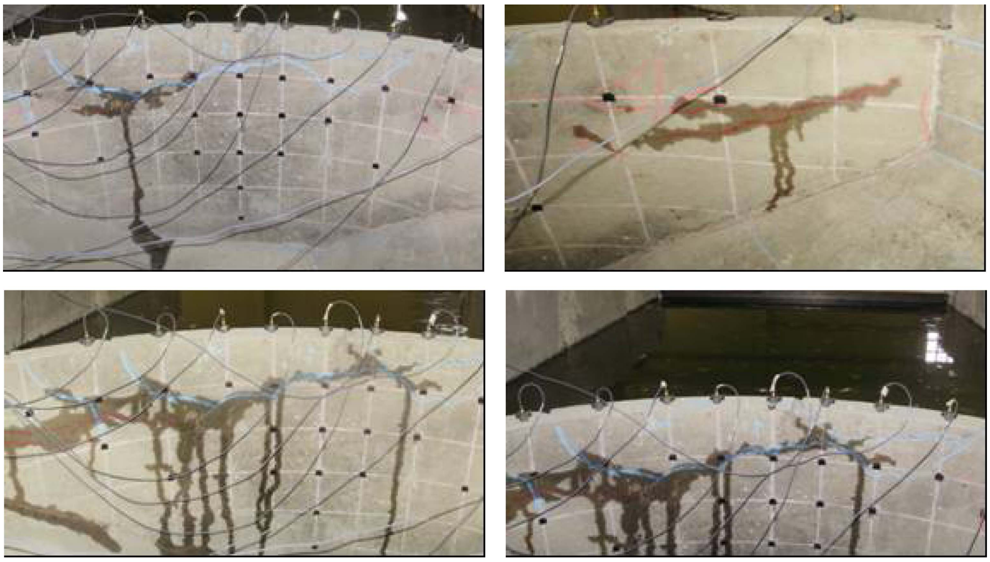
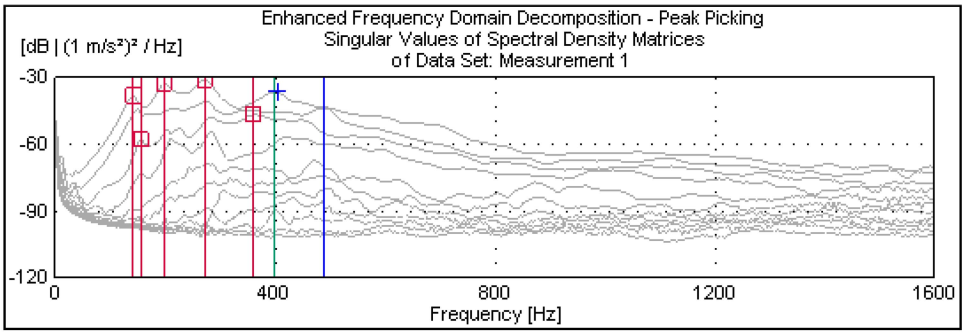
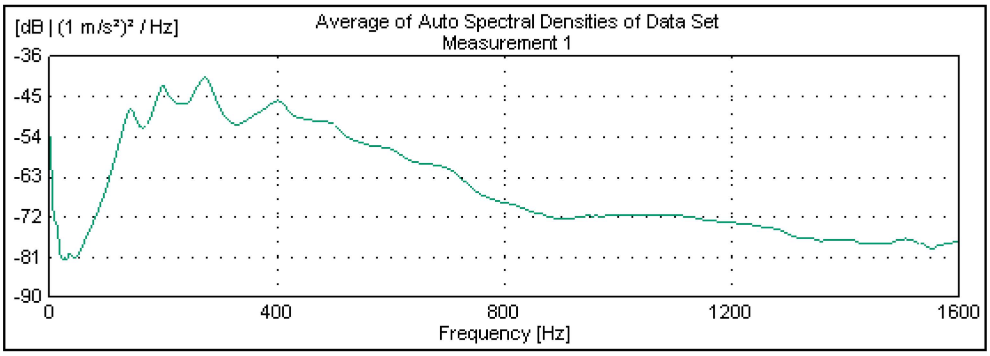


Fig. 18 Photographs from the forth test



(a) SVSDM of the data set



(b) AASD of data set

Fig. 19 SVSDM and AASD of the Case 4 data set

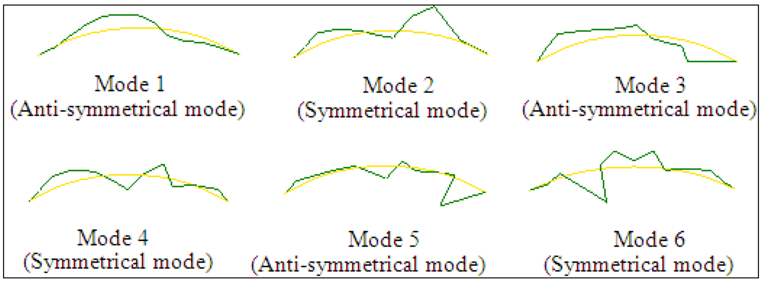


Fig. 20 Mode shapes of the Type-1 arch dam obtained from the fourth test

Table 2 Natural frequencies and damping ratios from Case 2 of the Type-1 arch dam

Mode	EFDD		SSI	
	Frequency (Hz)	Damping ratios (%)	Frequency (Hz)	Damping ratios (%)
1	211.3	1.05	215.2	1.33
2	223.7	1.50	227.1	3.78
3	293.8	1.64	294.3	1.43
4	374.7	1.41	375.5	2.17
5	410.4	1.86	409.1	1.65
6	441.9	0.79	439.4	1.96
7	514.4	2.37	511.6	1.20
8	595.1	1.28	595.1	2.00
9	665.5	1.06	666.4	1.93
10	716.5	0.76	722.6	1.72
11	1020	1.06	1018	1.15
12	1109	1.34	1084	2.73
13	1139	0.68	1306	1.70

Table 3 Natural frequencies and damping ratios from the Case 3, Type-1 arch dam

Mode	EFDD		SSI	
	Frequency (Hz)	Damping ratios (%)	Frequency (Hz)	Damping ratios (%)
1	143.2	1.68	-	-
2	166.7	3.51	234.9	4.43
3	214.9	2.14	-	-
4	296.7	2.31	-	-
5	367.7	2.30	-	-
6	428.7	2.23	438.9	4.23
7	634.8	2.51	-	-
8	726.6	2.58	-	-
9	865.1	1.99	-	-

Table 4 Natural frequencies and damping ratios of the Case 4, Type-1 arch dam

Mode	EFDD		SSI	
	Frequency (Hz)	Damping ratios (%)	Frequency (Hz)	Damping ratios (%)
1	141.4	4.31	-	-
2	156.7	4.99	-	-
3	200.3	5.58	-	-
4	271.9	3.82	-	-
5	359.8	3.65	-	-
6	400.2	2.78	-	-

Table 5 Comparison of the natural frequencies related to four cases

Mode	Case 1 (Hz)		Case 2 (Hz)		Case 3 (Hz)		Case 4 (Hz)	
	EFDD	SSI	EFDD	SSI	EFDD	SSI	EFDD	SSI
1	315.1	314.2	211.3	215.2	143.2	-	141.4	-
2	341.3	341.3	223.7	227.1	166.7	234.9	156.7	-
3	501.9	500.5	293.8	294.3	214.9	-	200.3	-
4	573.1	571.7	374.7	375.5	296.7	-	271.9	-
5	683.1	683.6	410.4	409.1	367.7	-	359.8	-
6	764.8	768.8	441.9	439.4	428.7	438.9	400.2	-

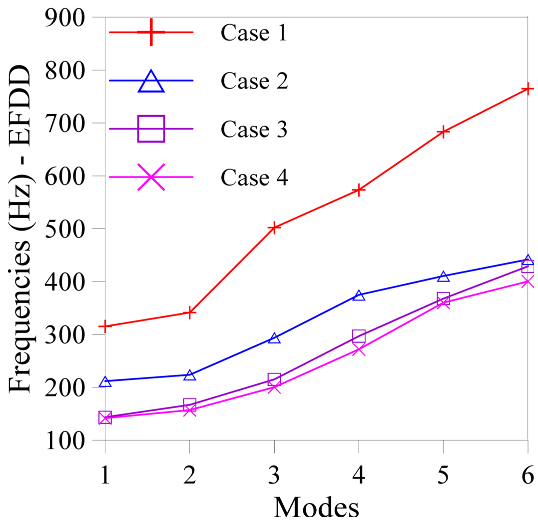


Fig. 21 Change in natural frequencies

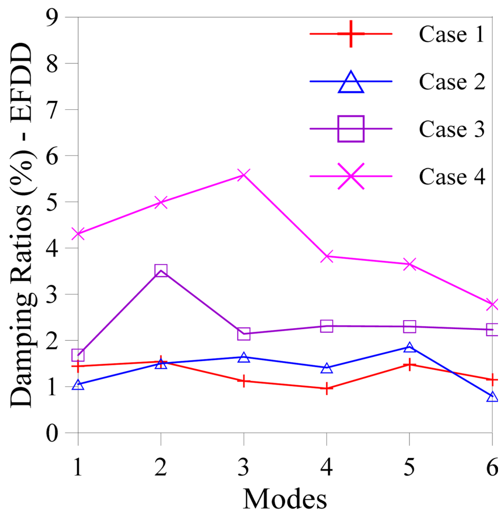


Fig. 22 Change in damping ratios

frequency is due to the cracks and fractures occurred in Case 3. Consequently, the apparent effect of water on the dam behaviour decreases.

Table 6 provides a comparison of the first six damping ratios obtained from four cases, and Fig. 22 shows the plots of the changes in damping ratios extracted by the EFDD technique. The damping

Table 6 Comparison of the damping ratios related to four cases

Mode	Case 1 (%)		Case 2 (%)		Case 3 (%)		Case 4 (%)	
	EFDD	SSI	EFDD	SSI	EFDD	SSI	EFDD	SSI
1	1.44	1.53	1.05	1.33	1.68	-	4.31	-
2	1.54	1.51	1.50	3.78	3.51	4.43	4.99	-
3	1.12	1.02	1.64	1.43	2.14	-	5.58	-
4	0.96	0.84	1.41	2.17	2.31	-	3.82	-
5	1.48	1.03	1.86	1.65	2.30	-	3.65	-
6	1.15	1.39	0.79	1.96	2.23	4.23	2.78	-

ratios show increase from Case 1 through Case 4.

The mode shapes (Fig. 9) obtained for Case 1 are very realistic. However, mode shapes obtained from Cases 2, 3 and 4 are not well suite.

The mode shapes are obtained as symmetrical and anti-symmetrical in Case 1. Because, the arch dam model is located within the elastic limits. So, the mode shapes in Case 1 represent the probable responses of arch dams more accurately.

The arch dam model is not located within the elastic limits in Case 2-4. When the damage is introduced, the system switches the non-linear region. So, it can be said that the mode shapes do not appear to be likely modes of undamaged arch dams.

4. Conclusions

This study identifies the modal parameters of a prototype arch dam model under some damage scenarios using Operational Modal Analysis. For this purpose, a prototype model of a Type-1 arch dam is constructed under the laboratory conditions considering both reservoir and foundation. Modal parameters of the arch dam for four cases are extracted using EFDD and SSI techniques. The following observations are arised from the research:

- The natural frequencies, mode shapes and damping ratios extracted using EFDD and SSI techniques for Case 1 and 2, are very similar. However, the SSI technique does not extract relevant data for the modal parameters for Cases 3 and 4.
- The first six natural frequencies are obtained between 315 Hz-765 Hz, 211 Hz-442 Hz, 143 Hz-430 Hz and 141 Hz-400 Hz for Cases 1-4, respectively.
- Approximately 35-40% difference exists between the natural frequencies obtained from Case 1 and Case 4.
- The natural frequencies of the dam considerably decrease with increasing cracks. However, the observations show that the filled reservoir slightly affects the modal parameters of the dam after severe cracking.
- The mode shapes obtained are symmetrical and anti-symmetrical. Apparently, mode shapes in Case 1 represent the probable responses of arch dams more accurately. However, the mode shapes in Cases 2-4 do not appear to be likely modes of undamaged arch dams.
- The damping ratios in Case 1 are 1-2%. However, they are about 5-6% for Case 4. Consequently, the

damping ratios have an increasing trend when cracking increases.
- It can be concluded that experimental measurement tests should be conducted to arch dams to obtain the structural behaviour and the observations should be used in the safety evaluations of arch dams.

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