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System identification of arch dam model strengthened with CFRP composite materials

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Abstract. This paper presents the structural identification of an arch dam model for the damaged, repaired and strengthened conditions under different water levels. For this aim, an arch dam-reservoir-foundation model has been constructed. Ambient vibration tests have been performed on the damaged, repaired and strengthened dam models for the empty reservoir (0 cm), 10 cm, 20 cm, 30 cm, 40 cm, 50 cm and full reservoir (60 cm) water levels to illustrate the effects of water levels on the dynamics characteristics. Enhanced Frequency Domain Decomposition Method in the frequency domain has been used to extract the dynamic characteristics. The dynamic characteristics obtained from the damaged, repaired and strengthened dam models show that the natural frequencies and damping ratios are considerably affected from the varying water level. The maximum differences between the frequencies for the empty and full reservoir are obtained as 16%, 33%, and 25% for damaged, repaired and strengthened model respectively. Mode shapes obtained from the all models are not affected by the increasing water level. Also, after the repairing and strengthening implementations, the natural frequencies of the arch dam model increase significantly. After strengthening, between 46-92% and 43-62% recovery in the frequencies are calculated for empty and full reservoir respectively. Apparently, after strengthening implementation, the mode shapes obtained are more acceptable and distinctive compared to those for the damaged model.

Keywords: ambient vibration test; dynamic characteristics; enhanced frequency domain decomposition; prototype arch dam-reservoir-foundation model; repairing; reservoir water effect; strengthening

1. Introduction

The actual performance of an arch dam under the earthquake loadings should be determined considering quantity of water in the reservoir. Because it is well known that the water considerably affects the dynamic behavior of arch dam during the earthquakes. When a dam-reservoir system is exposed to a dynamic loading like earthquakes, hydrodynamic pressures in excess of hydrostatic pressures occur on the dam due to the vibration of the dam and water in the reservoir. These hydrodynamic pressures and the deformation of the dam interact with each other (Perumalswami and Kar 1973). Hence, the water level effects on the dynamic behavior of arch dams must be considered.

In the literature, three approaches are used to consider the reservoir effects in the dynamic analyses: Westergaard, Euler, and Lagrangian approach. In Westergaard approach (Westergaard 1933), it is considered that a vibrated mass dispersion with the dam, which is similar to being hydrodynamic effect dispersion towards the dam upstream face. In Eulerian approach (Dungar 1978), the displacements are the variables in the structure; the pressures are the variables in the fluid. However, in Lagrangian approach (Wilson and Khalvati 1983), the displacements are the variables in both the fluid and the structure. So, there is no need of any extra interface equations in Lagrangian approaches. Thus, compatibility and equilibrium are automatically satisfied at the nodes along the interfaces between fluid and structure (Bayraktar *et al*. 2011).

Beside these approaches, it is emphasized that dynamic behavior of arch dams must also be investigated and monitored experimentally. Dynamic characteristics (natural frequencies, mode shapes and damping ratios) are the key parameters to monitor the structural safety and performance of structures during their service period. Many structural monitoring methods, based on the dynamic characteristics have been developed recently. The main aim of methods is to fallow the changes of dynamic characteristics. It is well known that the changes in the physical properties of the structures such as boundary conditions, stiffness will cause changes in dynamic characteristics. Therefore, the dynamic behavior of structures can be monitored by following the changing of dynamic characteristics, especially after earthquakes.

The ambient vibration testing technique has been often used to determine the structural performance and/or structural safety of large dams. Deinum *et al*. (1982) performed the ambient and forced vibration tests on the

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Emmoson arch dam to estimate the dynamic properties of the dam. Loh and Wu (1996) determined the dynamic characteristics of Fei-Tsui arch dam using finite element analysis and experimental measurement tests. Ziyad (1998) carried out the finite element analysis and experimental measurements on Morrow Point arch dam to determine the dam-water interaction effect and water compressibility. Ambient vibration tests on a 56 metre high concrete gravity dam were conducted by Daniell and Taylor (1999) to measure its modal properties for validating a finite element model of the dam. Darbe *et al*. (2000) achieved the resonance frequencies of the 250-m-high arch dam of Mauvoisin by using ambient vibration test. Proulx *et al.* (2001) investigated the water level effects on the dynamic behavior of arch dams. Darbre and Proulx (2002) preferred the continuous ambient vibration monitoring studies and their results related to Mauvoisin arch dam. Validation of numerical model of Pacoima Arch Dam using ambient vibration testing data was studied by Alves and Hall (2006). Oliveria and Mendes (2006) attempted the finite element development of a numerical model of 3D elements for Cabril Dam, based on the main fundamental parameters of the dynamic response of the dam, obtained on several experimental results on ambient vibration test. Okuma *et al.* (2008) conducted two kind of ambient vibration test to obtain present dynamic properties of Hitotsuse arch dam. Weng and Loh (2007) presented a paper on the system identification of the Fei-Tsui Arch Dam using the recorded seismic data and ambient vibration data. The modal properties of the dam for different reservoir water level were identified using the recorded seismic data from 84 earthquake events. The Berke Arch Dam, located in South Anatolia on Ceyhan River, was studied by Sevim *et al.* (2011a). Calcina *et al*. (2014) worked on the ambient vibration tests of the Punta Gennarta Arch Dam in two different studying conditions to evaluate the effect produced by two different reservoir water levels on the structural vibration properties. Tarinejad *et al*. (2014) performed forced vibration field tests and finite element analysis on the Shahid Rajaee concrete arch dam to determine the dynamic properties of the dam-reservoir-foundation system. Cheng *et al*. (2015) studied about the health monitoring method of a concrete dam based on the ambient vibration testing and kernel principal analysis. It has been seen from the literature that although the physical conditions are quite difficult for excitation of large dams, and tests become too expensive and require much time; results achieved by ambient vibration test are very useful. But, such kinds of difficulties motivate researchers to build scaled prototype dam models under laboratory conditions to determine the structural performance experimentally (Oliveira and Faria 2006, Wang and Li 2006, 2007, Mendes and Oliveira 2007, Wang and He 2007, Sevim *et al*. 2010, 2011b, 2012, Pan *et al*. 2011, Türker *et al*. 2014, Hariri-Ardebili and Sayed-Kolbadi 2015, Liu *et al*. 2016). Apparently, from the literature, studies into water level effects with the different conditions (damaged, repaired, strengthened) on the dynamic characteristics are sufficient. This study seeks to contribute to relieve the deficit.

In this paper, the ambient vibration tests have been carried out with the purpose of determining the water level effects on the dynamics characteristics of damaged, repaired and strengthened arch dam models. The ambient vibration test has been conducted on each arch dam models for varying water levels to present the natural frequencies, mode shapes and damping ratios. Enhanced Frequency Domain Decomposition (EFDD) technique has been used to extract the dynamic characteristics from the ambient vibration measurements. As a result of study, experimentally identified dynamic characteristics have been compared with each other for each situation to determine the effects of water levels.

2. Ambient vibration testing of the prototype arch dam model

2.1 Description of laboratory arch dam model

Type-1 arch dam, which is one of five arch dam types suggested at the "Arch Dams" Symposium in England in 1968 (Arch Dam 1968) is selected for experimental studies. Type-1 arch dam has a single curvature, constant radius and constant central angle. The geometrical properties of Type-1

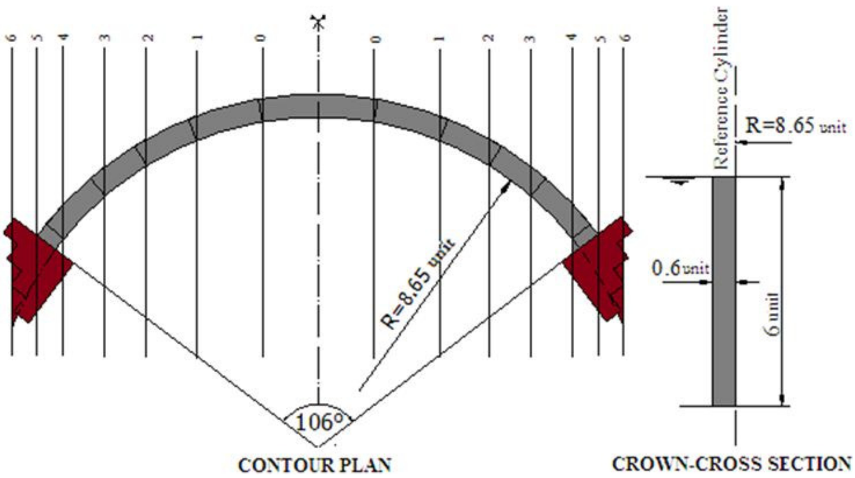


Fig. 1 Geometrical properties of Type-1 arch dam

arch dam are shown in Fig. 1. The dam has 6 unit height and 0.6 unit constant widths. 1 unit is selected as 10cm in the construction of the laboratory arch dam model. Therefore, dam height (H) and crest width are designed as 60cm and 6cm, respectively.

The Type-1 arch dam was developed considering the reservoir and foundation. The reservoir of the dam was extended as 3H (H: dam height); the foundation of the dam was an extension of about H in the downstream and downward directions, and it was an extension of the reservoir's length in the upstream direction (Calayır *et al*. 1996, Akköse *et al*. 2008, Sevim *et al*. 2010). Such kind of modelling is appropriate to represent the structural behavior of concrete arch dams (USACE 2003). Ultimate dimensions of Type-1 arch dam-reservoir-foundation models appear in Fig. 2. In the construction of the system, 6.25 m^3 concrete is used approximately. Some views of the Type-1 arch dam-reservoir-foundation system are shown in Fig. 3.

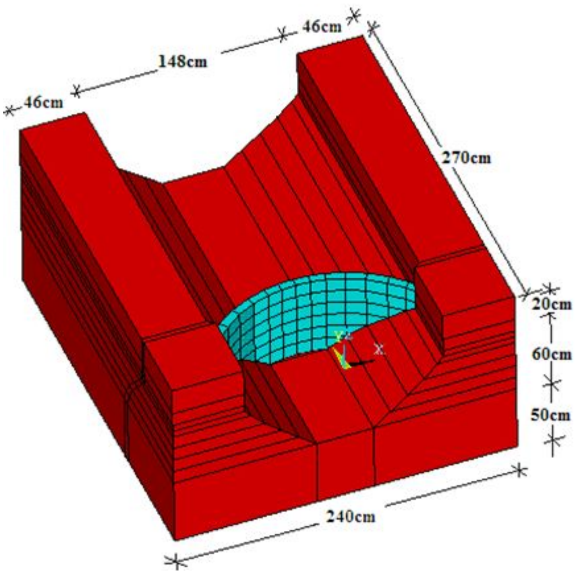


Fig. 2 Type-1 arch dam-reservoir-foundation system and its dimensions

2.2 Ambient vibration tests

Ambient vibration tests are conducted on the dam model to determine its dynamic characteristics such as natural frequencies, mode shapes and damping ratios. The test measurements are carried out for three different situations: damaged (Situation-1), repaired (Situation-2) and strengthened dam (Situation-3) models. Measurements are conducted with different water levels for empty reservoir (0 cm), 10 cm, 20 cm, 30 cm, 40 cm, 50 cm and full reservoir (60 cm) water levels. During the ambient vibration tests, a B&K 3560 data acquisition system with 17 channels and a B&K 4507-B005-type uni-axial accelerometers, uni-axial signal cables, a laptop, PULSE (PULSE 2006) and Operational Modal Analysis software (OMA 2006) are used. The frequency range is selected as 0-1000 Hz and eleven accelerometers are located on the crest surface, as shown in Fig. 4. The tests are carried out for 5 minutes.

2.2.1 Ambient vibration tests for damaged dam model (*Situation-1*)

For the crack formation, the dam body is damaged by loading a random impact effect. The minor cracks were occurred in the middle of the upper part of the dam and distributed through the abutments. In addition to the minor cracks, some severe cracks and fractures were generated in the body of dam. These cracks distributed below to the sides of the first cracks. The formation of these new cracks is expected and similar situations can be seen in the literature (USACE 2003, Karaton 2004, Oliveria and Faria 2006, Pan *et al*. 2011). Some views of the created cracks and fractures are shown in Fig. 5.

The ambient vibration tests were conducted on the damaged dam for empty reservoir, 10 cm, 20 cm, 30 cm, 40 cm, 50 cm and full reservoir (60 cm) water levels. Some photographs from the tests related to different water levels are indicated in Fig. 6.

Singular values of spectral density matrices (SVSDM) of the data set obtained from the EFDD method for the empty and full reservoir are illustrated respectively in Fig. 7-8. As seen from the Figs. the first six natural frequencies

Fig. 3 Some views of Type-1 arch dam-reservoir-foundation system

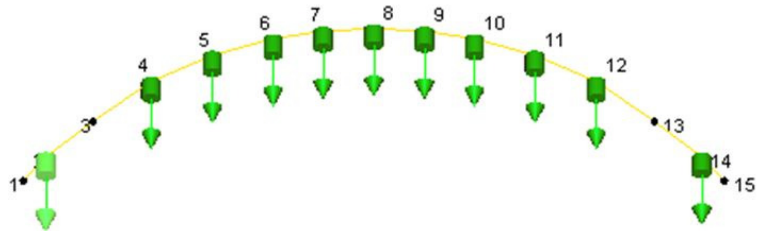


Fig. 4 Locations of accelerometers used in the ambient vibration tests

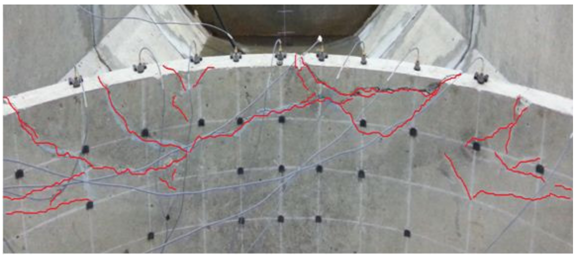


Fig. 5 Views of the generated cracks and fractures

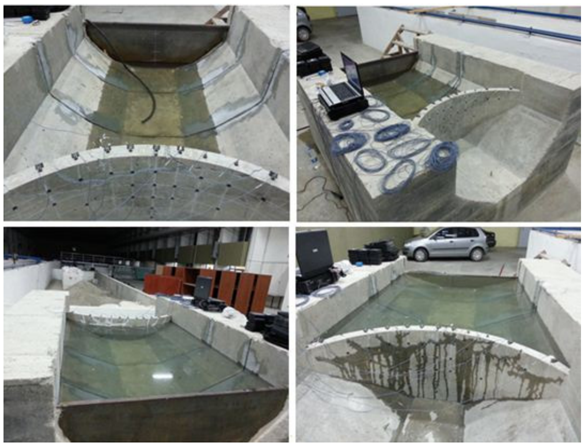


Fig. 6 Some photos related to ambient vibration tests during the situation-1

are obtained between 0 and-1000 Hz frequencies range. Mode shapes does not affected the changes of the water levels. Therefore, the mode shapes obtained from the empty and full reservoir water level are only given. Fig. 9 and Fig. 10 show the first six mode shapes for the empty and full reservoir water. As can be observed, only symmetrical and anti-symmetrical modes shapes are achieved due to location of accelerometers along the normal direction of arch span.

Six natural frequencies were carried out in the testing range of 0-1000 Hz. They are given in Table 1 along with the damping ratios. Fig. 11 illustrates the variation of the natural frequencies and damping ratios versus the water level for the first six natural frequencies along with

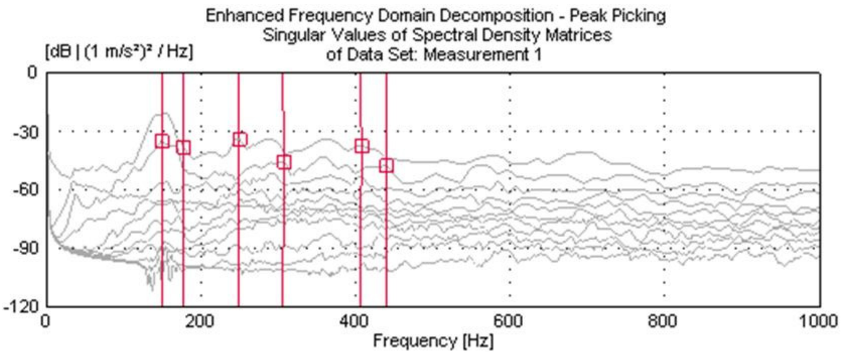


Fig. 7 SVSDM of the data set obtained from the situation-1 for the empty reservoir

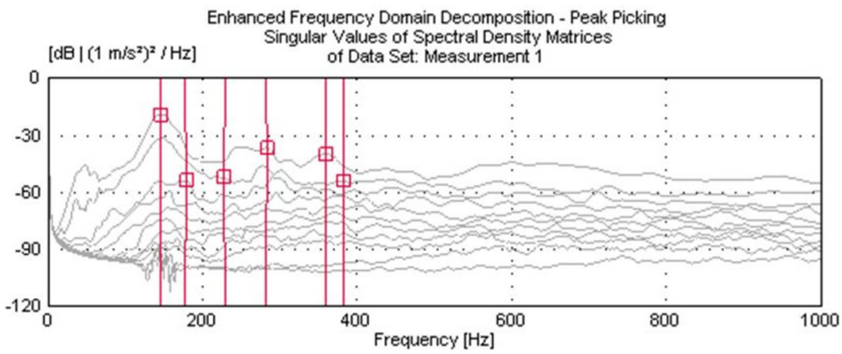


Fig. 8 SVSDM of the data set obtained from the situation-1 for the full reservoir

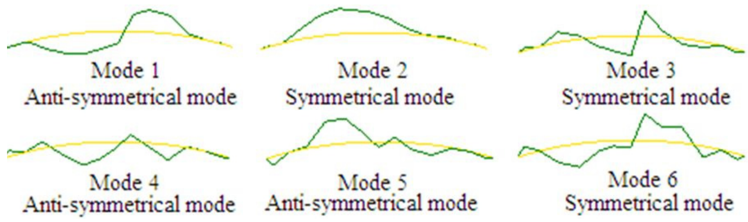


Fig. 9 Mode shapes of the damaged arch dam obtained for empty reservoir

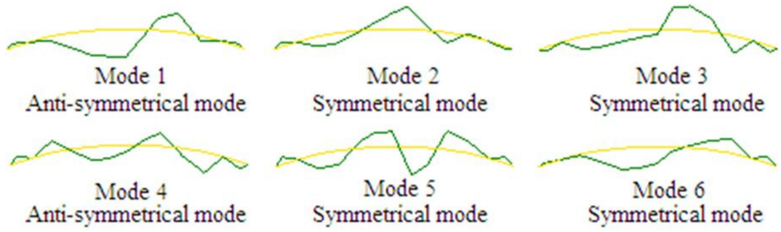
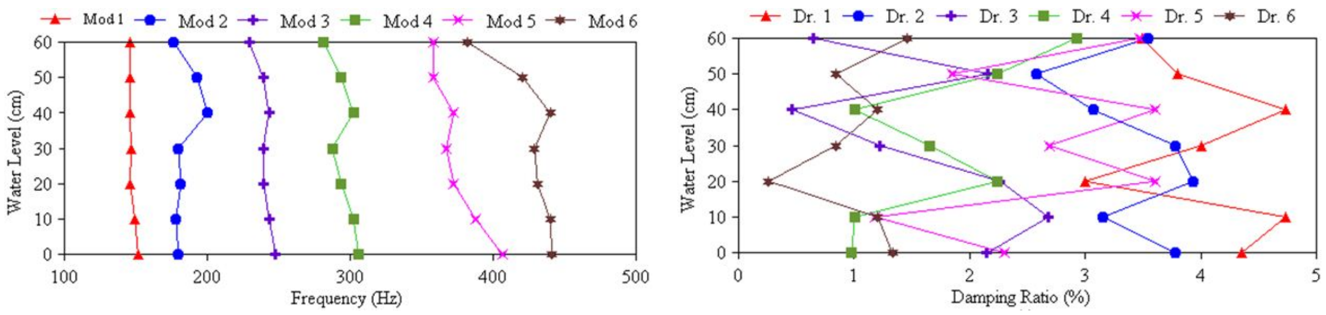


Fig. 10 Mode shapes of the damaged arch dam obtained for full reservoir

Table 1 Natural frequencies and damping ratios obtained from the situation-1

Mode	Water levels													
	Empty		10 cm		20 cm		30 cm		40 cm		50 cm		full	
	Freq. (Hz)	Dr. (%)	Freq. (Hz)	Dr. (%)	Freq. (Hz)	Dr. (%)	Freq. (Hz)	Dr. (%)	Freq. (Hz)	Dr. (%)	Freq. (Hz)	Dr. (%)	Freq. (Hz)	Dr. (%)
1	151.5	4.35	149.2	4.73	146.1	2.99	146.5	4.00	146	4.73	145.9	3.79	145.6	3.49
2	178.0	3.15	178	3.15	181.5	3.93	179.7	3.77	200.2	3.06	192.8	2.57	176.3	3.55
3	247.9	2.15	243	2.68	239.5	2.26	239	1.22	243	0.46	238.9	2.16	229.1	0.65
4	305.9	0.98	302	1.02	293.8	2.24	287.3	1.65	302.1	1.00	293.8	2.24	281.1	2.93
5	406.5	2.30	387.6	1.19	372.4	3.60	367.2	2.68	372.4	3.61	357.9	1.85	358.5	3.47
6	441.2	1.33	439.8	1.205	431	0.261	429	0.84	439.8	1.20	420.8	0.84	381.7	1.46

*Freg: Frequency; Dr: Damping Ratio



(a) (b)

Fig. 11 Effects of reservoir water level on natural frequencies (a) and damping ratios (b)

damping ratios.

When the reservoir water level increases from the lowest to a certain level (up to 30 cm), the natural frequencies slightly decrease with rising the water level (as shown in Fig. 11). After the water level arrived above 30 cm the natural frequencies start to increase (up to 40 cm) and then decrease with increasing water level. This meant that the added mass effect of the reservoir becomes dominant after the water level reached above 40 cm. The maximum variation of the frequencies obtained from empty and full reservoir is calculated as 16 per cent for the sixth mode. As shown in Fig. 11 the variation of the damping ratios for different water level is very complicated. This meant that damping ratios show a significant change with increasing water levels. The damping ratios are identified between approximately 0.26-4.35 per cent.

(a) Removal of the damaged concrete pieces

(b) Application of structural repair mortar using hand trowelling process

(c) Putting in the removed concrete pieces

Fig. 12 Repair process of arch dam with epoxy mortar

Table 2 Material properties of structural repair mortar (BASF 2007)

Material property	Amount
Density of the mixture	1.70 ± 0.05 kg/liter
Compressive strength (7 days)	75 MPa
Flexural strength (7 days)	25 MPa
Bonding strength to concrete (7 days)	> 3.0 MPa
Fully Cured at 20°C	7 Days

2.2.2 Ambient vibration tests for repaired dam model (Situation-2)

In this test situation, the pre-damaged dam body was repaired using high-strength structural repair mortar. The commercially available epoxy-based repair mortar marked as CONCRESIVE®1406 including two components was implemented. The material properties of CONCRESIVE® 1406 type repair mortar are given in Table 2. The repair phases are given step by step in Fig. 12.

(d) Hammering process

(e) Application of structural repair mortar on the surface of dam arc

Fig. 12 Continued

After repairing phases, ambient vibration test were conducted on the repaired dam to obtain the dynamic characteristics for empty reservoir, 10 cm, 20 cm, 30 cm, 40 cm, 50 cm and full reservoir (60 cm) water levels. During the measurement tests (especially for full reservoir), it was observed that the repair application was considerably reduced the water leakage from the body of the dam (Fig. 13).

Fig. 13 A test views from the situation-2

SVSDM obtained from the EFDD method for the empty and full reservoir water level are presented in Figs. 14-15. As seen in Figs., six natural frequencies are attained between 0-1000 Hz for each water level. The first six mode shapes obtained from the tests for empty and full water level appear in Figs. 16-17. The mode shapes are attained as symmetrical and anti-symmetrical for each water level, and they are the same for the each water level. Also, the identified mode shapes are more realistic and distinctive than those of the Situation-1. Table 3 presents the identified natural frequencies and modal damping ratios. Because of the fact that the water adds an extra mass on the dam body, the obtained natural frequencies are quite reduced when dam's reservoir is filled. The maximum differences between the natural frequencies for empty and full reservoir are obtained as approximately 33 per cent. The damping ratios are overly changed with increasing reservoir water level.

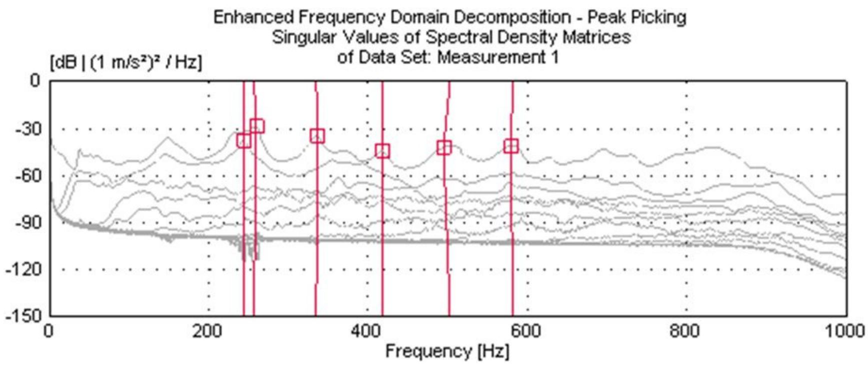


Fig. 14 SVSDM of the data set obtained from the situation-2 for the empty reservoir

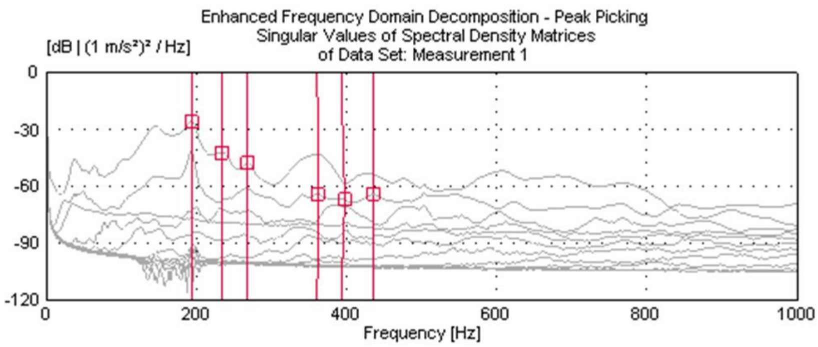


Fig. 15 SVSDM of the data set obtained from the situation-2 for the full reservoir

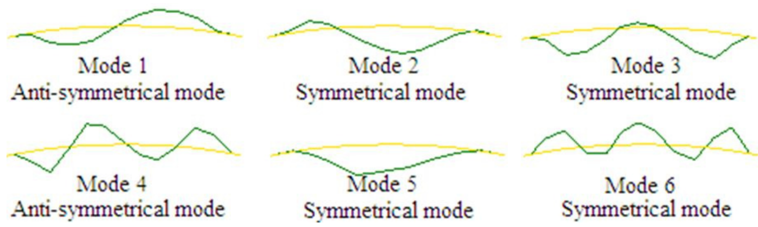


Fig. 16 Mode shapes of the repaired arch dam obtained for the empty reservoir

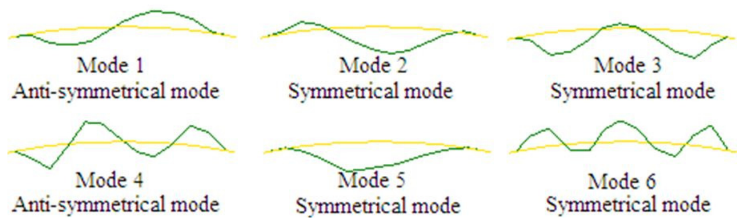


fig. 17 Mode shapes of the repaired arch dam obtained for the full reservoir

Table 3 Natural frequencies and damping ratios obtained from the situation-2

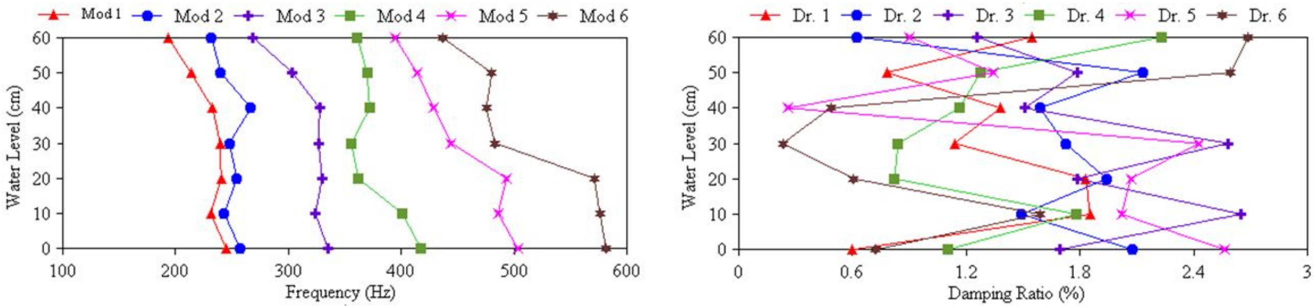
Mode	Water levels													
	Empty		10 cm		20 cm		30 cm		40 cm		50 cm		Full	
	Freq. (Hz)	Dr. (%)	Freq. (Hz)	Dr. (%)	Freq. (Hz)	Dr. (%)	Freq. (Hz)	Dr. (%)	Freq. (Hz)	Dr. (%)	Freq. (Hz)	Dr. (%)	Freq. (Hz)	Dr. (%)
1	244.9	0.59	231.1	1.85	240.4	1.83	239.6	1.14	232.8	1.38	213.6	0.78	193.5	1.54
2	257.1	2.07	243.3	1.49	254.47	1.94	247.6	1.72	266.8	1.58	240.2	2.13	232	0.62
3	335	1.69	323.9	2.65	329.9	1.78	326.7	2.57	327.8	1.51	303.8	1.78	268.9	1.26
4	417.7	1.10	400.8	1.78	361.9	0.82	355.9	0.84	372.1	1.16	369.7	1.27	361.6	2.23
5	503,3	2.56	485.8	2.01	493.3	2.06	444.3	2.42	429	0.26	414	1.34	394.7	0.90
6	581.4	0.72	576	1.58	570.9	0.61	483.1	0.23	475.4	0.48	480.3	2.59	436.4	2.68

*Freg: Frequency; Dr: Damping Ratio

But, there is no harmony in damping ratios. The damping ratios are calculated between approximately 0.23-2.68 per cent. Fig. 18 illustrates the variation of the natural frequencies and damping ratios versus the water level for the first six natural frequencies along with damping ratios. When the water level rises from the lowest to 40 cm water level, the natural frequencies usually fluctuate with increasing water level (refer to Fig. 18). After the water level reached above 40 cm the natural frequencies begin to decrease with rising water level. Similar to Situation-1, the added mass effect of the water becomes dominant after the water level reached above 40 cm.

2.2.3 Ambient vibration tests for strengthened dam model (*Situation-3*)

Chambon Dam is a 90-meter-tall, 293-meter-long concrete gravity dam on the Romance River in eastern France. The dam construction was completed in 1934 to

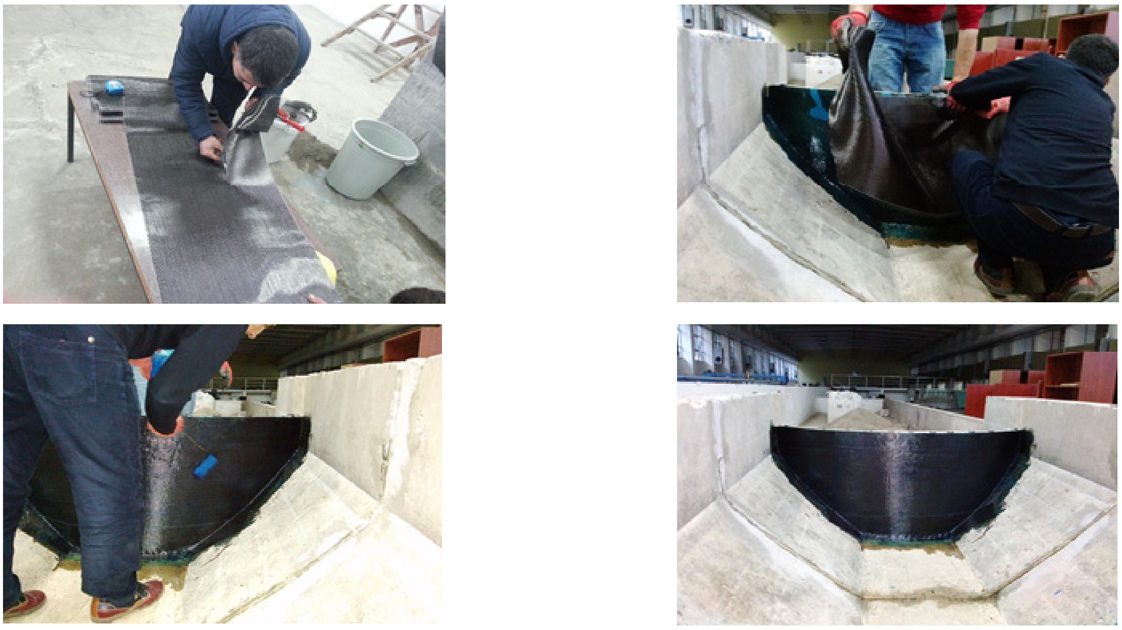


(a) (b)

Fig. 18 Effects of reservoir water level on natural frequencies (a) and damping ratios (b)

(a) Application of MBT-MBrace®Primer to the body surface

(b) Application of MBT-MBrace®Adesivo to the body surface



(c) Wrapping of MBT-MBrace®Fibre Sheet to the body surface

Fig. 19 Some phases of strengthening with CFRP sheet supply the power generation. The downstream face of Chambon Dam was strengthened with CFRP sheet to solve the three problems observed on the dam, mainly caused by the alkali-aggregate reaction phenomenon: cracking of the upper part of the dam, development of internal stress and major deformation, degradation of the downstream facing. CFRP sheet implementation is very effective method to the strengthen concrete members along with increasing stiffness. This paper also aimed to investigate how CFRP sheet implementation effects to dynamic characteristics with varying water levels.

After repairing, the dam body was strengthened using unidirectional CFRP sheet. Unidirectional CFRP sheet and its components were provided by the BASF Corporation. MBT-MBrace®Fibre, its Saturant and Primer were used for strengthening. The properties of the dry carbon fiber sheet are; 4900 MPa tensile strength; 230 GPa elasticity modulus; 2.10% ultimate rupture strain and 0.111 mm nominal thickness per ply. Strengthening phases were practiced in some steps: a thin layer undercoat of MBT-MBrace®Primer was applied (Fig. 19(a)) to the dam body (only upstream direction), approximately 48 hour were waited to prepare the arch surface for epoxy implementation (Fig. 19(b)), MBT-MBrace Adesivo was used as an epoxy to achieve full bond between the concrete surface and CFRP sheet, and the CFRP sheets were wrapped to the dam body after curing (Fig. 19(c)). In the upstream direction, three plies of the CFRP sheet were wrapped to the surface of the arch dam body.

After seven days of curing process, ambient vibration tests were carried out to obtain the experimental dynamic characteristics for same reservoir water levels. After the strengthening application, it is seen that water leakage is completely banned with the CFRP implementation (Fig. 20). SVSDM obtained from the EFDD method for Situation-3 are shown in Figs. 21-22. As shown in figures,

Fig. 20 Some photos from Situation-3

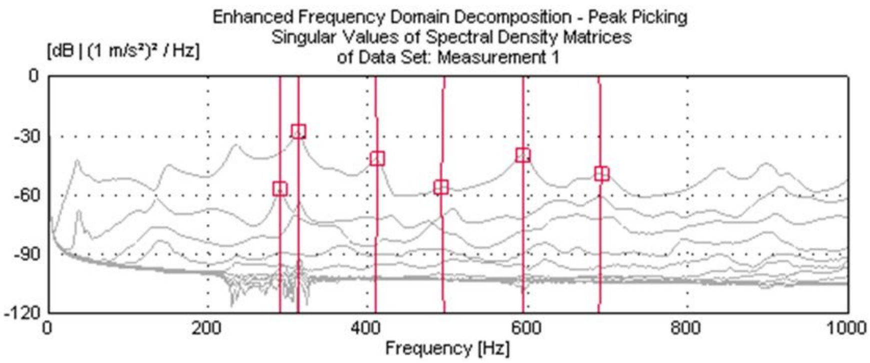


Fig. 21 SVSDM of the data set obtained from the situation-3 for the empty reservoir

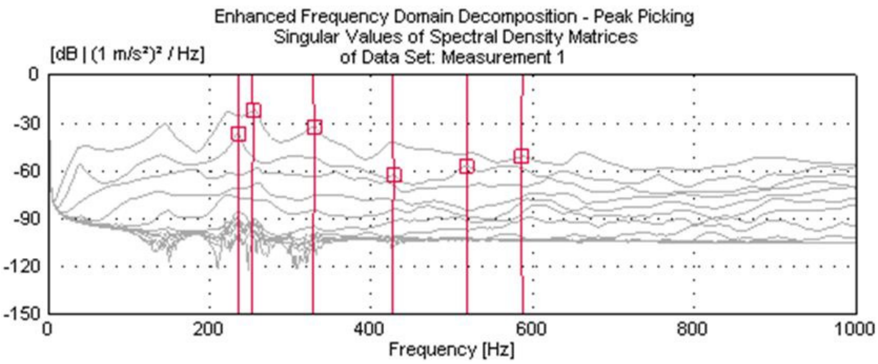


Fig. 22 SVSDM of the data set obtained from the situation-3 for full reservoir water level

six natural frequencies are obtained between 0-1000 Hz for empty and full reservoir water levels as in similar above situations. The first six mode shapes obtained for each different water level is given in Figs. 23-24. As seen in figures, symmetric mode shapes as well as antisymmetric mode shapes were observed, and they were quite realistic and close to the possible modes of undamaged dam model. The detailed information related to the undamaged dam model, such as singular values of spectral density matrices (SVSDM), average auto spectral densities of data set (AASD), mode shapes, Modal Assurance Criteria (MAC) and Coordinate Modal Assurance Criteria (COMAC) values can be obtained from the previous studies (Sevim *et al.* 2010).

The natural frequencies and damping ratios of strengthened dam model obtained for different reservoir water levels are given in Table 4. As shown in Table 4, the natural frequencies are identified between 290.4 Hz-689.6 Hz and 235.0 Hz-587.4 Hz for empty and full reservoir water level, respectively. In addition, the damping ratios are identified between 0.97-1.93 per cent and 0.81-3.09 per cent for empty and full reservoir water level, respectively. The variation of the natural frequencies and damping ratios versus the water level for the first six natural frequencies along with damping ratios are plotted in Fig. 25. The natural frequencies have a downward trend with increasing water level. This downtrend can be associated with modifications in the dam mass due to the additional mass of water. So the mass matrix of the dam, which is quite important in the dynamics behavior, is changed. The maximum difference of the frequencies obtained from the empty and full reservoir water level is calculated as approximately 25 per cent at the third mode. The damping ratios are extremely changed with increasing reservoir water level. Between the empty and full reservoir water level there is a sharp shift in the damping ratios. The damping ratios are calculated between approximately 0.10-4.42 per cent.

2.3 Examination of repairing and strengthening effects on the natural frequencies and mode shapes

Ambient vibration testing enables us to evaluate the

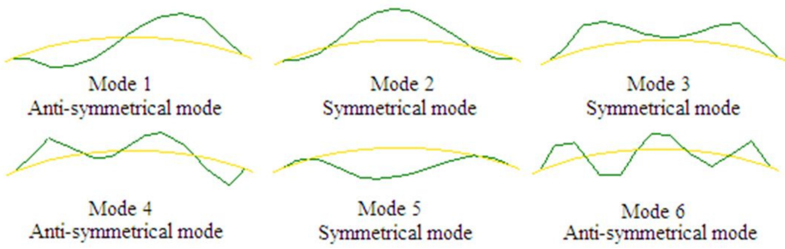


Fig. 23 Mode shapes of the strengthened arch dam obtained for the empty reservoir

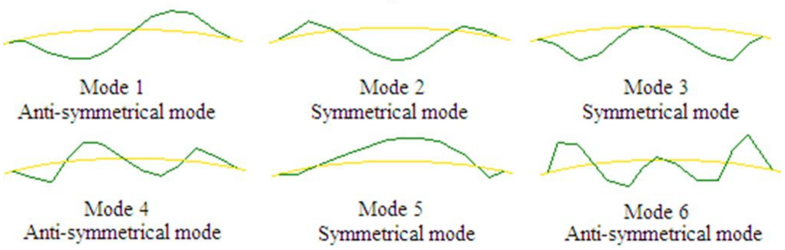
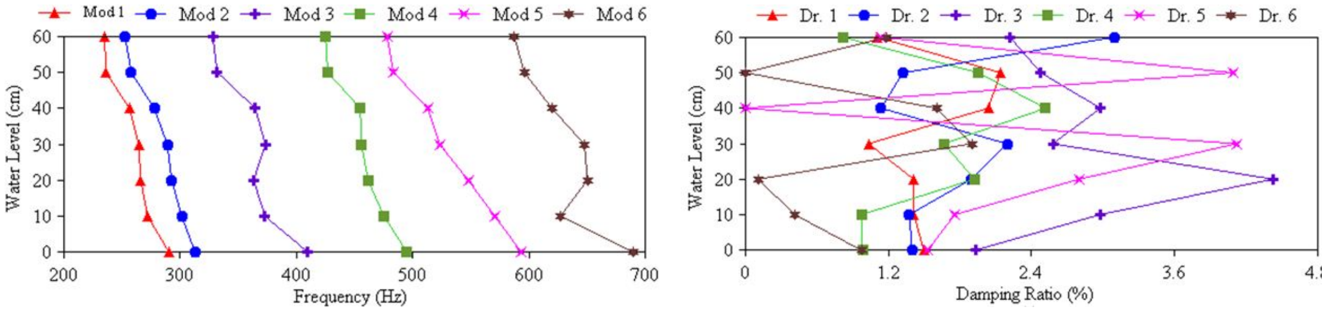


Fig. 24 Mode shapes of the strengthened arch dam obtained for full reservoir water level

Table 4 Natural frequencies and damping ratios obtained from the situation-3

Mode	Water levels													
	Empty		10 cm		20 cm		30 cm		40 cm		50 cm		Full	
	Freq. (Hz)	Dr. (%)	Freq. (Hz)	Dr. (%)	Freq. (Hz)	Dr. (%)	Freq. (Hz)	Dr. (%)	Freq. (Hz)	Dr. (%)	Freq. (Hz)	Dr. (%)	Freq. (Hz)	Dr. (%)
1	290.4	1.49	272	1.41	266.2	1.41	264.3	1.03	256.4	2.03	236.2	2.13	235	1.10
2	312.9	1.39	301.3	1.37	292.8	1.89	288.9	2.19	277.7	1.13	258	1.32	252.7	3.09
3	409.9	1.93	373	2.97	363.3	4.42	373.3	2.57	364.7	2.97	331.9	2.47	328.1	2.21
4	495.1	0.98	475.3	0.97	461.6	1.92	456	1.66	454.9	2.51	427	1.95	425	0.81
5	593.5	1.52	570.6	1.75	547.7	2.79	523.3	4.11	513	0	483.5	4.09	478	1.13
6	689.6	0.97	627.1	0.41	650.4	0.10	647.6	1.89	619.9	1.60	595.9	0	587.4	1.18

*Freg: Frequency; Dr: Damping Ratio



(a) (b)

Fig. 25 Effects of reservoir water level on natural frequencies (a) and damping ratios (b)

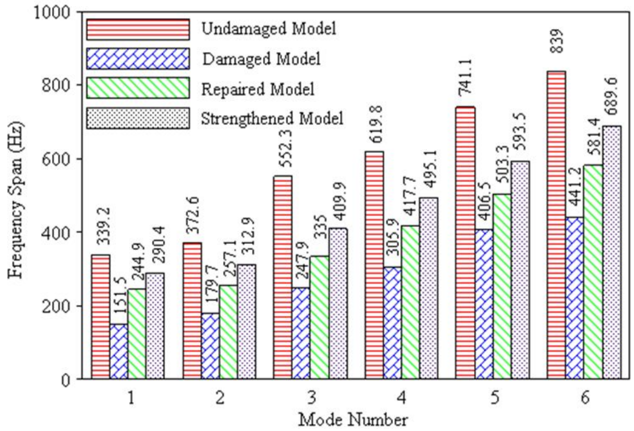


Fig. 26 Repairing and strengthening effect on the natural frequencies for empty reservoir

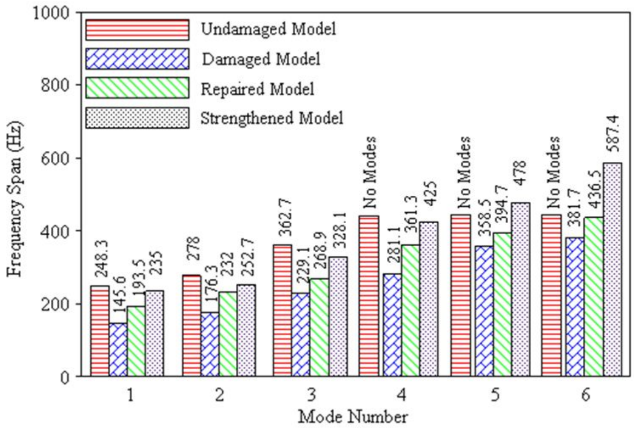
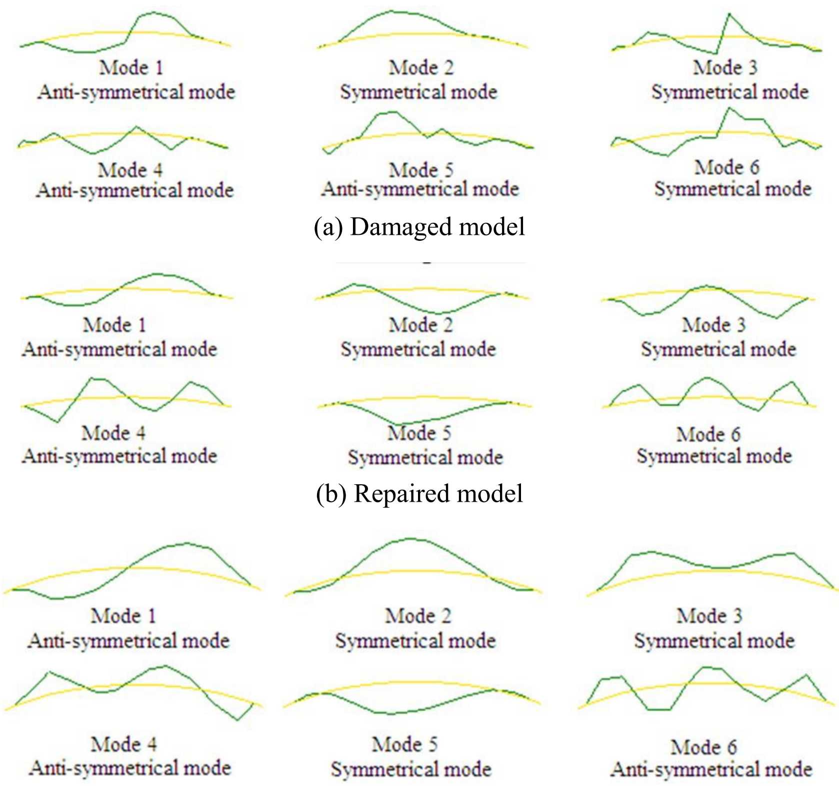


Fig. 27 Repairing and strengthening effect on the natural frequencies for full reservoir



(c) Strengthened model

Fig. 28 Repairing and strengthening effect on the mode shapes for empty reservoir changes in stiffness due to cracking, repairing or strengthening. Stiffness recovery because of repairing and/or strengthening can be determined by changes in frequencies. It is well know that the changes in the stiffness of a structural element can be estimated by variation of its dynamics characteristics such as frequencies, damping ratios and mode shapes (Pascale and Bonfiglioli 2001). In this part, the natural frequencies obtained from damaged, repaired and strengthened dam models for the empty and full reservoir are compared with each other to assess the effect of repairing and strengthening implementations on the frequencies. The mode shapes are also compared for the empty reservoir to see the changes of the mode shapes for the different situations. Fig. 26 shows the changes of natural frequencies with repairing and strengthening implementation for the empty reservoir. As can be observed, the natural frequencies increase considerably with the repairing and strengthening implementation. A total of six frequencies from damaged, repaired and strengthened dam models are obtained with a range of 151.5 Hz-441.2 Hz, 244.9 Hz-581.4 Hz and 290.4 Hz-689.6 Hz, respectively. After strengthening, between 46-92 per cent recovery in the frequencies is obtained.

Fig. 27 compares the changes in natural frequencies with repairing and strengthening implementations for the full reservoir. The natural frequencies have a decreasing trend after damage and increased significantly after repairing and strengthening for the full reservoir. From the experimental measurements of damaged, repaired and strengthened arch dam models, the six natural frequencies are identified between 145.6 Hz-381.7 Hz, 193.5 Hz-436.5 Hz and 235 Hz-587.4 Hz, respectively. From the undamaged measurements, the first three natural frequencies can only be obtained as 248.3 Hz, 278 Hz and 362.7 Hz. The frequencies recovery is obtained as between the 43-62 per cent for the full reservoir.

The first six mode shapes obtained from damaged, repaired and strengthened models for the empty reservoir is given in Fig. 28. As seen in Figs, the mode shapes after repairing and strengthening are more realistic and distinctive.

3. Conclusions

This study investigates the water level effects on the dynamic characteristics of damaged, repaired and strengthened arch dam models. To this end, ambient vibration tests are carried out on each model for different water levels to extract the natural frequencies, mode shapes and damping ratios. Ambient vibration testing are also used in this study as a method capable of assessing the stiffness variations due to both repairing and strengthening. Based on the results of this study the following conclusions are drawn:

- The first six natural frequencies before and after repairing range between 151.5 and 441.22 Hz, and 244.9 and 581.4 Hz for empty reservoir, respectively. The first six natural frequencies before and after repairing for the full reservoir range between 145.6 and 381.7 Hz, and 193.5 and 436.4 Hz. From the strengthened dam model, the obtained six natural frequencies for the empty and full reservoir are ranging between 290.4 and 689.6 Hz, and 235 and 587.4 Hz, respectively.
- The natural frequencies obtained from damaged, repaired and strengthened dam model have generally a decrease trend with increasing reservoir water levels. A decrease in frequencies associated with an augmentation of the dam mass due to added mass of water. The maximum difference between the frequencies for the empty and full reservoir are obtained as 16%, 33%, and 25% for damaged, repaired and strengthened model, respectively.
- Mode shapes are obtained as symmetrical and anti-symmetrical for each water level, and they are identical to each other. That is, mode shapes are not changed with increasing water levels. Apparently, mode shapes obtained from strengthened dam model are quite realistic and close to the possible modes of undamaged dam model.
- The increasing water levels affect damping ratios. But, there is no any harmony (regular increase or decrease) in damping ratios obtained from each water level for the all situations. The damping ratios are calculated between 0.26-4.35%, 0.23-2.68% and 0.81-3.09% for the damaged, repaired and strengthened dam models, respectively.
- The repairing and strengthening implementations have a remarkable effect in restoring the initial dynamic characteristics of the dam model. After strengthening, the frequencies recoveries are obtained as between 46-92% and 43-62% for the empty and full reservoir respectively.

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