Seismic Assessment of Existing Engineering Structures Using Ambient Vibrations

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Abstract— **Seismic assessment of existing engineering structures in earthquake zones is very important. This paper presents seismic assessments of a highway bridge and an arch dam using non-destructive tests under ambient vibrations. Firstly, finite element models of these structures are developed and analytical dynamic characteristics are attained. Secondly, experimental measurements under ambient vibrations are performed and dynamic characteristics are extracted using Enhanced Frequency Domain Decomposition and Stochastic Subspace Identification methods. Experimental and analytical dynamic characteristics are compared and finite element models are updated to eliminate the differences. Lastly, the seismic assessments of the selected structures are performed using the updated finite element models under earthquake ground motions.**

Keywords— seismic assesment; arch dam; highway bridge; dynamic characteristic; ambient vibration test; finite element model update

I. INTRODUCTION

It is generally expected that finite element (FE) models based on technical design data and engineering judgments can yield reliable simulation for both the static and dynamic behavior of engineering structures. However, because of modeling uncertainties such as stiffness of supports and non-structural elements, material properties and so on as well as inevitable differences between the properties of the designed and as-built structure, these finite element models often cannot predict natural frequencies and mode shapes with the required level of accuracy. This raises the need for verification of the finite element models of engineering structures after their construction. One of the important inspections is to apply ambient vibration tests to existing structures to estimate their dynamic characteristics and seicmic behavior [1-5].

II. FORMULATION

In this study, two different methods, which are Enhanced Frequency Domain Decomposition (EFDD) in the frequency domain and Stochastic Subspace Identification (SSI) in the time domain, are used for modal parameter extraction.

A. *Enhanced Frequency Decomposition Domain Method*

In EFDD technique, the relationship between the unknown input and the measured responses can be expressed as [6-8]

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

where $G_{xx}(jw)$ is the rxr Power Spectral Density (PSD) matrix of the input, r is the number of inputs, $G_{yy}(jw)$ is the mxm PSD matrix of the responses, m is the number of responses, $H(jw)$ is the mxr Frequency Response Function (FRF) matrix, and $*$ and superscript T denote complex conjugate and transpose, respectively. Solution of the Eq. (1) is given detail in the literature [9].

B. *Stochastic Subspace Identification Method*

SSI is an output-only time domain method that directly works with time data, without the need to convert them to correlations or spectra. The method is especially suitable for operational modal parameter identification, but it is an incredibly difficult procedure to explain in detail in a short way for civil engineers.

The model of vibration structures can be defined by a set of linear, constant coefficient and second-order differential equations [10]:

$$M\ddot{U}(t)+C\dot{U}(t)+KU(t)=F(t)=Bu(t) \qquad (2)$$

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. The force vector $F(t)$ is factorized into a matrix B describing the inputs in space and a vector $u(t)$.

III. APPLICATON

Gulburnu Highway Bridge and Berke Arch Dam are selected for application. The seismic assessments of these structures are presented using non-destructive tests under ambient vibrations.

Gulburnu Highway Bridge

Gulburnu Highway Bridge constructed within the context of East Black Sea Coast Road Recovery Project between 20+362 and 20+692km of Giresun-Espiye, Turkey, state highway is selected as an application. The construction of the bridge was started in November 2005 and the bridge was opened the traffic in May 2009. Some views of Gulburnu Highway Bridge are given in Fig. 1.

Figure 1. Some views of Gulburnu Highway Bridge.

The Gulburnu Highway Bridge is a twin prestressed concrete box girder structures. The superstructure of this bridge is a continuous single cell box girder constructed with cast-in-place which is the post-tensioned. The bridge deck consists of a main span of 165m and two side span of 82.5m each. The total bridge length is 330m and width of bridge is 30m. The deck consists of 65 segments. All of the segments[3] are nearly 5m length. The cross-section of the segments is variable along the bridge length. There are four columns, each have 4.50m height and 9.00x3.75m2 cross section areas. All columns are footing on the two raft foundation with bored piles.

Three dimensional finite element model of the bridge is constructed using SAP2000 [11] software. Deck, columns and bored piles are modelled by frame elements and raft foundations are modelled as shell element. Abutments are modelled using restricted boundary conditions and only longitudinal translational freedoms are released. Boundary conditions at the base of bored piles are defined using very rigidity springs. Post-tension cables are modelled using frame elements constrained to rotation and fixed to end of the each segments. Fig. 2 shows finite element model of the bridge. The first four mode shapes are obtained from analytical solution are given in Fig. 3. From the modal analysis, a total of four frequencies are attained between 0-5Hz. The mode shapes can be classified as vertical, torsional, transverse and longitudinal modes.

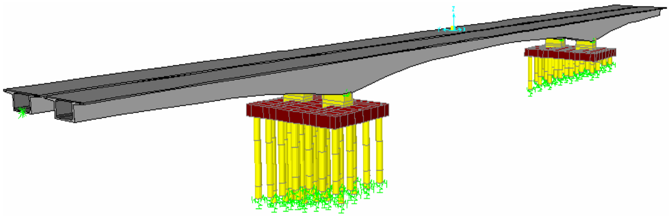
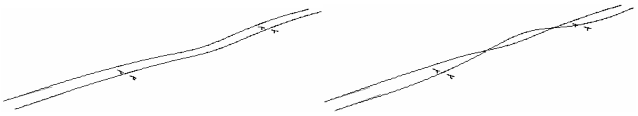
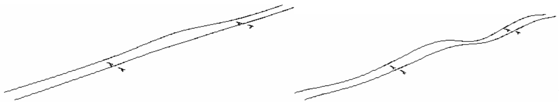


Figure 2. Finite element model of Gulburnu Highway Bridge.



f_1=1.086Hz
1st Vertical Mode

f_2=1.642Hz
1st Torsional Mode



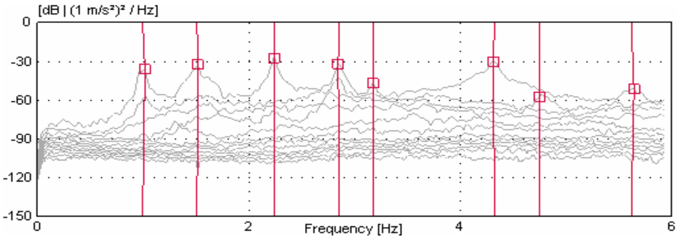
f_3=2.355H
z
1st Transverse Mode

f_4=3.102Hz
2nd Vertical Mode

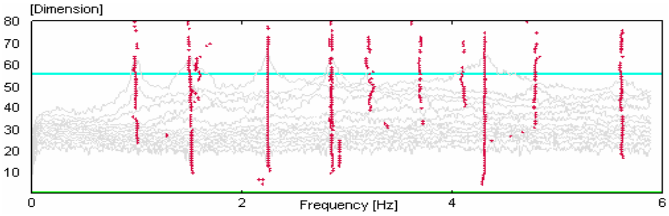
Figure 3. Analytically identified the first four mode shapes.

In the experimental measurements, the responses of the bridge are measured by uni-axial accelerometers. The signals are acquired in the data acquisition system and then transferred into the PULSE Lapshop software [12]. For parameter estimation, Operational Modal Analysis (OMA) software [13] is used. During the test in June 2009, normal traffic over the bridge was used as a source of ambient vibration. Five ambient vibration tests were carried out in the box girder. In this study only the first setup test results are presented. In the First Test Setup: Gulburnu Highway Bridge is divided into two symmetrical parts as Giresun and Trabzon. So, it is thought that dynamic characteristics of these parts should be determined and compare with each other. Therefore, Giresun part of the bridge is measured from the box girder on reciprocal points.

Singular values of spectral density matrices and stabilization diagram of estimated state space model of the first test setup attained from vibration signals using Enhanced Frequency Domain Decomposition and Stochastic Subspace Identification methods are shown in Fig. 4. The first four mode shapes obtained from experimental tests are given in Fig. 5.

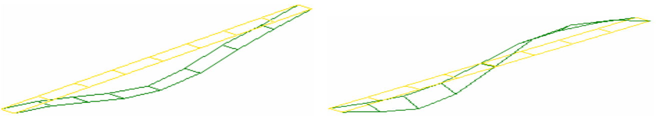


a) Singular values of spectral density matrices



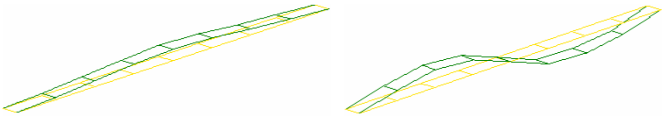
b) Stabilization diagram of estimated state space model

Figure 4. Dynamic characteristics are attained from the first test using EFDD and SSI methods.



f_{1EFDD}=0.994
f_{1SSI}=0.984
1st Vertical Mode

f_{2EFDD}=1.507
f_{2SSI}=1.500
1st Torsional Mode



f_{3EFDD}=2.238
f_{3SSI}=2.240
1st Transverse Mode

f_{4EFDD}=2.848
f_{4SSI}=2.847
2nd Vertical Mode

Figure 5. Experimentally identified first four mode shapes.

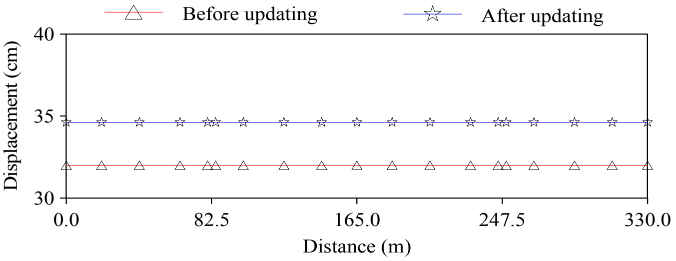
When the analytically and experimentally identified dynamic characteristics of the bridge are compared with each other, it is seen that there is a good agreement between mode shapes but some differences between natural frequencies. So, finite element model of the bridge is updated by changing of material properties (averagely %6) to eliminate these differences. Comparison of the analytical and experimental dynamic characteristics of the bridge is given in Table 1. According to Table 1, it is seen that maximum differences in the natural frequencies are reduced averagely from %9 to %2.

TABLE I. ANALYTICAL AND EXPERIMENTAL DYNAMIC CHARACTERISTICS AFTER MODEL UPDATING

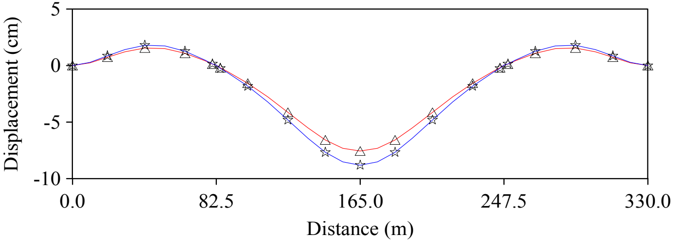
Freq. No	Analytical Freq. (Hz)		Experim. Freq. (Hz)	
	Before Update	After Update	EFDD	SSI2
1	1.086	0.994	0.994	0.984
2	1.642	1.510	1.507	1.500
3	2.355	2.285	2.238	2.240
4	3.102	2.910	2.848	2.847

Earthquake behavior of the bridge, before and after finite element model updating, is performed using Erzincan (1992) earthquake ground motion. EW, NS and UP components of the ground motion are applied to the bridge at the longitudinal, transverse and vertical directions, respectively [14]. Also, experimental damping ratios are considered in the updated analytical finite element model.

Distribution of longitudinal and vertical displacements along the bridge deck before and after finite element model updating is given in Fig. 6. It is seen that displacements after model updating are bigger than the other. Longitudinal displacements have a constant value. Vertical displacements have an increasing trend along to middle of the bridge deck. Distribution of bending moments along the bridge deck is given in Fig. 7. Bending moments have an increasing trend along to the columns and have a decreasing trend along to middle of the bridge deck.



a) Longitudinal displacements



b) Vertical displacements

Figure 6. Changing of max. displacements along the bridge deck.

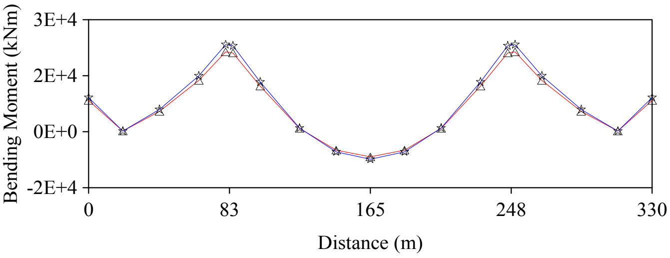


Figure 7. Changing of maximum bending moments along the bridge deck.

Berke Arch Dam

Berke Arch Dam taken place on Ceyhan River in Osmaniye is the highest arch dam in Turkey, and also it was the 16th highest arch dam in the World when it was constructed in 2001. It was built in 6 years (1995-2001) using about 700000m3 concrete on its body. It retains about 427E6m3 reservoir water and it generates about 1700E6kWh electrical energy in a year [15].

Berke Arch Dam takes place on a Narrow-V type site. It is a thin, doubled curvature arch dam. And also, it has variable radiuses and angels. It is a symmetrical arch dam along to crown cantilever. It has 201m dam height and 270m crest length [15]. Its crest length to height ratio is 1.34. The width of the crown cantilever is 4.3m at the crest and 27.12m at the base.

In 3D finite element model of Berke Arch Dam, the dam body is firstly created by ANSYS [16] software. The finite element model of Berke Arch Dam is developed considering reservoir and foundation. In 3D model, the length of the reservoir is taken to be as much as three times of dam height to represent the impounded water. The length of the foundation is taken as much as the dam height in the downstream, downward and cross directions. Because of foundation is assumed as massless, only the effects of foundation flexibility are considered in the analyses. So such a foundation model must extend to a distance beyond which becomes negligible on deflections and natural frequencies of the dam [17]. 3D finite element model of Berke Arch Dam considering reservoir and foundation is shown in Fig. 8. The first nine mode shapes and natural frequencies of Berke Arch Dam obtained from finite element analysis are shown in Fig. 9. The frequencies change between 2.19-11.27Hz. As it can be seen from Fig. 9, symmetrical, anti-symmetrical and vertical modes are obtained.

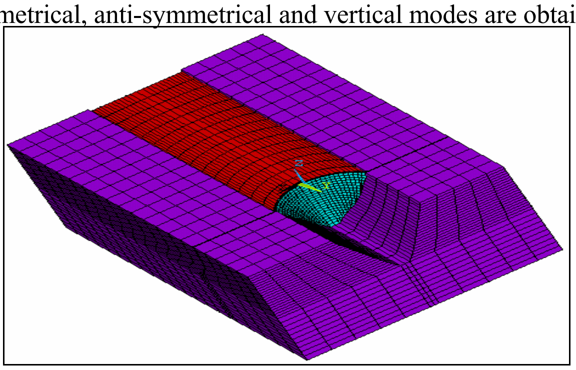


Figure 8. 3D finite element model of Berke Arch Dam-reservoir-foundation system.

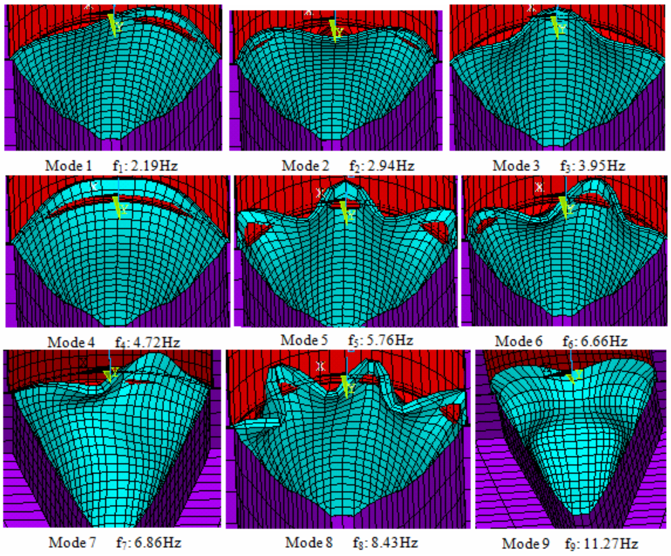


Figure 9. Analytically identified the first four mode shapes.

Six ambient vibration tests were conducted to Berke Arch Dam during the period between on May 24th and May 28th, 2009 to obtain experimental dynamic characteristics. In this study only sixth setup test results are presented. In the tests, the responses of the dam are measured using B&K 8340 type uni-axial accelerometers which have 10V/g sensitivity.

Singular Values of Spectral Density Matrices (SVSDM) of data set for the sixth test attained from vibration signals using EFDD technique is shown in Fig. 10. SVSMD of data sets obtained from the other tests are similar to this test, so they are not given in this paper.

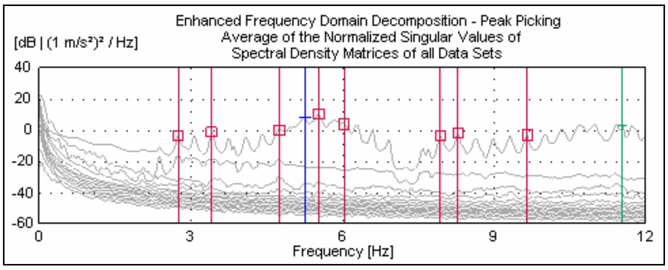


Figure 10. SVSDM of data set for the sixth ambient vibration test.

The mode shapes, natural frequencies and damping ratios of Berke Arch Dam obtained from the sixth test are shown in Fig. 11. The frequencies change between 2.75-9.66Hz. As it can be seen from Fig. 11, the first, forth, and eighth mode shapes are anti-symmetrical; second, third, and sixth mode shapes are symmetrical.

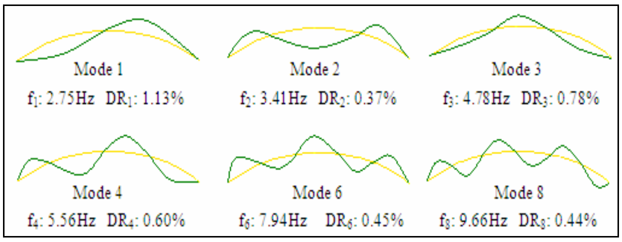


Figure 11. Experimental dynamic characteristics of Berke Arch Dam obtained from the sixth test.

It is clearly seen from Figs. 9 and 11 that there are some differences between analytical and experimental natural frequencies. The material properties are selected as updated parameter. Comparison of experimental, initial and updated analytical frequencies is given in Table 2.

TABLE II. ANALYTICAL AND EXPERIMENTAL FREQUENCIES OF THE DAM

Modes (Hz)	Anly. Initial	Diff, (%)	Exp. Test 6	Diff. (%)	Anly. Update
1	2.19	20	2.75	7.2	2.55
2	2.94	14	3.41	0	3.41
3	3.95	17	4.78	1.7	4.70
4	4.72	15	5.56	1.4	5.48
5	5.76	6.3	6.03	1.3	6.07
6	6.66	16	7.94	3.4	7.67
7	6.86	19	8.28	3.1	8.19
8	8.43	13	9.66	1.1	9.77

Earthquake behavior of Berke Arch Dam is investigated before and after the finite element model updating (calibration). Time history analyses of Berke Arch Dam are performed using C2T4998A/CYH-EW component of 1998 Ceyhan Earthquake [18].

The variation of maximum horizontal displacements on the crest section of Berke Arch Dam for the initial and calibrated FEM is shown in Fig. 12. The displacements are increased trough to middle of the crest. The displacements obtained from initial model are bigger than those of the calibrated model.

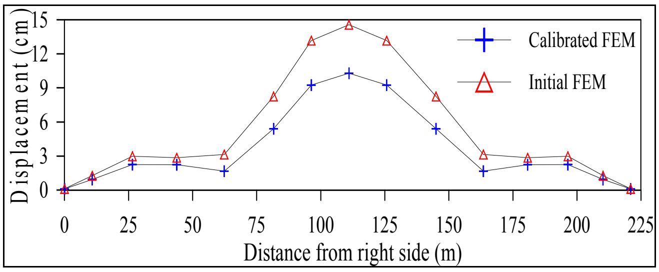


Figure 12. Variation of horizontal displacements on crest of dam

The variation of maximum and minimum principal stresses along key section is plotted in Fig. 13, respectively. The stresses are generally increased to 180m height, and then they are decreased a little at the top of the dam.

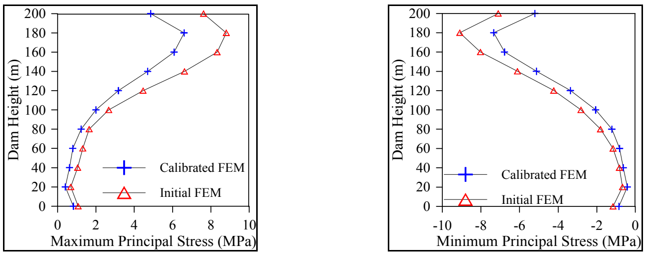


Figure 13. Variation of max. and min. stresses on key section

VI. RESULTS

In this paper the seismic assessments of Gulburnu Highway Bridge and Berke Arch Dam are investigated using non-destructive tests under ambient vibrations. The following observations can be made from this study.

Gulburnu Highway Bridge

- Analytical and experimental natural frequencies of the bridge were attained at ranges between 0-5Hz for the first six modes. These can be classified into vertical, torsional, transverse and longitudinal modes.

- There was an approximate 9% difference between natural frequencies predicted from the finite element model and modal testing, and analytical frequencies are bigger than those of the experimental. To eliminate differences, finite element model of the bridge was updated by adjusting of material properties. Maximum differences between analytical and experimental natural frequencies were reduced to 2%.

- Earthquake evaluation of the bridge was determined using Erzincan earthquake. Displacements, axial and shear forces and moments obtained from the updated finite element model of the bridge are bigger than those of the initial model.

Berke Arch Dam

- The first eight analytical and experimental natural frequencies are obtained between 0-10Hz. There is about 15% difference between initial analytical and experimental results.

- Mode shapes obtained from analytical and experimental solutions are similar to each other. Symmetrical, anti-symmetrical and vertical mode shapes are obtained from finite element analysis. However only symmetrical and anti-symmetrical mode shapes are obtained from ambient vibration tests.

- After calibration of the analytical model, the differences between natural frequencies become about 2-3%.

- Maximum displacements are obtained as 14.6cm and 10.3cm, respectively from earthquake analyses of initial and calibrated models. They are occurred at middle point of the crest. Also displacements are increased from the bottom to top of the dam, and they are decreased through to abutments at the crest.

- Maximum and minimum stresses obtained from the initial model are bigger than those of the calibrated model over the dam body.

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