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Full-scale experimental modal analysis of an arch dam: The first experience in Iran

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ABSTRACT

Forced vibration field tests and finite-element studies were conducted on the Shahid Rajaee concrete arch dam in Northern Iran to determine the dynamic properties of the dam–reservoir–foundation system. The first forced vibration tests on the dam were performed with two different types of exciter units, with a limited maximum force, bolted on the dam crest for alternative in-phase and out-of-phase sequencing. Because of an insufficient number of recording sensors, two arrangements of sensors were used to cover sufficient points on the dam crest and one gallery during tests. Two kinds of vibration tests, on–off and frequency sweeping, were carried out on the dam. The primary natural frequencies of the coupled system for both symmetric and anti-symmetric vibration modes were approximated during on–off tests in two types of sequencing of exciters, in phase and out-of-phase, with a maximum frequency of 14 Hz. The principal forced vibration tests were performed at precise resonant frequencies based on the results of the on–off tests in which sweeping around the approximated frequencies at 0.1 Hz increments was performed. Baseline correction and suitable bandpass filtering were applied to the test records and then signal processing was carried out to compute the auto power, cross power and coherence spectra. Nine middle modes of vibration of the coupled system and corresponding damping ratios were estimated. The empirical results are compared against the results from calibrated finite-element modeling of the system using former ambient vibration tests, considering the dam–reservoir–foundation interaction effects. Good agreement is obtained between experimental and numerical results for eight middle modes of the dam–reservoir–foundation system.

1. Introduction

Accurate earthquake analysis of dams is critical because their failure can result in major loss of life and cost. Any analysis process is evaluated by its capability to reproduce or predict observed behavior. Dynamic properties such as natural frequencies, mode shapes and damping ratios are very important parameters in computing the response of dams to earthquakes. Simplifying assumptions are usually made in analytical and numerical techniques when computing these properties. Such simplifications may lead to inaccurate results because of the complexity and uncertainties in the parameters of the coupled system. Uncertainties of a dam–reservoir–foundation system include: (a) material properties of concrete, jointed anisotropic rock masses, sediments, and reservoir bed structure; (b) geometry such as topographical features and mass distribution, joint contact surfaces, foundation cavities, and reservoir shape; (c) initial load condition, for example, noise, pore pressure, temperature, stress and boundary conditions; and (d) actual main load estimations. Full-scale dynamic tests are recognized as the most reliable method to evaluate a structure's vibration properties. The requirement for this kind of tests is increasing, as new analysis techniques are developed to consider the complex interaction phenomena that occur in many structures and particularly in dam–reservoir–foundation systems. The accuracy of state-of-the-art numerical methods used to evaluate the seismic behavior of dams can only be truly assessed by comparing results with experimental measurements on existing structures. Experimental investigations such as vibration tests are very useful toward this end, even with a low-level excitation. There are different kinds of vibration tests, which are used to obtain the dynamic properties of dams. A forced vibration test on an existing structure is one of the most accurate methods to obtain its dynamic properties, which legitimizes the cost of this kind of test. The most common forced vibration tests employ steady-state

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sinusoidal excitation. In “frequency sweeping” a harmonic load is applied on the dam at different frequencies and its response in the time domain is recorded. The dynamic properties can be estimated by computing the Fourier transform of these responses.

Hatano and Takahashi [1] were the first to use the auto correlation technique on experimental data to obtain the vibration period of structures. They used this method to evaluate the dynamic properties of a concrete arch dam using data collected on the crest of the dam during an earthquake. Takahashi et al. used the same technique on another dam [2]. Deinum et al. carried out forced and ambient vibration tests on the Emmoson arch dam and estimated the dynamic properties of the dam using the auto and cross power spectra [3]. The Monticello Dam was subjected to forced vibration tests in 1967 and again in 1982 and 1986. The 1967 tests employed two shakers (22 kN maximum force each, 10 Hz maximum frequency) with radial forces either in- or out-of-phase to excite symmetric or anti-symmetric responses. Resonant frequencies and mode shapes were computed in conjunction with earliest tests using an arch-cantilever model of the dam and a lumped mass representation of the water. All computed eigenfrequencies fell below the corresponding measured ones by between 12% and 19%, which could be due to inaccuracy in the arch-cantilever model or overestimation of the effect of the water. Two large shakers were employed in the 1982 tests (556 kN maximum force each, 30 Hz maximum frequency) to investigate possible nonlinear effects under different levels of exciting force. Variations in the total force level from 47 kN to 437 kN indicated no nonlinearity in either the frequency or damping of the fundamental mode [4]. The third set of forced vibration tests on the Monticello dam was carried out to investigate water compressibility effects and included measurements of dynamic water pressure at different depths. The water pressure responses peaked at frequencies close to those observed for the dam [4]. In 1990, Severn et al. conducted dynamic tests of a large arch dam along with a comparison with its mathematical model [5]. The results were obtained in terms of stresses and hydrodynamic pressures. Furthermore, in 1994, Duron et al. presented a paper on dynamic vibration tests (including forced and ambient) on the Big-Creek Dam [6]. They carried out an accurate identification process for symmetric and anti-symmetric first and second modes. In 1996, Loh et al. performed ambient vibration tests on the Fei Tsui Dam to study the decrease in the frequencies of the first two modes of the structure due to raising the reservoir water level [7]. In 1999, Daniell and Taylor precisely confirmed the ambient vibration test results with modal analysis methods [8]. Darbre et al. used ambient vibration test to obtain natural frequencies of the Mauvoisin Dam [9]. Proulx and Paultre carried out forced vibration tests on the Outardes 3 gravity dam in northern Quebec, Canada in summer and winter conditions [10]. The results indicated possible joint motions in hot summer conditions, which were even more obvious in harsh winter conditions. Forced vibration test results obtained during winter conditions clearly indicated joint motions, but more importantly highlighted a change in the dynamic behavior due to the thick ice cover present during winter [11]. Forced vibration tests carried out on the Emosson arch dam, on the border of France and Switzerland, during a 1-year period have shed some new light on the important dam–reservoir interaction effects and on the impacts of the water level [12]. Several attempts have been made to identify the modal properties of the Pacoima Dam since the San Fernando earthquake in 1971. Forced vibration tests were performed in July 1971, April 1980 and July/August 2002; and recordings from the 1994 Northridge and January 13, 2001 earthquakes were employed in a system identification study. In all cases, two fundamental modes were identified with symmetric and anti-symmetric shapes, and the symmetric mode had a lower frequency than the anti-symmetric mode. However, the natural frequencies and damping of the identified modes varied [13].

While state-of-the-art mathematical modeling for dynamic analysis of concrete dams has advanced rapidly during recent years, few verification studies have been done using experimental tests around the world, and in particular no tests have been conducted in Iran. This paper describes the first forced vibration test on a modern concrete arch dam in Iran using equipment with rather limited capabilities. Due to the absence of effective equipment such as an adequate number of sensors for recording the response and exciters with appropriate force levels, we had to be innovative in our testing. Classical signal processing using the auto, cross and coherence spectra of the records from the forced vibration tests was used to evaluate the dynamic properties of the concrete arch dam.

2. Forced vibration tests on Shahid Rajaee arch dam

A forced vibration test was conducted on the Shahid Rajaee double curvature concrete arch dam in Iran. The dam is located on the Tajan River, approximately 35 km South-East of Sari City, the capitol of the Mazandaran Province (200 km North-East of Tehran). Its design and construction was performed between 1989 and 1997. The reservoir water level was 18 m below the crest during the forced vibration tests. The main specifications of the dam are presented in Table 1.

A non-traditional approach to forced vibration testing was adopted for the experiments on this dam. Typically, tests are performed using a large crew and a significant amount of test equipment. The forced vibration test described herein was especially designed to utilize the minimum amount of equipment that was available.

Forced vibration tests were conducted using available IIEES (International Institute of Earthquake Engineering and Seismology) testing facilities and equipment as described below:

- One single motor and one double motor exciter units with maximum exciting forces of 30 and 20 kN, respectively, were used. Such exciters are commonly used for small structures like buildings. Since these exciter units had different properties and smaller capacities than what are used for massive structures such as dams, some electronic and mechanical devices were designed and used to control the synchronization of the exciter's operation to produce a reasonable exciting force and their operation in dual in-phase and out-of phase sequences.
- Two types of response recording sensors, nine FBA-11 accelerometers and nine SS-1 seismometers.
- Six SSR-1 data acquisition system and two portable computers.

2.1. Optimal arrangement of exciter units and sensors

A finite element model of the dam–reservoir–foundation system corresponding to the real geometry of the dam and site topography was developed. Modal analysis of the finite element model was carried out and the mode shapes of the dam were represented on the plan view to find the best arrangement of the exciter units and sensors. From a theoretical aspect, the best

Table 1
Shahid Rajaie dam specifications.

Type of dam	Double curvature
Crest length	427 m
Height	138 m
Thickness at base	27 m
Thickness at crest	7 m
Reservoir volume	191.5×10^6 m^3