The Value Added of Field Testing on Concrete Dams

by

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ABSTRACT

In general, field testing of concrete dams has not been widely embraced by dam owners and it is not typically regarded as an essential component in the process of evaluating the seismic performance of these massive structures. Over the years, proponents of field testing and the use of measured response behavior to validate numerical models have had difficulty convincing the broader consulting community of the added value associated with the costs of field testing. This is not to say, however, that the importance of field testing is not fully appreciated or understood. This paper is intended to present a current viewpoint associated with the state of field testing of concrete dams and the potential benefits derived from the availability of test data in evaluating seismic performance. A brief description of a recently completed seismic evaluation is discussed and presented as a case study to investigate the role played by the associated field testing and inspection program.

KEYWORDS: Field Testing; Seismic Evaluation; Concrete Dams.

1. INTRODUCTION

In 1990, a comprehensive report prepared with support of the National Research Council of the United States reviewed the state of practice on seismic design and evaluation of concrete dams and identified the corresponding research needs (NRC, 1990). This document also provided recommendations and improved criteria for evaluating the seismic performance of concrete dams. It was noted that as early as the 1950s, concrete dams were assumed essentially rigid systems even though the importance of their dynamic behavior was partially recognized. About a decade later, it was understood that amplifications large enough to cause damage could occur in concrete dams, but the analytical tools were not yet widely available for a proper consideration of these effects. With the introduction of analytical tools to evaluate effects of dam-foundation-reservoir interactions in the 1970s, improvements in the criteria to evaluate results from analytical studies were needed. For example, it was recognized that the numerical prediction of tensile stresses large enough to indicate initiation of cracking and/or compressive stresses larger than allowable working levels did not necessarily indicate instability. With the advent of advanced analytical techniques and computer technology, nonlinear analysis techniques and nonlinear material behavior of dams occupied much of the research focus in the 1980s and 1990s. Still, it is probably the case today that many consultants would prefer to avoid a full nonlinear analysis in-lieu of a linear elastic study supported by post-earthquake stability evaluation. Although inherently restricted by the linearity assumption, undoubtedly these types of studies still provide a great deal of information about the earthquake response that can be expected under realistic conditions.

An exhaustive review of experimental behavior and field-test data of concrete dams was presented by Hall (1988). This study examined available knowledge of the seismic behavior of concrete dams from observations made during actual earthquakes and from experiments conducted on prototype and model dams. Near the end of his review, Hall addressed the

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usefulness of testing techniques in the context of model validation. For example, a model's ability to reproduce field-test data acquired at varying water depths tests the model's distributed qualities in that comparisons are not only made at resonant peaks, but at frequencies between resonances as well. In addition, resonances predicted by models using material properties obtained from sample core testing can be compared against field-test findings. Furthermore, dynamic tests on dam models can be used to determine resonant frequencies and response shapes, and model testing can be most useful in the investigation of nonlinear dam response behavior.

Hall made a rather significant observation concerning water compressibility and model validation. Although a number of investigators had attempted to gather information on water compressibility, Hall reported that only one study had ever claimed the presence of significant water compressibility effects. Since his review, however, additional attempts at measuring compressibility effects have been made. Forced vibration tests were conducted on large concrete gravity dams in Canada during the 1990's in which measurements of acceleration and hydrodynamic pressure along the upstream dam face were used to evaluate dam-reservoir interaction effects (Proulx, 1994; Duron, 1995). Another series of experimental studies were conducted at Longyangxia Dam in China under the U.S.-China Protocol on Earthquake Studies (Ghanaat, 1999). The excitation for these field measurements was generated by the controlled detonation of explosive charges. In all these cases, the investigators were able to show probable compressibility effects associated with measured response behavior in the dam and in the reservoir. However, an exhaustive investigation regarding the significance of these effects in the context of a complete seismic evaluation has yet to be pursued.

Ventura and Horyna (1996) recently presented an updated literature review on vibration tests of large dams covering the period from 1975 to 1995. In general, these types of experimental studies are usually associated with a companion model validation effort. For example, the U.S. Bureau of Reclamation recently conducted a series of seismic safety evaluation studies of Morrow Point Dam using numerical models and available experimental measurements (Nuss and Chopra, 2001; Nuss et al., 2003). The objective of these studies was to adjust material properties and reservoir absorption coefficients to match measured behavior from the forced vibration tests on the dam. These studies attempted to characterize the sensitivities to various input parameters based on comparisons against measured field test results. Dramatic differences were found in the predicted maximum tensile stresses depending upon the analysis technique employed. For example, following a traditional analysis in which the foundation is considered as massless and incompressible added masses are used to represent the hydrodynamic effects, stresses as high as 9.9 MPa were obtained as compared to 2.3 MPa from an analysis with foundation mass and water compressibility interactions.

The availability of measured or observational evidence of how a dam system behaves can provide the analyst with a wealth of knowledge with which to critically evaluate analytical findings. In what follows, the authors will present a case study in which low level ambient field tests were instrumental in providing insight into the predicted seismic performance of a large concrete dam.

2. CASE STUDY: SEISMIC EVALUATION OF FLORENCE LAKE DAM

2.1 Description

Florence Lake Dam is located on the South Fork of the San Joaquin River, on the western slope of the Sierra Nevada, in Fresno County, California, approximately 93 km northeast of the city of Fresno. The dam and reservoir are owned and operated by Southern California Edison Company and is a 46-meter-high, reinforced concrete multiple-arch dam with a total crest length of 962 m. The dam, which was completed in 1926, consists of 58 arches (inclined 48 degrees to the vertical), each with a span of 15.2 m supported by counter forted buttresses. The dam consists of five tangent sections to take advantage of a rock ridge at the lower end of the reservoir basin. An aerial view is shown in Figure 1.

2.2 Analysis Approach

Florence Lake Dam had been the subject of various seismic evaluations since 1971 and the most recent study was commissioned in 1992 and completed in 2001. Complicating factors in the analysis of Florence Lake Dam stemmed from the complexity of the dam geometry, foundation stability concerns, and the acceptance of proposed analysis techniques for a multiple, thin arch reinforced concrete dam. While it is not the purpose of this paper to review the details associated with the Florence Lake Dam study, the study does serve as a great example to illustrate the value added of field investigations to improved understanding of predicted response behavior.

A diagram of the evaluation procedure followed for this study is shown in Figure 2. The numerical analyses performed for the seismic evaluation of Florence Lake Dam essentially consisted of two separate approaches. Each analysis, however, was motivated by different objectives. When the original analysis was conducted, it was determined that modeling the entire dam would be inefficient and unnecessary since a particular portion of the dam, namely the River Section, contained the 9 tallest arches and was considered to be the most critical portion for the evaluation. The engineers further determined that this section exhibited sufficient symmetry about the middle arch and that a symmetric analysis approach could be pursued. The numerical model (hereafter referred to as the symmetric model) for the symmetric analysis approach is shown in Figure 3. The finite element analysis of the symmetric dam-foundation-reservoir model was completed using the computer program EACD-3D.

Results from the symmetric analysis were presented to a Review Board in 1994 but did not meet with full acceptance over concern that a region of the River Section not contained in the symmetric model might not be accurately evaluated. The Board expressed additional reservations concerning the foundation material properties and stability at that time. Largely in response to the Board’s concerns, a detailed 3-D numerical model of the full River Section (hereafter referred to as the full model) was developed and analyzed using commercially available software. The model is shown in Figure 4.

2.3 Conflicting Analysis Results

The decision to continue the seismic evaluation of Florence Lake Dam by pursuing a second analysis approach resulted in seemingly irreconcilable differences in the predicted stress and deformation characteristics of the River Section. Static stress levels (both tensile and compressive) based on the symmetric model were found to be within acceptable concrete strength limits. Corresponding stress results using the full model, however, predicted regions of comparatively high static tensile stress in the dam near the arch-haunch interface. Static tensile stresses approaching 5.52 MPa were predicted in these areas, suggesting that the arches would be cracked parallel and adjacent to the haunch. Dynamic stress results from the symmetric model indicated that dynamic tensile stresses of 5.1 MPa (earthquake only, not considering static loading) would occur near the top of the highest arches in the River Section during a large earthquake. Results from the full model predicted dynamic tensile stresses on the order of 6.90 MPa occurring at about the same location.

2.4 Model Validation Efforts

Model validation based on observable information could provide enhanced confidence to utilize model results in assessing the current and predicted behavior of a dam. In the case of Florence Lake Dam, the analysts performing the analysis felt the need to comparatively assess the accuracy of the full model using the results from a validated symmetric model of the dam to perform their assessment. Upon validation, the symmetric model served to provide a context for the results obtained from the full model and aided the analysts in assessing relative conservatism in predicted stress levels in the dam.

Validation of a model is achieved if response characteristics derived from the analysis (e.g. resonant frequencies and response shapes) can be matched favorably against actual observed behavior. In the absence of actual dam response measurements due to earthquake excitation, dynamic testing of the complete river section using artificially applied excitation was considered. Available options for applying a known excitation to the dam included eccentric mass vibrators or low-level impact devices such as a calibrated hammer. Both options were discarded due to logistics associated with transporting heavy test equipment to the dam site and with safety concerns associated with the installation of large machinery onto the narrow crest at Florence Lake Dam.

Dynamic testing of the river section of Florence Lake dam was performed using the ambient testing technique. Ambient testing was particularly well suited at Florence Lake since no artificial excitation to the dam is required for an ambient test. In addition, ambient responses could be obtained with relative ease, with sufficiently high reliability and accuracy, and at low cost. The test procedure involves the monitoring of ambient acceleration responses over a sufficient length of time to ensure adequate signal quality and statistical confidence in identified response characteristics.

Acceleration responses were obtained using extremely sensitive servo force-balance accelerometers with micro-g sensitivity and flat frequency response characteristics. A triad (three accelerometers mounted in a small aluminum block) was used to acquire responses in the radial, tangential, and vertical directions at each measurement station along the arches. Figure 5 is a schematic of the measurement layout followed during the ambient tests. Two separate ambient surveys were completed at Florence Lake Dam in September 1995 and again in December 1995 under full and empty reservoir conditions, respectively. Testing under varying reservoir conditions presented a unique opportunity to investigate dam-foundation and dam-reservoir interaction effects as predicted by the results from the EACD-3D numerical model. Test procedures, instrumentation details, and measurement layouts were identical for each test. A total of 37 measurements along the crest (arches 52, 53, and 54) and 4 locations along the height of the tallest buttress between arches 52 and 53 were acquired. The location to the left of the center of arch 53 was selected as the reference for each test. Actual testing was completed by simply placing the triad block of accelerometers at each measurement station (two stations and the reference were monitored at a time) and time histories were acquired over a 6-minute period sampled at 200 samples per second. Signals were band-passed filtered and amplified prior to digitization.

Subsequent data analysis was performed using traditional fast Fourier transform (FFT) techniques in which spectral estimates of power spectral density (PSD), frequency response (FRF), and coherence functions were computed. Resonances in the dam were identified based on observed resonant peaks in the PSDs coincident with high coherence values (approaching unity). A comparison of the PSD (radial) reference response under both full and empty reservoir conditions is shown in Figure 6. Both curves indicate excellent data quality in terms of signal-to-noise ratios and identified resonances, typical throughout both series of tests. FRF information was combined over all measurement stations to produce response shapes for each identified resonance. Data from each ambient survey were used to validate the model as described below.

Ambient response shapes derived from the tests were easily characterized as either symmetric or antisymmetric, facilitating a direct comparison with computed symmetric and antisymmetric model characteristics. A first evaluation of whether the symmetric model and analysis approach could adequately represent the actual dam response behavior was based on comparisons of dam-foundation eigenvalues and eigenvectors against resonances and response shapes identified from the empty reservoir ambient tests. A second comparison was performed using the computed complex frequency response of the generalized coordinates for the dam-foundation-reservoir system. The computed characteristics were then compared against those determined from the full reservoir ambient responses.

Results from the first comparison between the eigensolution of the dam-foundation sub-system and the empty reservoir ambient test results are described below. Table 1 lists computed eigenvalues and measured resonances below 10 Hz. The frequency comparisons provided a measure of confidence that the model response characteristics were in good agreement with observed behavior. A better understanding of the model response behavior, however, was obtained by comparing the measured response shapes with the eigenvectors.

The measured response shapes from the ambient tests are interpreted as linear combinations of the actual modal responses of the dam system. In as much as the measured power spectral density functions indicate well-spaced, lightly damped resonant responses, the measured shapes can be considered as mode shapes. Therefore, the comparison of eigenvectors associated with the dam-foundation sub-system against mode shapes from the empty reservoir ambient survey was considered appropriate. Shown in Figures 7 and 8 are comparisons of the fundamental symmetric and antisymmetric responses. A reasonable match in mode shape for each case is observed.

The second comparison was made between the computed frequency response behavior of the model against the measured characteristics from the full reservoir ambient survey results. Table 2 lists the computed system resonances along with measured resonances from the ambient (full reservoir) tests. The comparison in Table 2 is deemed quite favorable, and it provides additional evidence to support the analysis approach taken. The computed response shape at 3.5 Hz against the measured shape from the ambient (full reservoir) tests is shown in Figure 9. Computed resonances beyond 3.5 Hz are characterized by broader, more closely spaced peaks indicating some degree of modal coupling is present in these responses. Associated response shapes are more likely to contain contributions from higher frequency mode shapes.

Based on the comparison studies completed, and the results presented above, the response characteristics associated with the symmetric model appeared to be in good agreement with known response characteristics associated with the dam for both empty and full reservoir conditions. The validated symmetric model allowed the analysts to evaluate the degree of conservatism associated with the results from the full model. The validated model provided a sound baseline for the analyses using the full model and these comparisons increased the confidence in its application.

2.5 Consideration of Additional Field Data

In an attempt to correlate the analytical predictions of static stresses with probable cracked areas in the dam, a site inspection was conducted in 1998 under empty reservoir conditions. The detailed inspection included examination of every arch for signs of cracking consistent with analysis findings. The upstream arch faces, covered with 7.6 cm (nominal thickness) of shotcrete were observed to be in excellent condition. No significant cracking was observed in the shotcrete, at least any that could be attributed to the possible presence of cracks in the original or parent concrete. No cracking could be seen along the arch-haunch interface. Inspection of the downstream arch faces, however, did reveal the presence of cracks. The cracks, however, were not in the location suggested by the calculations, but were oriented vertically along the height of the arch (almost symmetrically placed about the crown) over each quarter point. It is interesting to note that the cracking observed is of the type discussed by Janas and Sawczuk (1964). These observed crack patterns at Florence Lake Dam were not consistent with the predicted regions of high static tensile stress from the full model analysis.

As a result, additional field evidence was sought that could reconcile the discrepancy between the predicted static behavior and the observed condition of the arches. Attention focused on the results from a previous analysis of the structural behavior of arch 21 in the dam (Bechtel, 1952). This study was based on data gathered at approximately forty locations along the downstream face of the arch. Based on the measured data, the maximum static deflection magnitude at the crown was estimated as 0.18 cm. The corresponding value predicted using the full model was 0.25 cm. In general, it was found that the static deflected shape predicted by the full model was in good agreement with the measured deflections demonstrating that tension could be developed in the arch under static loading at the crown and near the haunch.

The magnitude and pattern of the deflections observed in the 1952 study seemed to indicate the development of tensile stresses in the arch under full reservoir loading. However, the analyst rejected these measurements as unreliable based on the assumption of compressive arch behavior under static loading. This conclusion was probably correct, but not because the measured deflections were not real. Instead, the combined effects of different phenomena probably resulted in a redistribution of the load carrying capacity of the arch. Time variant conditions such as the cyclical loading and unloading associated with daily temperature variations and seasonal freezing and thawing cycles can affect the heterogeneous material composition of concrete. While creep can cause stress intensities to change, shrinkage stresses induce self-balancing stresses of unknown magnitude resulting in erratic, unpredictable crack patterns. Although finite element analysis may indicate that the arches could develop static tensile static stresses as high as 5.52 MPa, significant stress relief and redistribution in the arches is believed to have occurred over the dam's lifetime ensuring continued and adequate load carrying capability. Considering these factors, it is unlikely that the exact state of stress in the dam prior to an earthquake can be accurately known.

The predicted static stress state, therefore, if it ever existed in the dam, must have occurred during its early years (uncracked condition, prior to significant reservoir loading). At that time, cracking probably relieved excessive tensile stresses and subsequent loads were then carried by compressive, tensile, and shearing stresses in the remaining uncracked portions of the arch. In fact, much of the cracking observed in the arches must have occurred upon initial filling of the reservoir and was probably a result of the dam initially acting as an unreinforced or plain concrete structure. Therefore, any linear elastic representation of an actual dam in a cracked condition would tend to overestimate the current static stress state.

It is clear that the exact magnitudes of the dynamic stresses in the dam cannot be predicted accurately for reasons similar to those expressed earlier in the discussion of the static stress condition. However, the strong motion duration as long as 30 seconds (indicated in the stress time histories) and the large number of expected stress cycles suggested that tensile stresses in the dam would likely exceed the tensile strength of the concrete during the earthquake and lead to cracking. Therefore, an evaluation approach that considered the possible cracking scenarios would be needed to complete the study. This led to the development of a deformation-based evaluation approach for the final assessment of the expected seismic performance of the dam, as an attempt to resolve the discrepancies in stress results.

2.6 Deformation-Based Evaluation

Examination of the deformed shape of the dam during earthquake loading was used to provide understanding of the locations in the dam where cracking could be expected to occur. In particular, a review of the predicted animated dam response (using the full model) revealed excessive rotation at the haunch driven by cross-stream movements of the buttresses. Arches were squeezed when two adjacent buttresses moved toward each other, and were flattened when the buttresses moved away from each other. The importance of the rotation at the haunch and its effect on the expected condition of the arches led to a series of parametric studies aimed at identifying the range of motions that the haunch could experience during strong motion. Parameters included concrete modulus and/or section properties in the arches, buttresses, and at the haunch interface. Results from these studies focused attention on the arch side of the haunch, while demonstrating that the buttress side of the haunch would experience low tensile stress levels during the earthquake.

Cracking associated with seismically induced deformations would not occur simultaneously on both faces of the arch, but would occur on one face during one cycle and then on the other face in the next cycle. As the earthquake progressed into its strong motion period, arch stiffness would be reduced in these cracked regions, leading to non-linear behavior. For a reinforced concrete structure such as Florence Lake Dam, evaluation of this non-linear response would be difficult to interpret and validate. Nonetheless, evaluating the consequences of this behavior was thought to be a critical component in the assessment of the dam. For this purpose, evaluation of cracked arch behavior was based on estimated arch deformation capacity compared to predicted deformation levels in the arches.

Therefore, the evaluation approach examined the deformation state in the dam, rather than the stress state during the earthquake. The evaluation approach effectively dealt with the somewhat differing linear stress results obtained from the symmetric and full river section analyses by assuming that the stress levels in the dam that would be present during the evaluation earthquake could reach concrete tensile limits. This assumption was conservative since the stress levels as predicted from the symmetric analyses indicated a lower overall stress state than the corresponding full model analyses.

Furthermore, the inability of either numerical model to include the effects of reinforcing steel present in the dam limited the confidence of each model to predict the stress state immediately after cracking of the concrete began. In lieu of conducting non-linear analyses using special finite elements that may incorporate reinforced characteristics, a series of linear analyses were conducted to obtain a range for the expected deformations of the dam during the evaluation earthquake. The deformations were estimated using the full model, and this was judged appropriate based on the agreement between measured and predicted static deflections for arch 21.

These deformations were the basis on which the evaluation of Florence Lake Dam was performed. The demand, in terms of expected seismic deformation, was compared to the capacity of the reinforced arches and buttresses of the dam. In this manner, a ratio of these quantities was used to indicate a safety margin and provide some indication of the expected behavior of the dam. An additional consideration in this evaluation was the confinement of the concrete necessary to resist or minimize loss of concrete that would significantly affect the dam's ability to impound the reservoir water during the earthquake.

In the buttresses, the coupled buttress-haunch motion produced small relative deformations indicating that any tensile stresses developed in the buttresses would be below concrete strength limits. For this reason, the buttresses were judged to perform adequately under the Maximum Credible Earthquake (MCE). The arches, however, driven by lateral buttress movements, required the review of two deformation states. The first one of these considers the effect on arch deformation resulting from buttresses moving toward each other, and the second is based on the buttresses moving away from each other. For each configuration, theoretical arch deflection formulas were combined with experimentally derived moment-curvature relationships for reinforced concrete sections in order to determine deformation capacity. These estimated deformation capacities were then compared to predicted values from the numerical model results. For the various stages of expected cracking in the arches, the ratio of capacity to predicted deformation was always greater than 1.0.

3. CONCLUSIONS

A series of finite element analyses were completed for the seismic evaluation of Florence Lake Dam. Two separate analysis approaches provided comparative means for estimating both stress and deformation states that would be expected to occur in the dam during an extreme earthquake. Considering the age of the dam (over 70 years of service) and the limitations associated with using linear homogeneous material properties to represent composite (reinforced concrete) material behavior, calculated stress states were judged as inappropriate for the final evaluation of the dam. Furthermore, non-linear analyses were not pursued since model validation and interpretation of results would be difficult for this type of structure. In view of these limitations, a new evaluation approach was developed for Florence Lake Dam.

The availability of field data allowed the engineers to pursue a somewhat unorthodox approach to the seismic evaluation of Florence Lake Dam. These data were in the form of both historical and more recent field measurements of both static and dynamic response behavior. A field inspection was critical to placing predicted stress states in the context of the standing dam. The engineers were able to utilize a symmetric model validated in terms of linear elastic dynamic behavior to assess the relative conservatism of an analysis that employed a full model. The results form the validated symmetric model, although indicative of stable response behavior during the MCE, were not judged adequate by the review Board. Nonetheless, the successful validation of the symmetric model was very useful in assessing both the stress and deformations associated with the full model analysis. Based on the understanding gathered from the ambient vibration testing and other field data, the engineers were able to develop a deformation-based assessment of Florence Lake Dam that was met with acceptance by the Review Board.

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The field measurements acquired at Florence Lake Dam were processed and evaluated using ***iDAMS***, an internet based database for the analysis of measurements of large civil structures. Mr. Gene Lee and Mr. Daniel Sutoyo, De Pietro Fellows in Civil Engineering at Harvey Mudd College have developed the current version of this software through the generous support of the De Pietro Fellowship Program at Harvey Mudd College.

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Table 1. Comparison of measured and computed resonances (empty reservoir).

Experimental (Hz)	Frequency Analysis (Hz)
3.0	3.3
3.4	3.6
5.5	5.9
6.2	6.5
6.6	6.8
7.3	7.5
7.7	7.9

Table 2. Comparison of measured and computed resonances (full reservoir).

Experimental (Hz)	Frequency Analysis (Hz)
3.5	3.5
6.3	6.4
6.8	7.3
9.9	9.5
11.7	11.8
14.3	14.0
16.8	16.8

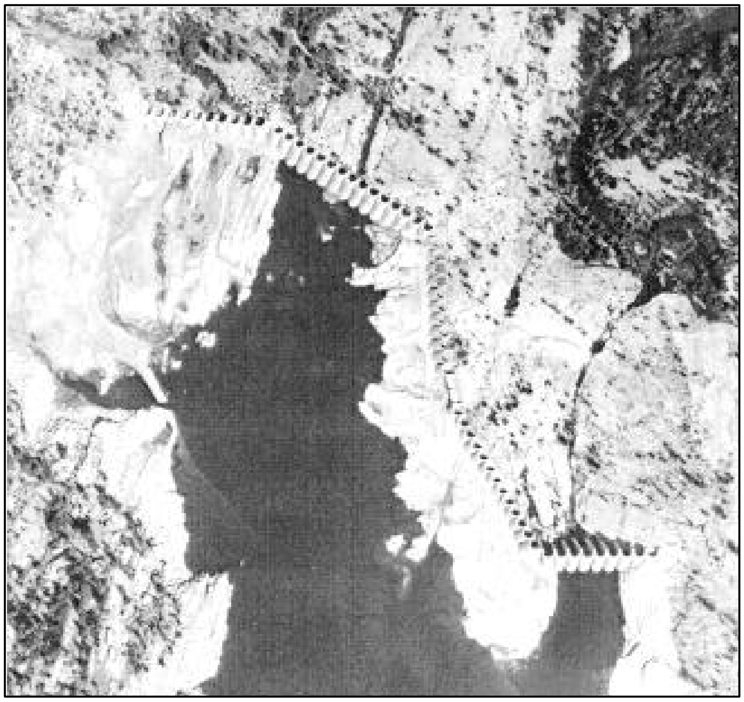

Figure 1. Aerial view of Florence Lake Dam.

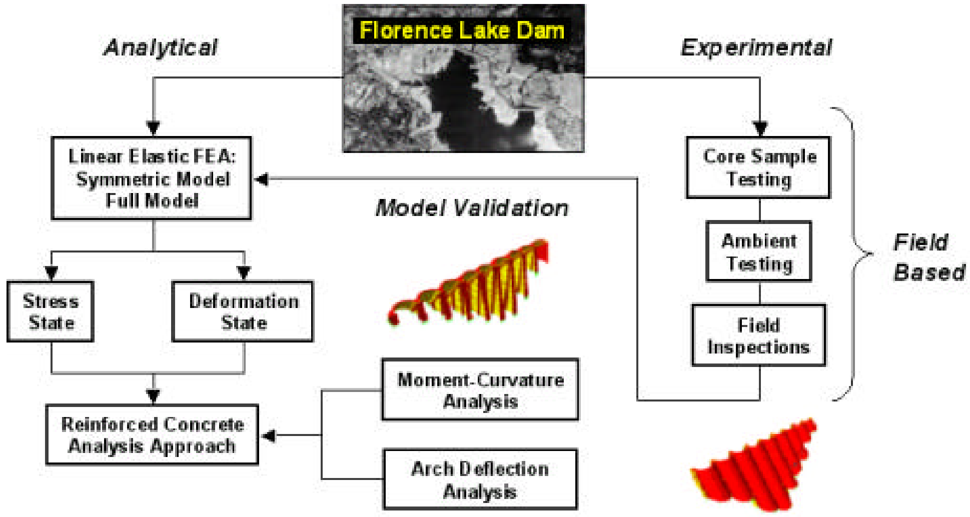

Figure 2. Overview of evaluation procedure.

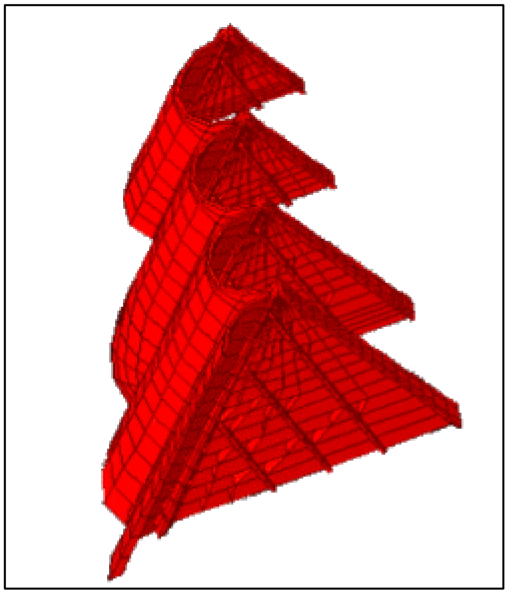

Figure 3. Symmetric numerical model of the River Section of Florence Lake Dam.

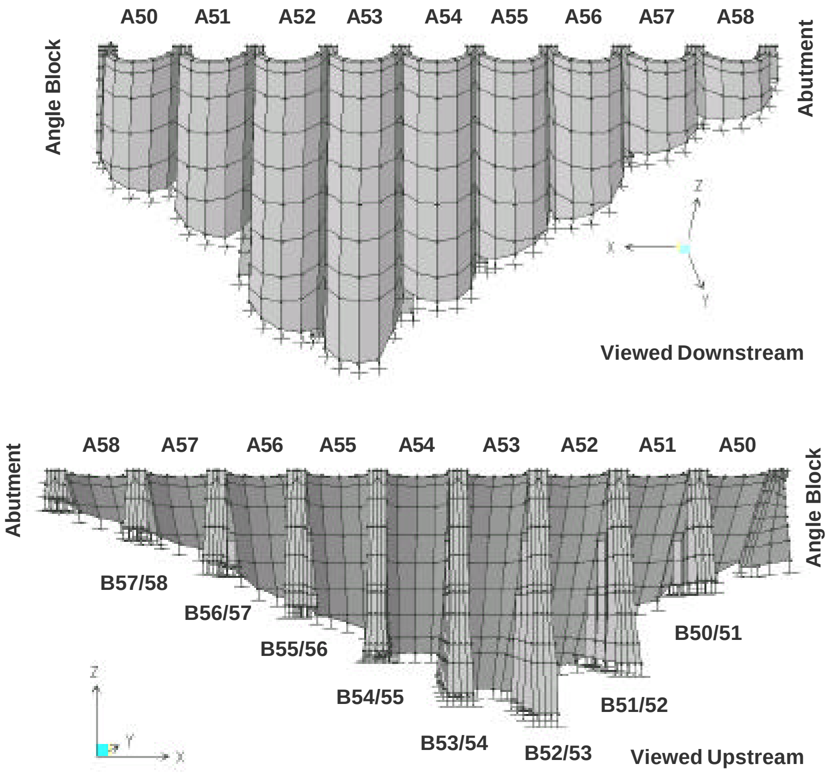

Figure 4. Full 3D numerical model of the River Section of Florence Lake Dam.

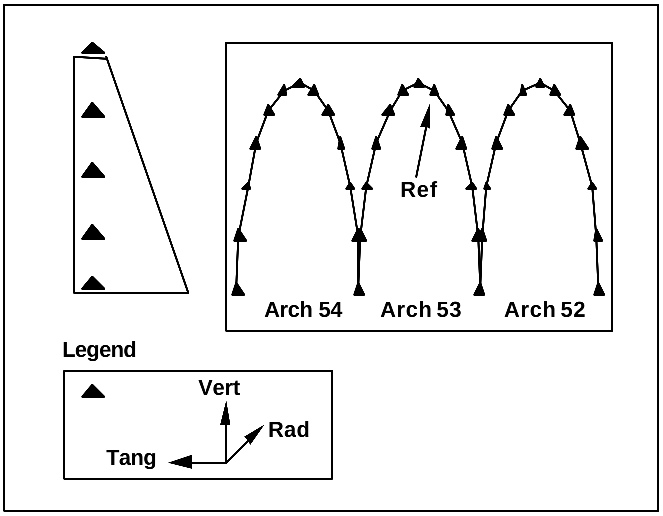

Figure 5. Measurement layout used during ambient testing at Florence Lake Dam.

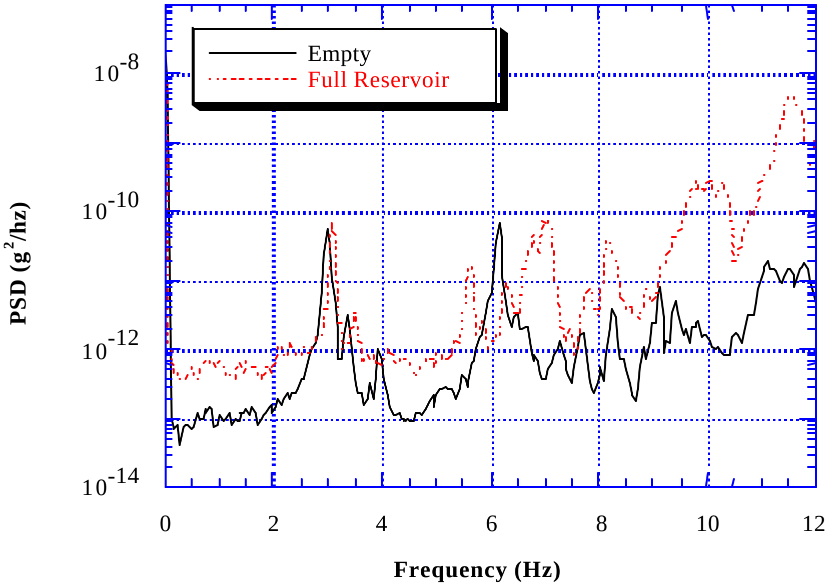

Figure 6. Measured power spectral density functions at Florence Lake Dam under empty and full reservoir conditions.

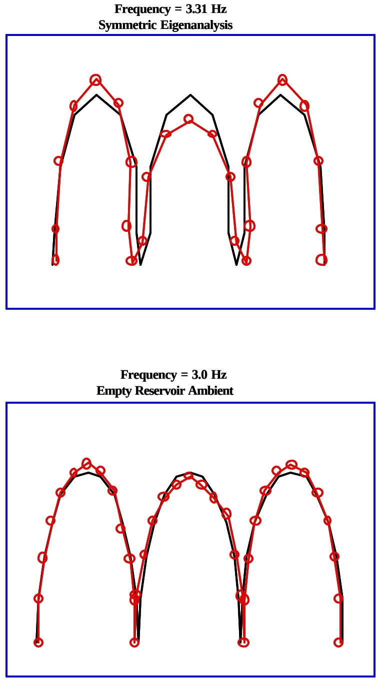

Figure 7. Comparison of predicted (top) and measured (bottom) fundamental symmetric response shapes at Florence Lake Dam under empty reservoir conditions.

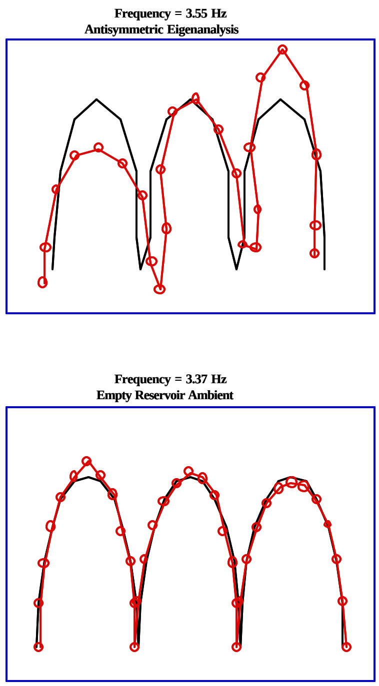

Figure 8. Comparison of predicted (top) and measured (bottom) fundamental antisymmetric response shapes at Florence Lake Dam under empty reservoir conditions.

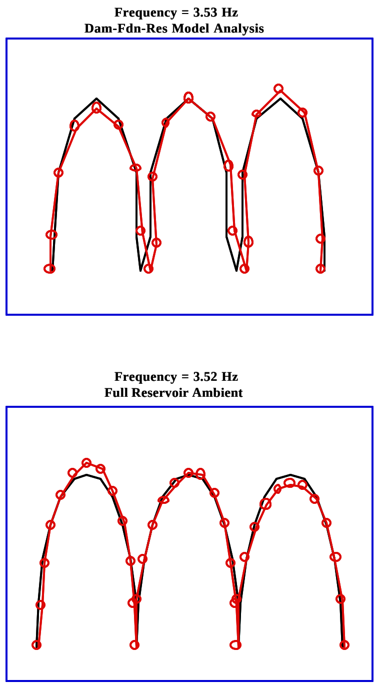

Figure 9. Comparison of predicted (top) and measured (bottom) fundamental symmetric response shapes at Florence Lake Dam under full reservoir conditions.