Vibration testing of a 1/4-scale containment model

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1 INTRODUCTION

Both the U.S. Nuclear Regulatory Commission (USNRC) and the Electric Power Research Institute (EPRI) have undertaken programs to validate soil-structure interaction analysis methods with data that include ground and structural response motions during natural earthquakes and structural response motions from low-level vibration tests. The primary source of the data is the 1/4-scale containment building situated in Lotung in a seismically active region of Taiwan.

The analysis validation program involves blind predictions of site and structural responses to the vibration test excitations and to a selected strong-motion seismic event, and the subsequent comparison of these predictions with corresponding measurements. The details of these programs are described more fully elsewhere (Kot et al., 1986). The present paper focuses on the vibration testing of the model containment structure and the determination of its dynamic characteristics from the experimental data.

The 1/4-scale reinforced concrete containment structure, built by EPRI in cooperation with Taiwan Power Company, is located within an array of strong-motion seismographs, known as the SMART-1 array. Figure 1 shows a cross section of the structure. The structure is not a replica model of a typical nuclear power plant containment building. The roof slab had to be made massive to ensure that the fundamental frequencies of the model structure would fall within the frequency range of seismic excitation typical for the site.

2 PERFORMANCE OF FORCED VIBRATION TESTS AND DATA EVALUATION

The purpose of the low-level vibration tests, sponsored by the USNRC, was to define the dynamic characteristics of the soil-structure system in an as-built condition before the system was subjected to strong-motion events. Furthermore, the test results were to be predicted blindly by various analysts and subsequently to be used by them to refine their predictive models. The testing was performed in two stages. In the first stage, tests were performed with only the basemat completed. In the second stage, the completed structure was tested. This paper concerns only the vibration testing of the completed structure.

Steady-state excitation with a single eccentric-mass vibrator was provided in each test run. The two counter-rotating masses of the shaker apply a uniaxial force whose direction remains constant and whose amplitude varies sinusoidally with time. The eccentricity of the rotating masses was varied from test run to test run. In each run, the eccentricity was held constant, as the shaker was operated at a number of discrete frequencies successively. In each frequency the shaker was operated long enough to obtain a steady-state response at that frequency.

Figure 2 shows the driving point and accelerometer mounting locations on the cylindrical structure. In any test run, the direction of forcing was one of the following: horizontal north-south (N-S) or horizontal east-west (E-W). These directions correspond to radial and tangential excitation, respectively. All fundamental modes, except purely vertical translation, were excited in this manner.

The response was measured by Endevco 5241A accelerometers, which have a frequency response range of 0.2 Hz to 2000 Hz. Twenty accelerometers were used to measure the response at 11 locations, as shown in Fig. 2, during the tests. The response data were stored, for each excitation frequency, in the form of amplitude and phase with respect to forcing, or alternatively as real and imaginary parts of the complex response. The data were in the form both of acceleration as measured and of displacement normalized to a constant force.

Inspection of the plots of the complete normalized data for the building response records revealed that most response data at low frequencies (in the range of 1 Hz to 3 Hz in many cases and even up to 5 Hz in some cases) were dominated by noise. This is due to the fact that at these low frequencies, the shaker force amplitudes are relatively small and give rise to low response signals. A sharply rising signal with decreasing frequency in this range was indicative of this. Close examination of the data showed that the signal threshold below which the noise is too high varied from channel to channel and ranged from 3×10^{-4} g to 7.3×10^{-4} g. Consequently, the noise floor for each channel was estimated and all data below this floor were discarded in the selection process.

With the elimination of unacceptable segments of data as described above, the retained data had sufficiently strong signals to be considered valid. However, a coherence-like quantity, calculated from the raw data, showed that many high-frequency response measurements included in the data had a "coherence" of less than unity. The segments of response data with a "coherence" of less than 0.8 were identified and considered somewhat less acceptable than the rest. A few of these data were in the frequency range of 18.98 to 30.25 Hz but most fell in the range of 25 to 30 Hz.

3 ESTIMATION OF MODAL PARAMETERS FROM TEST DATA

An experimental modal analysis of the test response data was performed with the MODALII software of an HP5451C system. Two sets of transfer functions were used. The first set consisted of those from the N-S, or radial excitation, tests and the second consisted of those from the E-W, or tangential excitation, tests. Though each set comprised 20 transfer functions, only a subset of these could be used for modal estimation because for any given excitation, not all the channels had all the resonances well excited. Thus, only 9

measurements were used for the radial excitation tests and 10 for the tangential excitation tests.

The modal parameter estimation algorithm solves a set of simultaneous nonlinear equations to obtain the frequency, damping, and complex residue of each modal resonance from each transfer function. The estimation algorithm is iterative in nature. The technique is based on the application of a least-squares estimator to fit the measured transfer function data to an analytical expression of the transfer function for a viscously-damped linear system with multiple degrees of freedom and complex mode shapes. With each iteration the estimates of all four parameters of each mode are updated. After the modal parameters are identified, the analytical (fitted) transfer function is constructed and visually compared with the test transfer function. The difference between the data and the fit, or the error of fit, is also displayed. The iterations are continued until the analyst determines from the error of fit display that the convergence of the fit cannot be improved by further iterations. Thus, the results depend to some extent on the judgment of the analyst.

4 RESULTS

Only one mode (i.e., the lowest) could be identified from each set of transfer functions with high confidence. However, the transfer functions from the tangential excitation permitted partial identification of two additional modes, though the confidence in these estimates is lower.

The modal parameters estimated from the test data are summarized in Table 1 and the mode shapes of the two fundamental modes are shown in Figs. 3 and 4. In these figures, the thicker lines represent the undeformed structure and the thinner lines show the mode shape. It is evident from the figures that the fundamental modes are primarily rocking modes. Though a small amount of translational motion is present, it is not significant compared to the contribution of the rocking motion. As noted earlier, the confidence in the modal estimates for the fundamental modes is high because they are so well excited. The frequencies of the two rocking modes are almost the same. Though the damping for the rocking about the N-S axis is slightly greater than that for the rocking about the E-W axis, the difference is not of significance. The mode shapes for the two modes are also very similar. These similarities simply confirm the symmetry of the system.

Two higher modes were also identified from the tangential excitation tests. However, the confidence in these estimates of modal parameters is not as high as that in those of the first mode. The primary reasons are that the strongly excited first mode contaminated the higher modes and that the algorithm used is not capable of isolating the weaker modes efficiently. Certain obvious discrepancies in the estimates for the mode shape vector also indicated that these estimates are less reliable. For purposes of comparison with analytical calculations, these values should be used with some caution. The partial mode shapes obtained for these modes suggest that the second mode is a coupled rocking-horizontal-sliding mode and that the third is a torsional mode.

5 CONCLUSION

This paper describes the vibration testing of the 1/4-scale containment model in Lotung, Taiwan, and the determination of modal properties from the test data. Though it was possible to identify only the fundamental modes with confidence, it is clear that these are the predominant modes in determining seismic response, as the strong motions recorded by the SMART-1 array are noted to have most of their energies in the range of 0-10 Hz, with the peak values occurring at frequencies of about 3 Hz or lower (Bolt et al., 1982). Even though the blind theoretical calculations of the modal parameters have been completed by most of the analysts as of the date of this writing, these results have been frozen and will not be published until all major phases of the validation program are completed. Comparison of the experimentally determined modal parameters with those calculated by different analysts can be reported only after that.

ACKNOWLEDGMENTS

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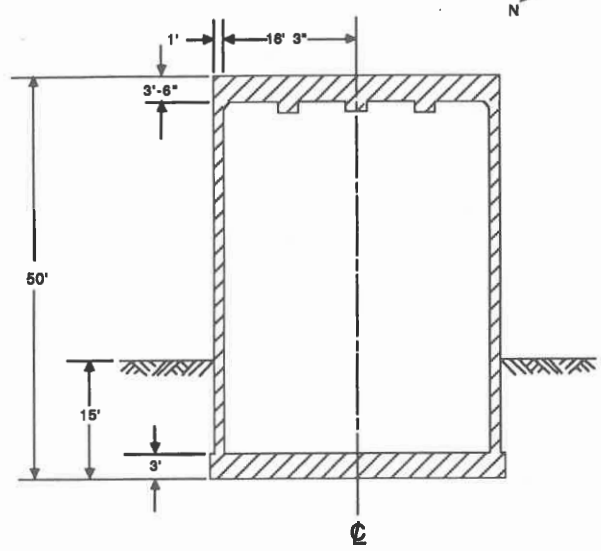

Figure 1. Cross Section of 1/4-Scale Containment Model

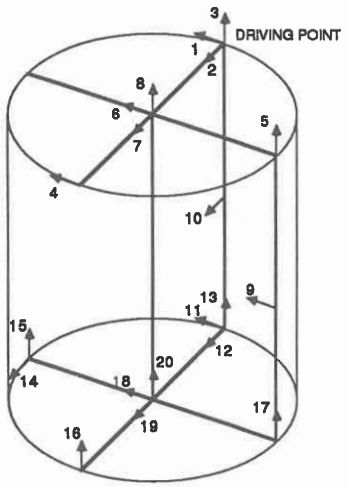

Figure 2. Instrumentation Channels

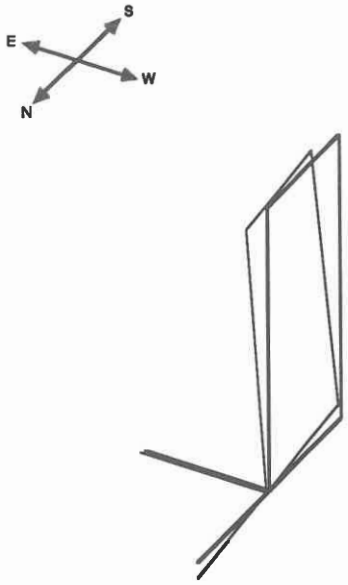

Figure 3. First Mode Identified from N-S (Radial) Excitation

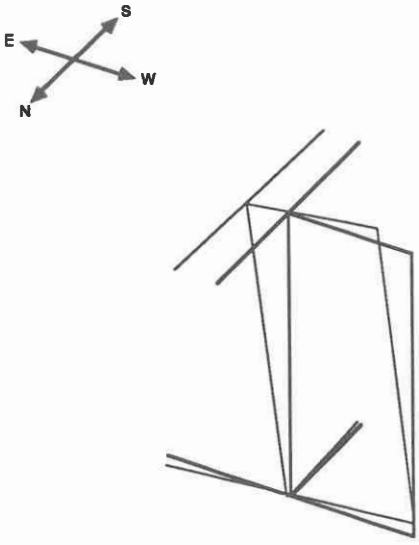

Figure 4. First Mode Identified from E-W (Tangential) Excitation

Table 1. Modal Parameters Estimated from Test Response

Mode No.	Excitation direction	Modal frequency (Hz)	Modal damping (% critical)	Modal stiffness* (N/m)
1	N-S	3.81	9.65	577.2
1	E-W	3.83	10.49	584.7
2	E-W	5.86	11.54	
3	E-W	10.86	23.76	

*Scaled to unit modal mass.