SEISMIC INSTRUMENTATION FOR SOIL-STRUCTURE INTERACTION ASSESSMENT

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ABSTRACT

Discussed in this paper are considerations and needs of seismic instrumentation for large and long structures for the purpose of assessing soil-structure interaction effects. Two examples of past instrumentation programs for evaluation of soil-structure interaction effects are described to serve as illustrations of the considerations that need to be taken prior to deployment of seismic instrumentation.

Key words: soil-structure interaction, seismic instrumentation, seismic input, foundation

INTRODUCTION

Measurements from strong-motion instrumentation of structures play an important role for assessment of seismic performance of structures. To achieve a proper assessment, instrument-recorded data must be properly interpreted and utilized. Such data must include those required for a proper definition of the seismic excitation input and those representing the structural response output.

All instrument-recorded data obtained from an earthquake are data representing the earthquake responses at the instrumented locations, even if they are obtained at so-called "free-field ground recording stations". To use such data as the bases for assessing the behavior and/or condition of a structure during an earthquake, one must understand the process by which the earthquake input and the structural response output are inferred from such recorded data. Without such an understanding, the results of the assessment could be misleading and, in some cases, could lead to unrealistic conclusions.

Experiences from seismic performance assessment of structures with seismic instrumentation indicate that, among many factors that influence the earthquake response of a structure during an earthquake, the most important one is a realistic and accurate definition of the earthquake excitation input to the structure during the earthquake. In all cases of structure with instrumentation, the actual earthquake input to the structure is not directly measurable. Instead, it is inferred from the so-called "free-field ground response motions" recorded at the "free-field ground recording stations" that are located at some distances away from, but adjacent to, the structure. The use of such motions to infer the actual earthquake input to the structure involves many assumptions with respect to how the actual earthquake input to the structure is related to the ground response motions recorded at the free-field ground stations.

The primary objective of this paper is to examine the various implicit assumptions embedded in using the recorded “free-field ground response motions” to infer the earthquake input to an instrumented structure. The secondary objective is to discuss the instrumentation needs for obtaining adequate recording data during an earthquake that can be used for a more accurate representation of the earthquake input to the structure.

In-depth analyses of instrument-recorded earthquake response data of structures supported on soil sites in the past have provided ample evidences to demonstrate that, in order to accurately assess the earthquake response behavior of the structures, the effects of soil-structure (or, more broadly, ground-structure) interaction must be properly taken into consideration. Two such examples with which the author had a direct experience are described herein to illustrate the importance and need of proper instrumentation for the purpose of assessing soil-structure interaction effects. These two examples are (1) the Lotung, Taiwan, soil-structure interaction field experiment conducted in late 1980’s and (2) the correlation study of the earthquake response of an instrumented three-span segment of the San Francisco Bay Area Rapid Transit (BART) elevated guideway structures during the 1989 Loma Prieta, California, earthquake.

GROUND-STRUCTURE INTERACTION

In its most fundamental sense, the dynamic excitation to a structure during an earthquake should be characterized in terms of the traction time-functions (or time-histories) acting on the structure from the supporting ground medium on all ground/structure (or, more appropriately, ground/foundation) interface boundaries. The integration of such traction time-functions over the entire ground/foundation interface boundary of each structural foundation produces the so-called “seismic driving force” time-function acting on the foundation. While it is realistically not feasible to measure such time-functions directly and sufficiently by instrumentation, the objective of seismic instrumentation is, thus, to obtain sufficient instrumental data that can be used to characterize such forcing functions acting on the structural foundations produced by the earthquake. To enable such a characterization, it is necessary to characterize the following parameters relating to the ground medium immediately adjacent to each foundation from which the earthquake excitation input to the foundation is originated:

(1) Time-histories of free-field ground motion of the surrounding ground medium at all points on the ground/foundation interface boundaries.

(2) Dynamic traction vs. displacement relationships of the surrounding ground medium at all points on the ground/foundation interface boundaries.

It is obvious that deployment of instruments to measure the free-field ground motions described in Item (1) above is logically and practically unachievable. This is because, even if instruments could actually be placed to measure such motions, the measured motions are not free-field motions. Instruments can, however, easily be installed to measure the seismic response motions of each foundation, even though in reality such measurements are rarely made. Of course, such motions if measured have already included the ground-structure interaction effects.

The characterization of the dynamic traction-displacement relationships of the surrounding ground medium, as described in Item (2) above, involves a complete characterization of the constitutive relations of the soil and/or rock materials of the ground medium surrounding each foundation under the dynamic loading condition of the earthquake. This subject in itself is rather complex and is currently under intense research. It involves characterization of the generally nonlinear and inelastic near-field behavior and the generally linear and elastic far-field behavior of the soil/rock medium under the seismic loading condition. Within the scope of this paper, this subject will not be discussed further. Readers who are interested in the subject are referred to relevant recent publications (e.g., Tseng and Penzien, 1998 and 2000).

As mentioned previously, a common practice presently being employed in defining the seismic input to an instrumented structure during an earthquake is to use the ground response motions measured at some instrumented free-field ground stations located at some distances away from but in the vicinity of the structure. To utilize such recorded motions to infer the free-filed seismic input motions to each foundation as described in Item (1) above, assumptions on the seismic input motion environment applicable to each foundation of the structure are required, which include the following:

(a) Seismic wave field in free-field ground medium within the dimensions of each structural foundation.

(b) Influence of ground geology and topography on the seismic wave field in the ground region of the structure.

(c) Influence of soil/rock dynamic response characteristics, including their nonlinear characteristics, on the free-field seismic ground motions.

(d) Spatial variations of ground motions (due to wave-passage and scattering effects) in free-field ground region surrounding each foundation and variations of such motions among all such regions of the structure.

(e) Scattering of free-field seismic waves due to presence of the structural foundations, i.e., so-called "foundation scattering" of free-field ground motions.

It should be emphasized that the assumptions listed above involve the ground medium and ground motions within the "local" site region of the structure and its foundations. Results derived from seismological research, which generally involves variations of ground motions in the larger-scale "global" region of the site, should be interpreted carefully before they are adopted for use in assessing the "local" ground-structure interaction effects.

Because of the necessity of employing the these assumptions to infer the seismic input to a structure, it would be highly desirable to deploy an adequate instrumentation program, both in the free-field and on the structure, to obtain sufficient instrument-recorded earthquake response data for use to validate and/or modify such assumptions for the specific site condition considered and to quantify their effects on the seismic response of the structure. Before discussing the needs of such instrumentation, it is useful to review relevant instrumentation programs used in past field experimental programs designed for assessing soil-structure interaction effects. The objective of the review is to examine the lessons learned from such experiments relative to the appropriateness of the seismic instrumentation programs used for the specific objective of the experiments.

FIELD EXPERIMENTS ON SOIL-STRUCTURE INTERACTION

In-depth analyses of instrument-recorded earthquake response data obtained from a few instrumented structures in soil sites in the past have provided ample evidences to demonstrate that the effects of ground-structure interaction must be properly taken into account in order to appropriately assess the earthquake response behavior of such structures. Two of such examples with which the author has had a direct experience are briefly described below.

Lotung, Taiwan, Soil-Structure Interaction Experiment

The first example involves a comprehensive soil-structure interaction field experiment, referred to as the “large-scale seismic test” (LSST) program, conducted under the joint sponsorship of the U. S. Nuclear Regulatory Commission (USNRC), Electric Power Research Institute (EPRI), and Taiwan Power Company (TPC) in the 1980’s. This experimental program involved a large ¼-scale cylindrical shell structure simulating a prototypical nuclear power plant reactor-containment structure. The model was constructed at a relatively soft soil site located in a seismically very active region of Lotung in Taiwan. Figures 1 and 2 show the location and configuration of the experimental model structure. The objective of that experimental program was to investigate soil-structure interaction behavior of and quantify its effects on a prototypical nuclear containment structure supported in a soil site similar to that of the model structure subjected to actual earthquake excitations.

Extensive instrumentation was deployed to measure the earthquake response motions and soil/structure interface pressures of the containment model, and the response motions of the internal structure and piping system supported thereon inside the model structure. Extensive free-field instrumentation was also provided to measure the free-field ground surface as well as subsurface soil response motions at the site. The free-field instruments were installed in a form of a local array in order to measure the spatial variation of free-field ground motions in the vicinity of the model structure. Figures 3 and 4 show the locations of free field and in-structure instruments deployed. In addition to the instrumentation deployed as described above, the LSST instrumentation was also supplemented by the extensive free-field instruments installed for the well-known large-scale “SMART-1” free-field instrument array located in the LSST site region (Bolt et al., 1982). This instrument array produced further recording data for characterizing the free-field ground-surface response motions in the site region during earthquakes. The data recorded by this “global” free-field instrument array supplemented the data recorded by the “local” free-field instrument array installed for the LSST program.

The LSST experimental facility was completed in late 1986. During the following year in 1987, a total of 16 earthquakes had occurred near the Lotung site region, producing a vast amount of instrument-recorded data for this field experimental facility. The free-field horizontal ground surface accelerations recorded at the site varied from a low value of a few percent to a moderately high value of 23% g (EPRI 1989). A set of typical free-field ground accelerogram recordings obtained from the local LSST free-field instrument array during one of the higher intensity event, called Event 16, is shown in Fig. 5.

In-depth post-earthquake analyses were conducted utilizing the data recorded at the free-field ground surface as well as down-hole recording stations, and at in-structure instrument locations for several earthquake events (EERI 1989). A typical comparison of the 5%-damped response spectra computed for the instrument-measured structural response motions with the corresponding spectra obtained from the post-earthquake prediction analyses using several different soil-structure interaction analysis methods, each having a different set of analysis assumptions embedded in it, is shown in Fig. 6. Results of the extensive post-earthquake correlation studies of the predicted and measured responses of the experimental structure have indicated the following conclusions (Tseng and Hadjian 1991):

(1) Spatial variations of free-field ground motions at the site were significant, although such variations had a relatively small effect on the dynamic response of the model structure, which had a relatively small (15m-diameter) foundation footprint.

(2) Free-field ground motions varied with depth below the ground surface, and such variations can be approximately modelled in the local ground region of the model foundation using vertically propagating plane shear and compression seismic waves, respectively, for the horizontal and vertical motions.

(3) Scattering of free-field ground motions due to the presence of the structural foundation was important; and, its effect must be taken into account in assessing the dynamic response of the model structure.

(4) Soil-structure interaction was found to be significant for this model structure, which was supported on the relatively soft soil condition of the site; and, its effect must be appropriately considered in assessing the seismic responses of the structure.

Because of the comprehensive free-field and in-structure instrumentation program deployed in this experimental program, the data collected from the instruments were adequate for an in-depth evaluation of the validity of each assumption relating to the inference of seismic input to the model structure at this site. Thus, the data from this experimental program were very useful and helpful in clarifying and quantifying the soil-structure interaction effects of the type of structure supported in the soft soil site simulated in this experimental program.

Response of a BART Elevated-Structure Segment during the Loma Prieta Earthquake

The second example cited herein is concerned with the earthquake response of a three-span segment of the elevated train-guideway structures of the San Francisco Bay Area Rapid Transit (BART) system, located near the BART Hayward Station, during the 1989 Loma Prieta, California, earthquake. The California State Department of Mines and Geology (CDMG) had instrumented this segment of structure with strong-motion accelerometers prior to the Loma Prieta earthquake. The instrumentation installed was capable of recording both the ground-surface motions at one free-field ground station and in-structure earthquake response motions at several structural locations. The arrangement of the instruments installed for this structure is shown in Fig. 7. During the Loma Prieta earthquake, both free-field ground-surface and in-structure response motions were recorded. The recorded earthquake response motions are shown in Fig. 8. The peak horizontal free-field ground-surface acceleration recorded was 0.16 g.

In-depth post-earthquake analyses of the recorded earthquake response data were conducted to correlate the analytically predicted and the instrument-measured structural response motions during the earthquake (Tseng, Yang, and Penzien 1992). The study made use of the three-component acceleration time-histories recorded at the free-field ground station as the seismic input motions and took into account ground-structure interaction effects. Extensive comparisons were made of the analytically predicted structural response motions and the corresponding instrument-recorded motions. A typical comparison, expressed in terms of the 5%-damped acceleration response spectra computed for the transverse response motion at the elevated deck level, is shown in Fig. 9. Results of the study indicated that the ground-structure interaction effect was important for this structure and it must be considered in the seismic response analysis in order to obtain a reasonable correlation between the analytically predicted and recorded structural response. Without accounting for the ground-structure interaction effect, the predicted structural response amplitudes could be underestimated by as much as 30 to 50%.

The study also indicated that the foundation rocking motions dominated the transverse structural response at the deck level during the earthquake. Due to lack of direct instrument-measured data on the foundation rocking motions, a direct correlation of the foundation response during the earthquake, which was most affected by the ground-structure interaction effect, was not possible.

INSTRUMENTATION NEEDS

From the foregoing discussions, one can easily deduce that the use of instrument-recorded free-field ground response motions and in-structure response motions for assessing the structural condition and seismic response behavior during an earthquake must also take into account the ground-structure interaction effects that occur during the earthquake. The only possible exceptions are structures supported directly on hard-rock sites, in which case the ground-structure interaction effects are usually negligible. As direct measurement to provide data needed for characterizing ground-structure interaction effects is difficult in practical situations, one must carefully design the instrumentation program such that sufficient measured data are available for inferring the free-field seismic input and the various effects of ground-structure interaction occurring during an earthquake.

It is the author's opinion that, in addition to the free-field ground surface instruments normally provided, additional instruments should be installed for measuring earthquake response motions that can be used to more precisely characterize the free-field seismic input and the ground-structure interaction effects. As a minimum, instruments should be installed to measure earthquake response motions with both translational and rotational motion-components of each foundation of the structure directly. This is especially needed for large and long structures with multiple foundations such as large, long bridges. Instruments should also be installed to measure ground motions at multiple free-field ground-surface as well as down-hole stations. Data recorded from such instruments can be used to characterize the horizontal as well as vertical spatial variations of ground motions within the ground region of the structure and within the soil depth of the structural foundations. They can also be used to characterize the influence of global linear as well as local nonlinear soil response behaviors on the overall structural response. Furthermore, in order to use instrument-recorded data effectively to assess ground-structure interaction effects, extensive pre-earthquake assessment of the ground-structure interaction effects on the structural response must be carried beforehand.

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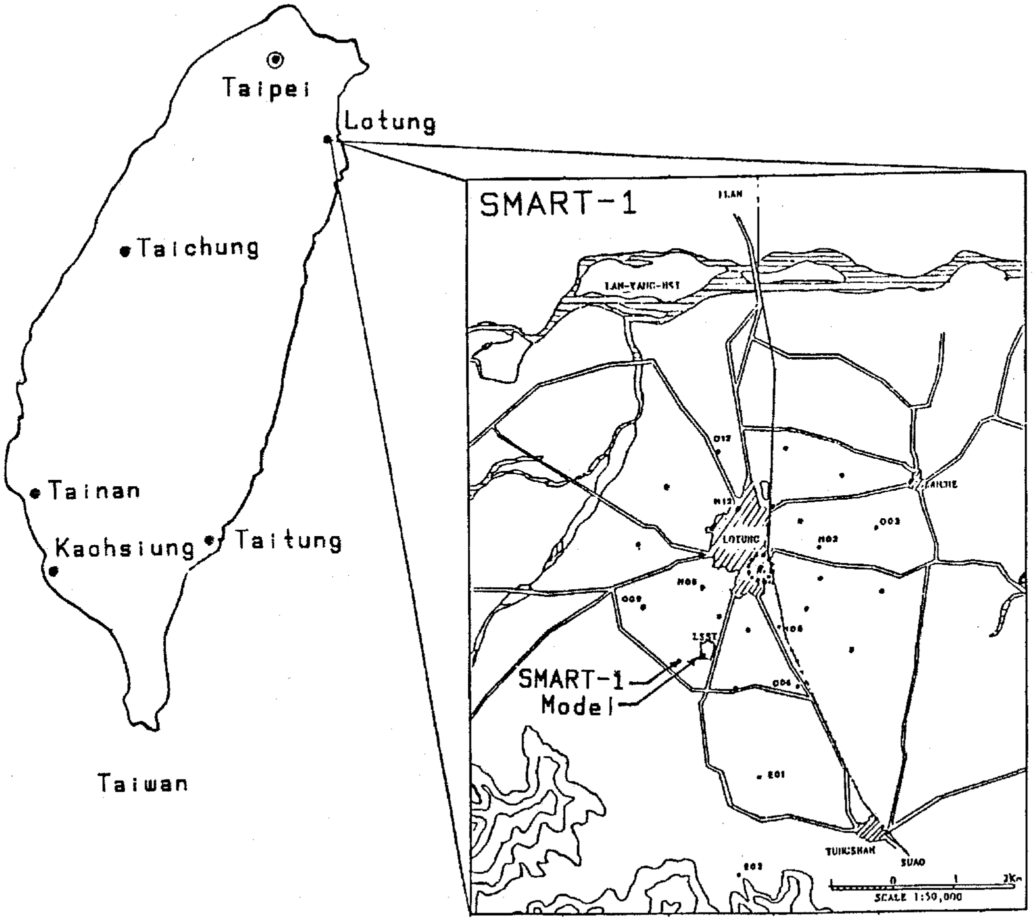


Figure 1 1/4-Scale Model Containment Site within SMART-1 Array at Lotung, Taiwan

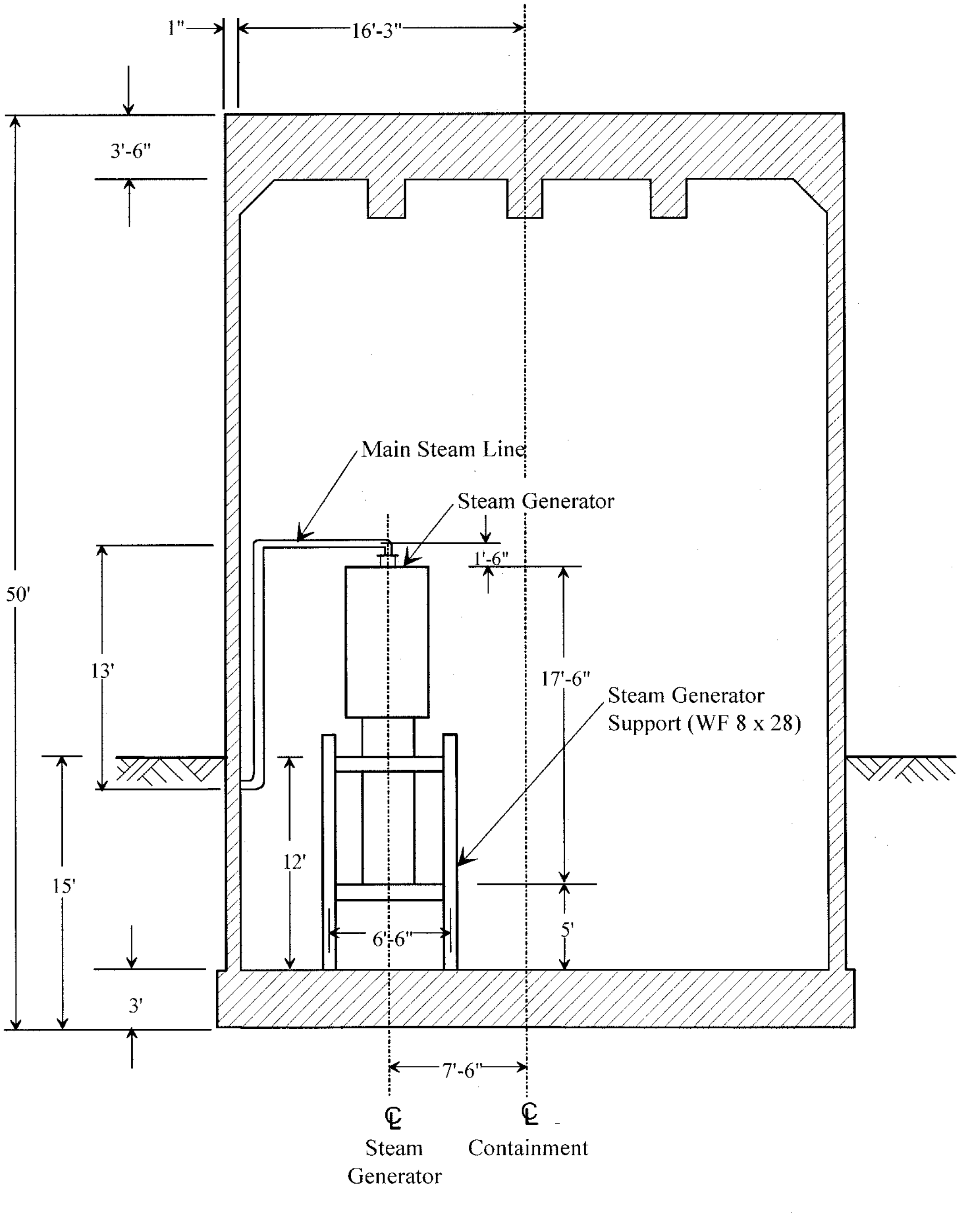
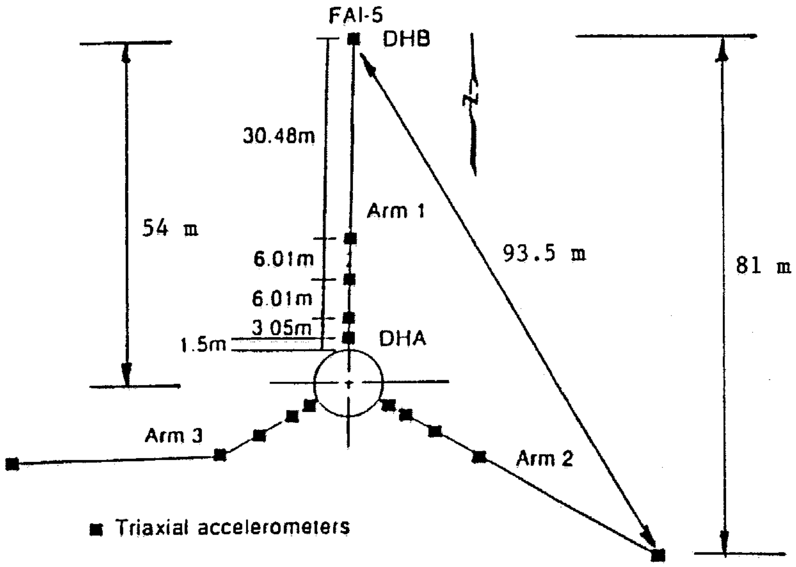
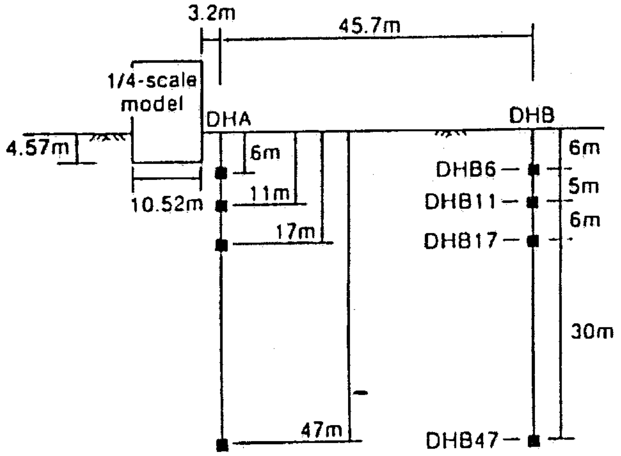


Figure 2 Vertical Cross-Section of Containment Model



(a) Surface instrument array



(b) Downhole instrument array

Figure 3 Locations of Accelerometers of Surface Array and Downhole Array

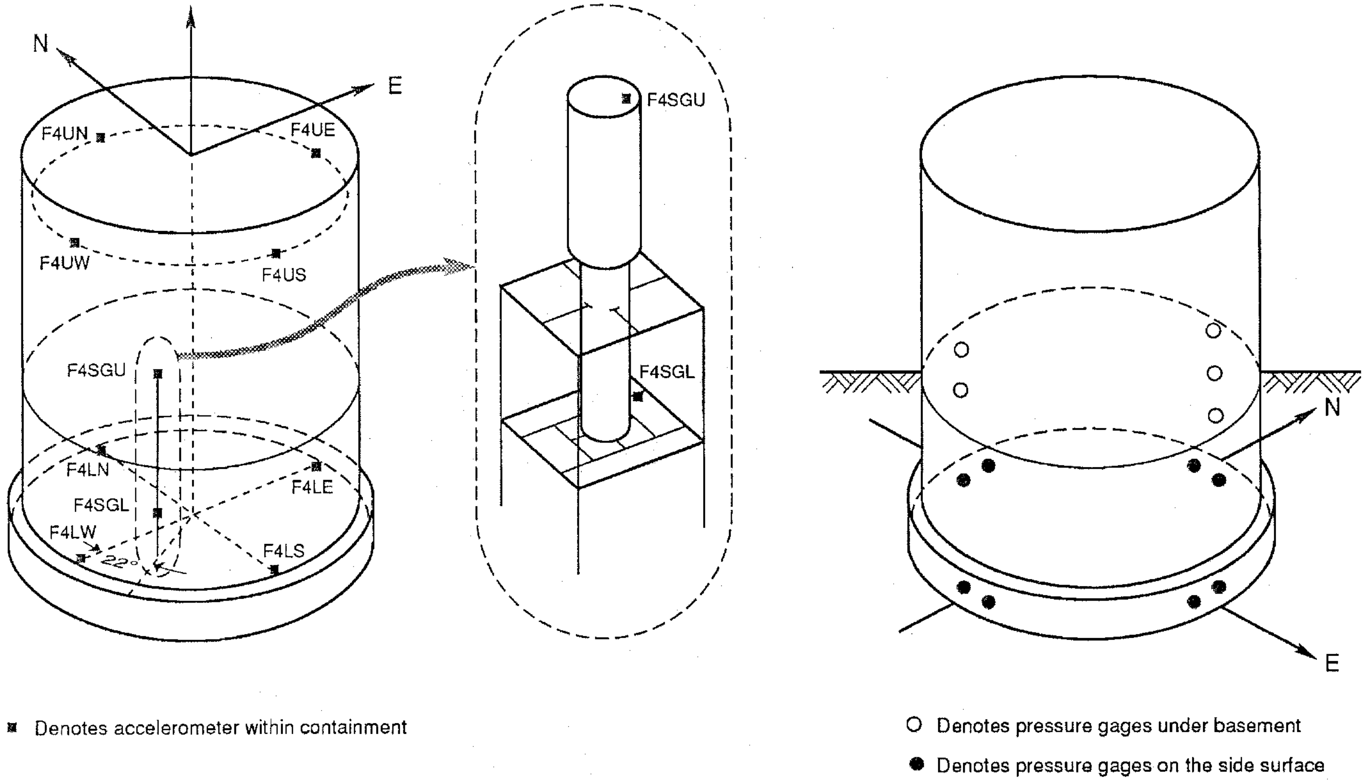


Figure 4 1/4-Scale Model Accelerometer and Pressure Guage Layouts

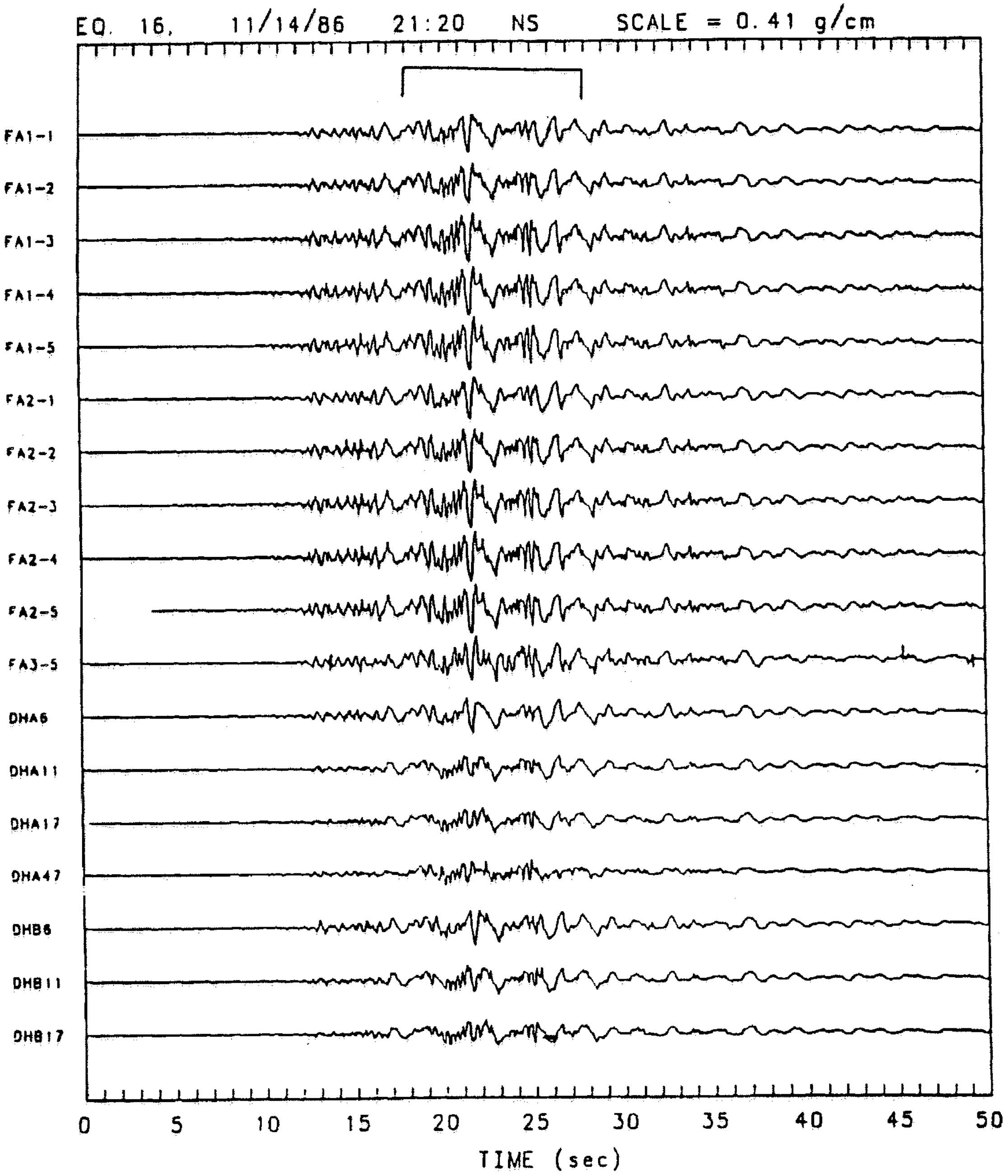


Figure 5 A Set of Typical Free-Field Ground Accelerogram Recordings for Event 16

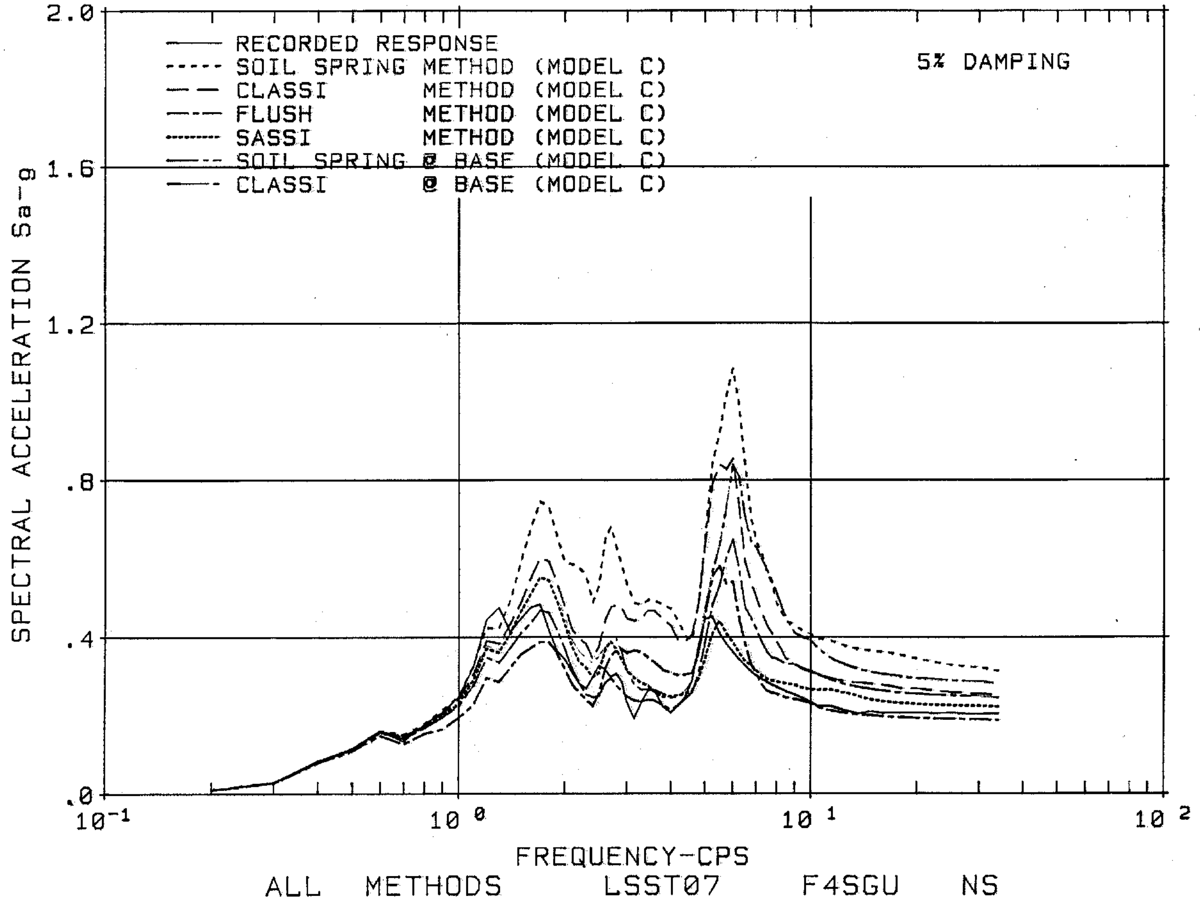


Figure 6 Comparison of 5%-Damped Acceleration Response Spectra Obtained from the Instrument-Measured Structural Response Motions with the Post-Earthquake Prediction Analyses

SENSOR LOCATIONS

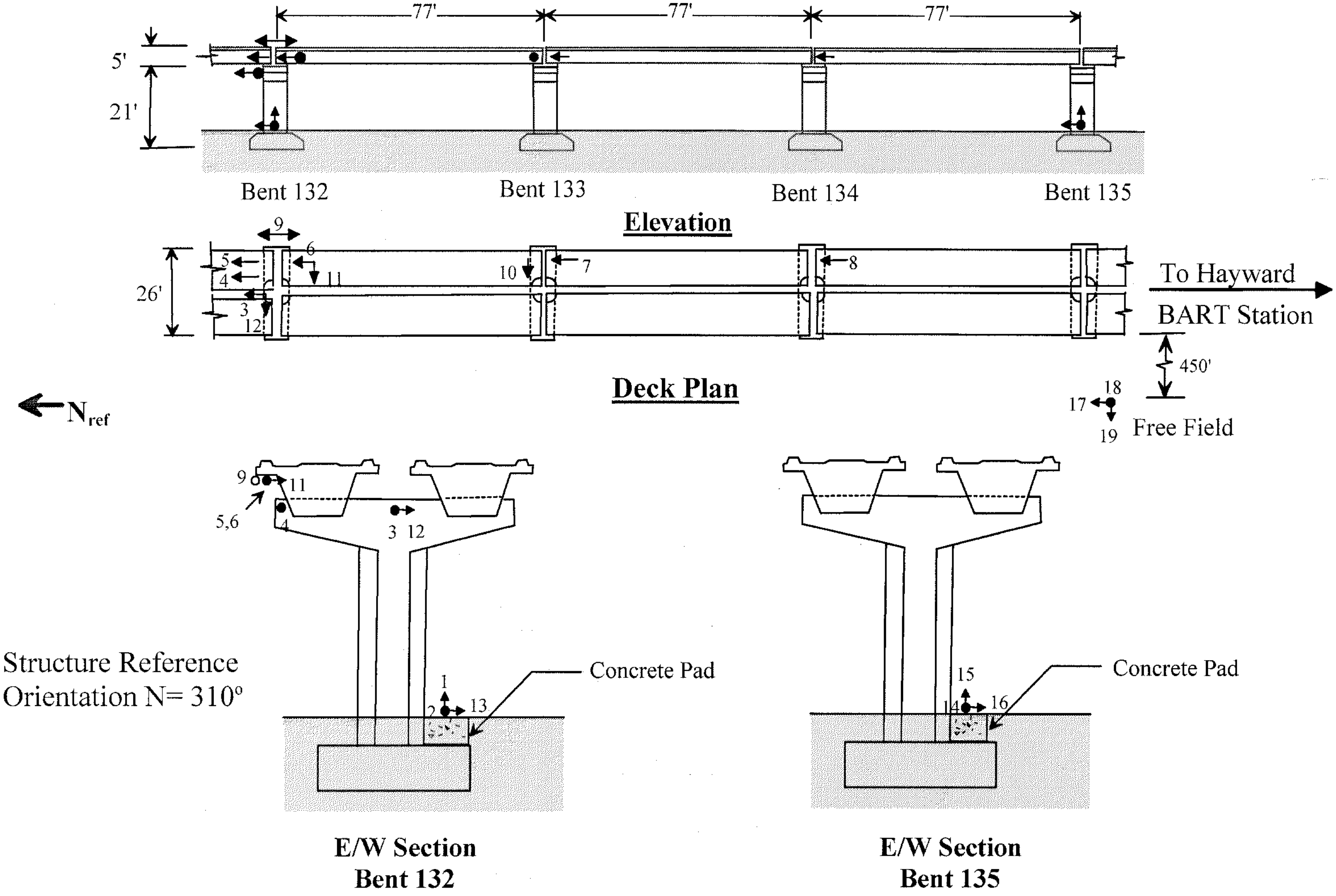


Figure 7 Structure Configuration of Hayward-BART Elevated Section and Sensor Locations (CSMIP Station No. 58501)

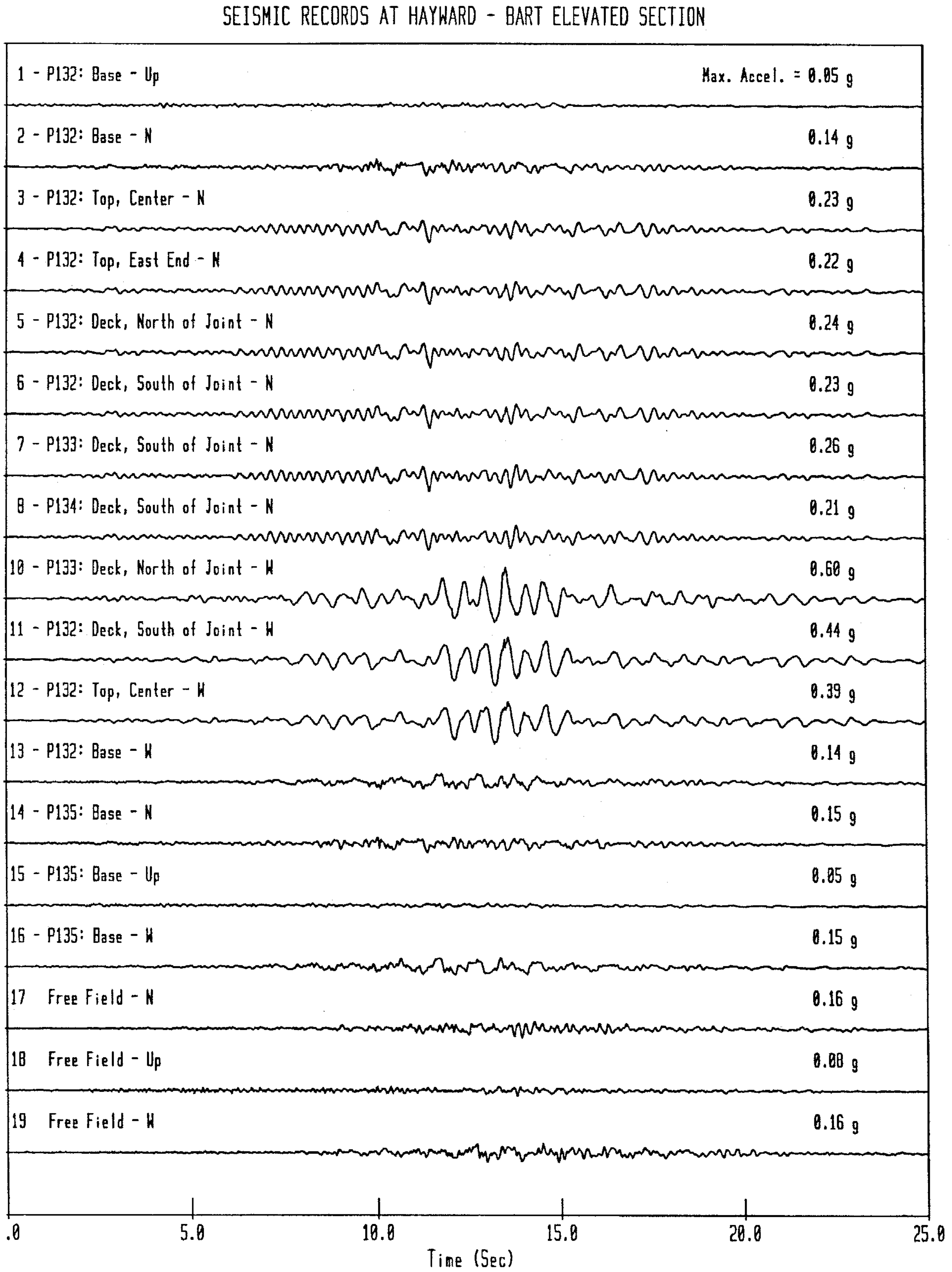


Figure 8 Accelerograms Recorded During the Loma Prieta Earthquake of 1989

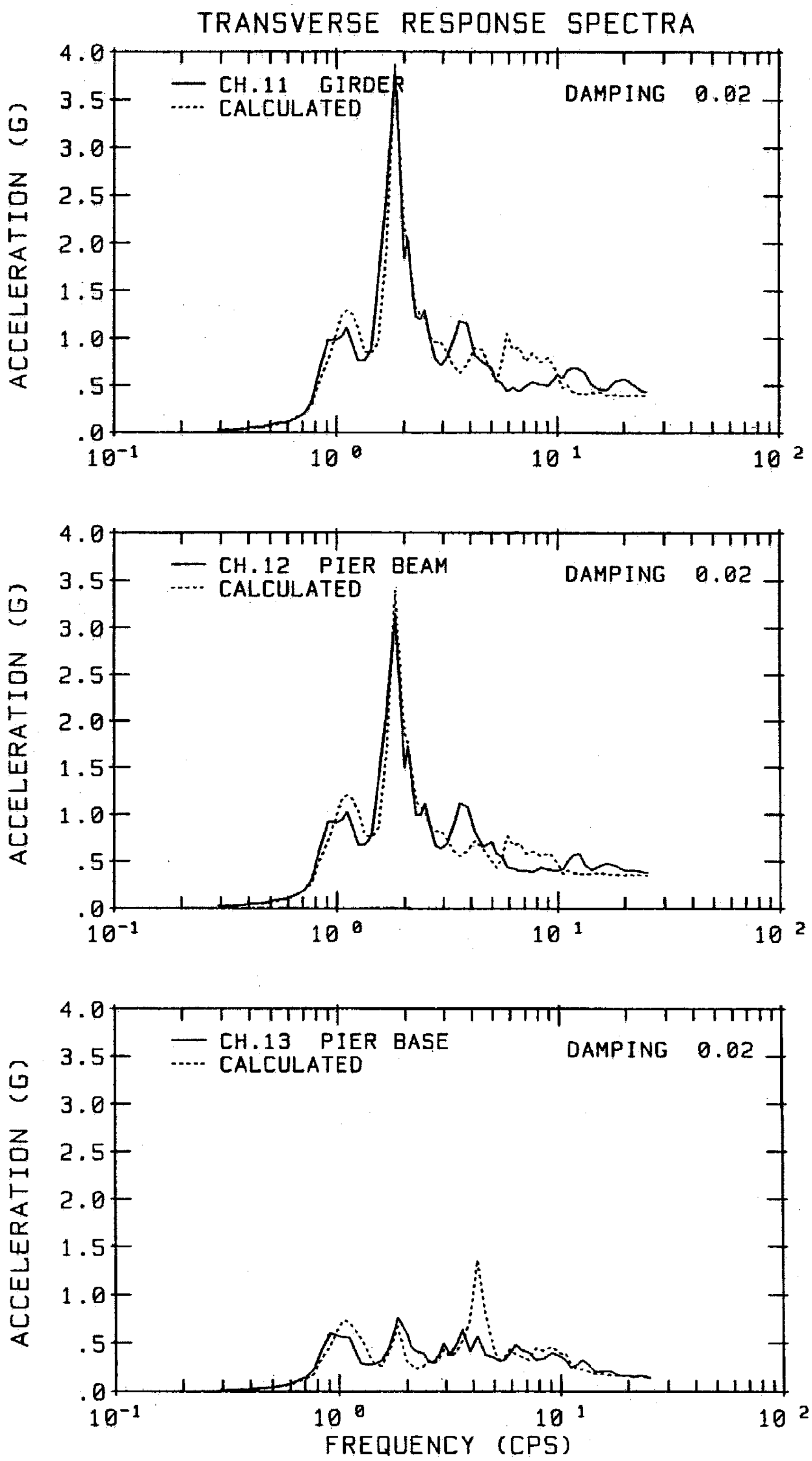


Figure 9 Comparisons of Analytically-Predicted and Measured Responses