CONF-8610135--54

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DE87 004937

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EPRI/NRC Cooperation in Lotung, Taiwan, Experiments

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October 1986

INVITED PAPER to be presented at the 14th Water Reactor Safety Research Information Meeting, Gaithersburg, MD, October 27-31, 1986.

*Work supported by the United States Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, under Contract W-31-109-Eng-38.

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ABSTRACT

The cooperative program between NRC/ANL and EPRI on the validation of soil-structure interaction analysis methods with actual seismic response data is described. A large scale-model of a containment building has been built by EPRI/Taipower in a highly seismic region of Taiwan. Vibration tests were performed, first on the basemat before the superstructure was built and then on the completed structure. Since its completion, the structure has experienced many earthquakes. The site and structural response to these earthquakes have been recorded with field (surface and downhole) and structural instrumentation. The validation program involves blind predictions of site and structural response during vibration tests and a selected seismic event, and subsequent comparison between the predictions and measurements. The predictive calculations are in progress. The results of the correlation are expected to lead to the evaluation of the methods as to their conservatisms and sensitivities.

INTRODUCTION

While much effort has been devoted in the past to the development of seismic soil-structure interaction (SSI) analysis methods, relatively little has been done to verify these methods with seismic experimental data, i.e., structural and site response data recorded during natural earthquakes. Among the few notable exceptions is the work by Seed and Lysmer [1,2], which included comparisons of analytical predictions with measurements recorded in the Humboldt Bay Nuclear Power Station during a strong motion earthquake. In general, the assumptions and approximations made in the various SSI analysis methods used in the design, licensing and risk assessment of nuclear power plants and the uncertainties they introduce into the results have not been systematically investigated vis-a-vis recorded data obtained for this specific purpose. To remedy this situation, both the U.S. Nuclear Regulatory Commission (NRC) and the Electric Power Research Institute (EPRI) have undertaken programs for the validation of SSI analysis methods using experimental data that include motions recorded during natural earthquakes. A cornerstone of these efforts is the EPRI/NRC cooperation in the seismic experiment with scale-model containment structures built in Lotung, Taiwan within the SMART-1 array.

The objective of the experiment is to verify or assess analytical predictions of important SSI aspects with extensive seismic ground motion and structural response data collected over a period of years at a site in which strong motion events are known to occur frequently. Modeling techniques for site response, foundation input motions and response of the structures and subsystems are among the major issues that will be subjected to verification. In addition to natural earthquake, the model structures were subjected to dynamic testing with steady-state excitation for obtaining baseline dynamic characteristics of the systems just after the construction and prior to the occurrence of any strong-motion earthquake.

The validation process consists of the performance of blind predictions of site and structural response to the dynamic test excitation and to a selected strong motion seismic event, and subsequent comparison of predictions with corresponding measurement records. Different methodologies, varying from the relatively simple to the state-of-the-art, are used by different analysts to make the predictions. The predictions and comparisons will be made in distinct phases. In each phase, the same input data is provided to all the analysts and independent models are devised and blind predictions are made. Subsequent to the completion of the predictions, the analysts are provided with measurement data with which they perform comparisons. If the event modeled is the dynamic test, the comparison may lead to an improved model in the subsequent phase in which seismic response is predicted.

DESCRIPTION OF LOTUNG SITE AND MODEL STRUCTURE

EPRI, in cooperation with the Taiwan Power Company (Taipower), has built two scale-model (1/4- and 1/12-scale) concrete containment structures in Lotung, Taiwan. The selected site is located in a highly seismic region and is within an NSF/U.C. Berkeley array of strong-motion seismographs, the SMART-1 array [3]. The SMART-1 array consists of a central element and three concentric circles each with 12 surface seismographs and radii of 200 m, 1 km and 2 km, respectively. The 1/4-scale EPRI model is located between the outer and middle circles of the array (Figure 1). From October 1980 (soon after the installation of the array began) through May 1984, 29 earthquakes with local magnitude ranging from 3.8 to 7.3 had been recorded by the SMART-1 array [4]. Of the first nine earthquakes recorded, three were located directly below the array at focal depths of 59 to 76 km, and the other six had shallow depths and epicentral distances from 7 to 193 km [3]. Thus past experience has clearly indicated that the site selected for the experiment is ideal from the seismic data collection point of view.

The soil at the site mainly consists of saturated sandy silt and silty sand with a shear wave speed in the range of 500 ~ 1000 fps. During the design stage, the results of a seismic refraction survey of the SMART-1 area, the results of which are reported in [4], were available. More detailed data from additional site exploration and laboratory soil testing have since been obtained and will become available to the analysts for analytical modeling. Figure 2 shows a cross section of the 1/4-scale containment structure and its major dimensions. A scaled steam generator and piping loop are installed inside the building. The structure is not a replica model of a typical nuclear power plant containment building. The massive roof slab was necessary in order to ensure that the fundamental frequencies of the model will fall within the frequency range of seismic excitation typical of the region. It is not the intention of this program to scale-up the measured response to a prototype containment structure. Soil-structure interaction is expected to occur during earthquakes and the measured responses will be directly used for verifying predictive methodologies.

PERFORMANCE OF FORCED VIBRATION TESTS

The purpose of the low-level vibration tests -- sponsored by NRC -- was to define the dynamic characteristics of the soil-structure system in an as-built condition before the system is subjected to strong-motion events. The results of the tests are to be first predicted by the analysts and subsequently to be used for refining the predictive models. The testing was done in two stages. In the first stage, the tests were performed with only the basemat completed. The configuration of the basemat during the tests is shown in Figure 3. As the water table was very close to the ground surface, water was being pumped from the excavation during these tests. In the second stage, the tests were performed on the completed structure. The excavation was backfilled and the sheet piles shown in Figure 3 were removed prior to the start of the second stage testing.

Steady-state excitation with a single eccentric-mass shaker was provided in each test. The two counter-rotating masses of the shaker result in a uniaxial force, the direction of which remains constant while the amplitude varies sinusoidally in time. The eccentricity of the rotating masses 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. The shaker was operated in each frequency long enough to obtain steady-state response at that frequency. For the basemat tests, the direction of forcing in any test run was one of the following: horizontal N-S (radial excitation), horizontal E-W (tangential excitation), or vertical. Figure 4 shows the shaker location and the placement of 15 accelerometers. Table 1 summarizes the details of excitation of the basemat. For the test on the completed structure, with the shaker located on the roof slab, the direction of forcing was either radial or tangential. Figure 5 shows the shaker location and the placement of the 20 accelerometers. Table 2 summarizes the details of excitation of the completed structure. The forcing of the basemat was designed to excite all translational and rotational degrees of freedom while that of the completed structure was designed to excite all fundamental modes except the purely vertical translational mode. The measurement locations were selected so that all rigid body motions of the basemat and the lowest modes of the completed structure can be determined from the measured data. The accelerometer (Endevco 5241A) signals were conditioned by anti-alias (low-pass) filter/differential amplifiers. The signal resolution was adequate to capture response of at least one percent g, the acceleration due to gravity. 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.

Subsequent to the performance of tests, all the response data were normalized to a constant force of excitation. The data were evaluated by ANL for its quality and most of the data were found to have sufficiently high signal to noise ratio. The response data from the basemat tests were used to determine the following experimental soil impedance functions: vertical, K_v; torsional, K_t; sliding, K_h; rocking, K_r; and the coupled sliding-rocking, K_{hr}. Approximate values of the resonant frequencies of the fundamental modes of the basemat were estimated by inspection of the data. The response data from the completed structure were used with a HP 5451C system's modal identification software to determine a modal model of the system. The modal model consists of estimates of the lower natural frequencies, modal damping, mode shape vectors and the modal mass.

As the validation plan includes blind predictions of the vibration test response also, the results obtained from the above noted analyses performed at ANL will be published only after the completion of the predictive calculations that are being performed by various analysts at the present time.

It should be noted that EPRI instrumented with six additional accelerometers the piping system inside the model containment structure during the vibration tests. Furthermore independent low-level impact tests were also performed on the piping system to define its dynamic characteristics.

COLLECTION OF EARTHQUAKE DATA

Soon after the completion of construction, by the end of October 1985, all seismic instrumentation was installed by the Institute of Earth Sciences, Academia Sinica, who also have the responsibility to maintain, collect, reduce and analyze the seismic response data for Taipower and EPRI. Ground motion measurements on the surface and downhole in the field and response measurements of the structure are made with triaxial strong-motion accelerometers. In addition, interfacial pressure transducers measure the contact pressure between the containment structure and the surrounding soil.

The surface instrumentation installed in the field consists of an array of three arms as shown in Figure 6. Each arm contains five stations and in each station the accelerometer is set on a concrete pad and is enclosed by a fiber-glass housing. The downhole instrumentation consists of two vertical arrays, aligned along arm 1 of Figure 6, and located as shown in Figure 7. Each vertical array has four downhole accelerometers at different depths as indicated in the above figure.

The structural instrumentation of the 1/4-scale containment model consists of 10 accelerometers installed inside the containment structure. Of these, four are installed at the base, four at the top below the roof slab, one each at the base and at the top of the model steam generator. The schematics of the structural instrumentation is shown in Figure 8.

The interfacial instrumentation of the 1/4-scale containment structure consists of 13 pressure gages as shown in Figure 9. Eight of these are buried underneath the basemat with two gages per each principal direction. Of the remaining, three are mounted below ground level along a vertical axis on the outside of the wall in the north side, and two are similarly mounted in the west side.

Since the model completion in October 1985, the EPRI Lotung experiment has recorded more than a dozen seismic events. The recorded earthquakes range from magnitudes 5.3 to 6.5 in Richter scale with epicenter distances varying from less than 2 km to over 80 km. Among them, the three most significant ones occurred on January 16, May 20, and July 30 of this year, with free-field peak ground accelerations recorded at 0.25 g, 0.2 g, and 0.18 g, respectively. Data reduction has indicated that a good earthquake data base has been obtained.

While the primary use of the records of the strong motion event is in the validation exercise, the recorded structural response will also be used for the identification of modal parameters. The modal characteristics thus obtained will be compared with those derived from the vibration test response data to determine the change in the system during the earthquake.

SSI METHODOLOGY VALIDATION PROGRAM

The methods selected for validation range from the relatively simple lumped-parameter models to the recently developed techniques involving detailed analytical/numerical treatment of the different aspects of the problem. The current program focuses on validating common practice in SSI analysis using existing methods. There will be no code/method development. Only the 1/4-scale model is covered in this program. While EPRI has selected different industrial practitioners to perform the tasks, NRC/ANL has sponsored a similar program in the universities from where many of the SSI analysis techniques originated. The methods selected include both the direct and the substructure techniques, while the site modeling may use finite-boundary or continuum approaches. Specifically, the following methodologies or their variations have so far been selected for validation:

- Lumped-parameter models.

- FLUSH, a two-dimensional finite-element method that uses transmitting boundaries to model the site [5].

- CLASSI, a substructure approach to analyze linear three-dimensional SSI problems that involves determination of an impedance matrix, the foundation input motion, the modal analysis of the superstructure on a fixed-base, and finally the combination of the above to calculate the structural response [6].

- SASSI, a three-dimensional, substructure method that uses a flexible-volume technique that involves a single finite element analysis to obtain solutions for the impedance and scattering problems [7].

Some of the analysts may use versions of FLUSH, CLASSI, or SASSI that have been modified from their original forms.

The plans for the validation program involve independent effort by each analyst to devise models, perform blind predictive calculations, and compare predictions with measurement leading to evaluation of the methodology. At least two models are to be constructed by each analyst in successive phases. In the earlier phase, the model(s) devised will be based only on information typically available in nuclear plant design phase, i.e., soil boring and geophysical data. With such a model, the analyst will predict the response to dynamic excitation of the vibration tests, if the methodology will permit such calculations. In the latter phase, the model of the earlier phase may be modified, reflecting any additional knowledge gained from the vibration tests. The analysts will then use both the original and the modified models to predict both the site response and the structural response to a selected strong motion seismic event, with only a measured free-field motion being given as input. Finally, the analyst will compare the predictions with measurements and document the results as well as descriptions of the approaches used and their justification. A workshop is planned in which all the analysts are expected to present and discuss the results. The evaluation of the methodologies including the conservatisms (or their absence) and sensitivity of the results to different SSI parameters will be based on the results. Though generally conforming to the framework described above, there are some differences between the workscope adopted by EPRI and that by NRC/ANL. The NRC/ANL plan is shown in Figure 10 and EPRI's plan is given in Figure 11.

CONCLUDING REMARKS

This paper describes the cooperative program between EPRI and NRC/ANL on the validation of SSI analysis methods using the data from a seismic experiment. As blind analytical predictions are being performed by different analysts with different methods, no measurement data is reported here. The results of this program are expected to form the basis for evaluating the methods as to their conservatism and the sensitivity of the results to various assumptions and procedures. The findings will be used in assessing plant seismic design conservatism/margins and for improving plant licensing procedures.

REFERENCES

1. Seed, H. B., and J. Lysmer, "Soil-Structure Interaction Analyses by Finite Elements - State of the Art," Nuclear Engineering and Design, 46, (1978), pp. 349-365.

2. Seed, H. B., and J. Lysmer, "The Significance of Site Response in Soil-Structure Interaction Analyses for Nuclear Facilities," 2nd ASCE Conference on Civil Engineering and Nuclear Power, Vol. II: Geotechnical Topics, September 15-17, 1980, Knoxville, Tennessee, ASCE, pp. 14-1-1 - 14-1-61.

3. Bolt, B. A., Y. B. Tsai, K. Yeh, and M. K. Hsu, "Earthquake Strong Motions Recorded by a Large Near-Source Array of Digital Seismographs," Earthquake Engineering and Structural Dynamics, 10, (1982) pp. 561-573.

4. Wen, K. L., and Y. T. Yeh, "Seismic Velocity Structure Beneath the SMART-1 Array," Bulletin of the Institute of Earth Sciences, Academia Sinica, 4, (1984), pp. 51-72.

5. Lysmer, J., T. Udaka, C. F. Tsai, and H. B. Seed, FLUSH - A Computer Program for Approximate 3-D Analysis of Soil-Structure Interaction Problems, Report No. EERC 75-30, Earthquake Engineering Research Center, University of California, Berkeley, November 1975.

6. Wong, H. L., and J. E. Luco, Soil-Structure Interaction: A Linear Continuum Mechanics Approach (CLASSI), Department of Civil Engineering, University of Southern California, Los Angeles, California, CE79-03, 1980.

7. Lysmer, J., M. Tabatabaie-Raissi, F. Tajirian, S. Vahdani, and F. Ostadan, SASSI - A System for Analysis of Soil-Structure Interaction, Report No. UCB/GT/81-02, Geotechnical Engineering, Department of Civil Engineering, University of California, Berkeley, April 1981.

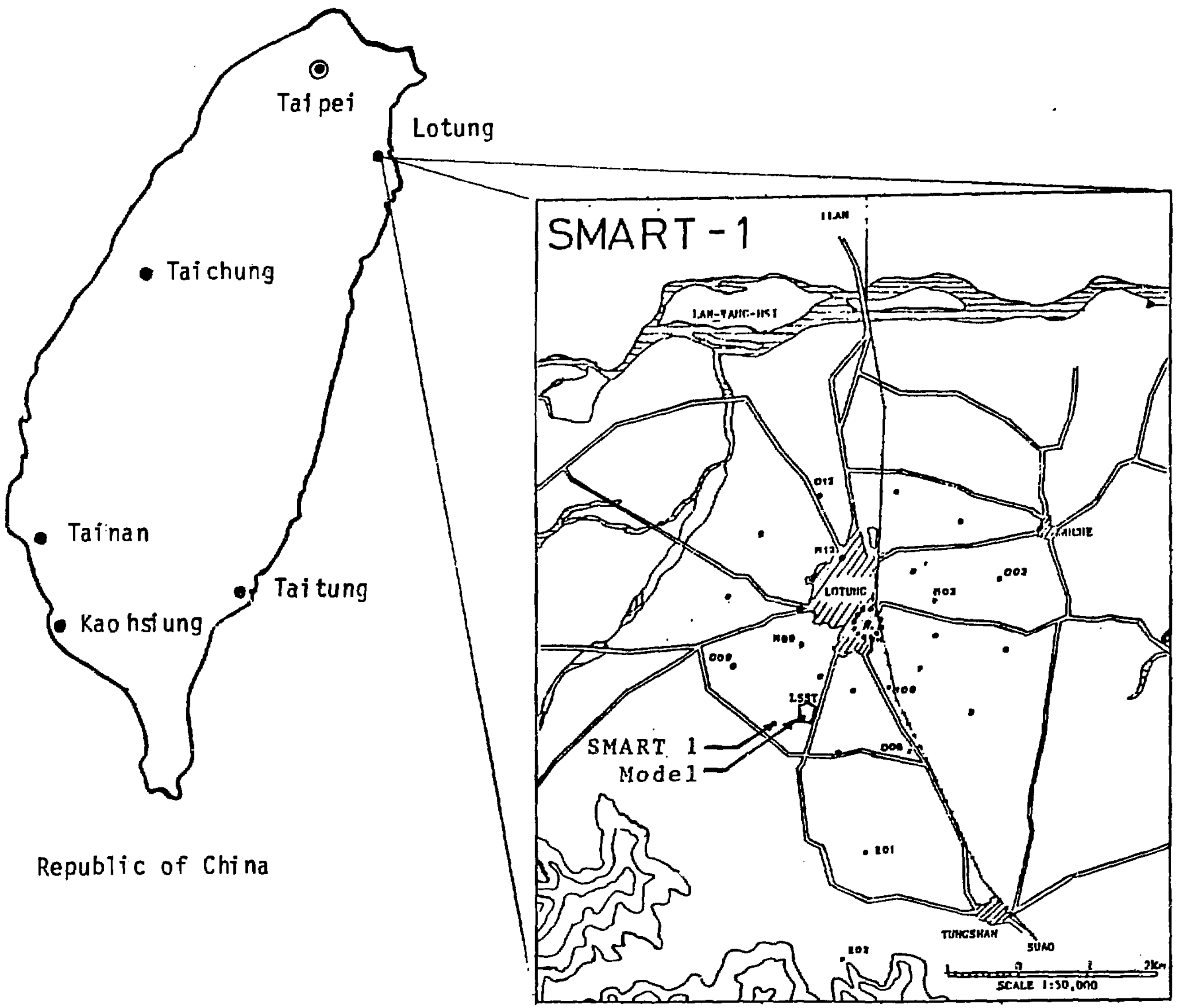


Figure 1. Test Site Location

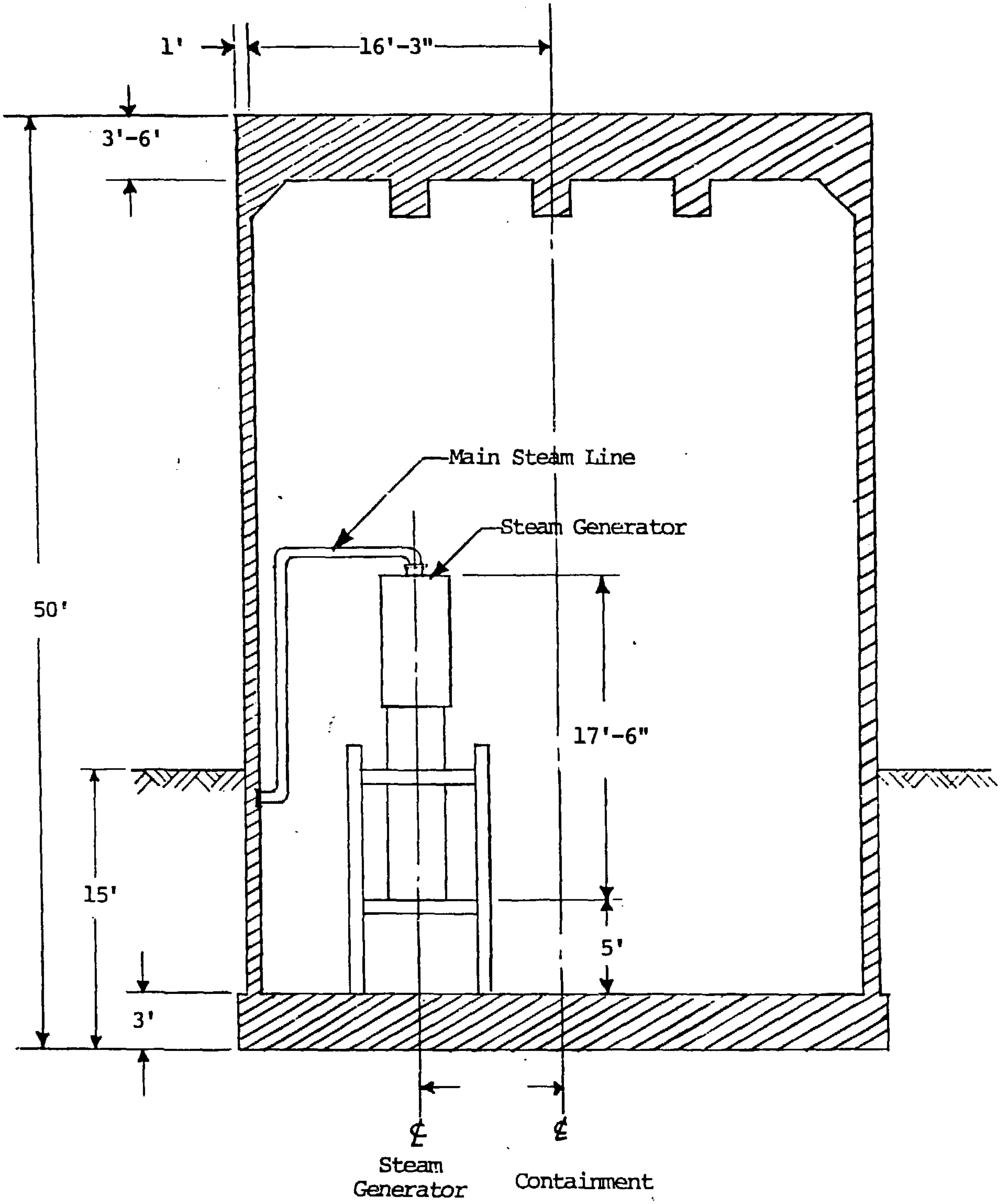


Figure 2. Cross Section of 1/4-scale Containment Model

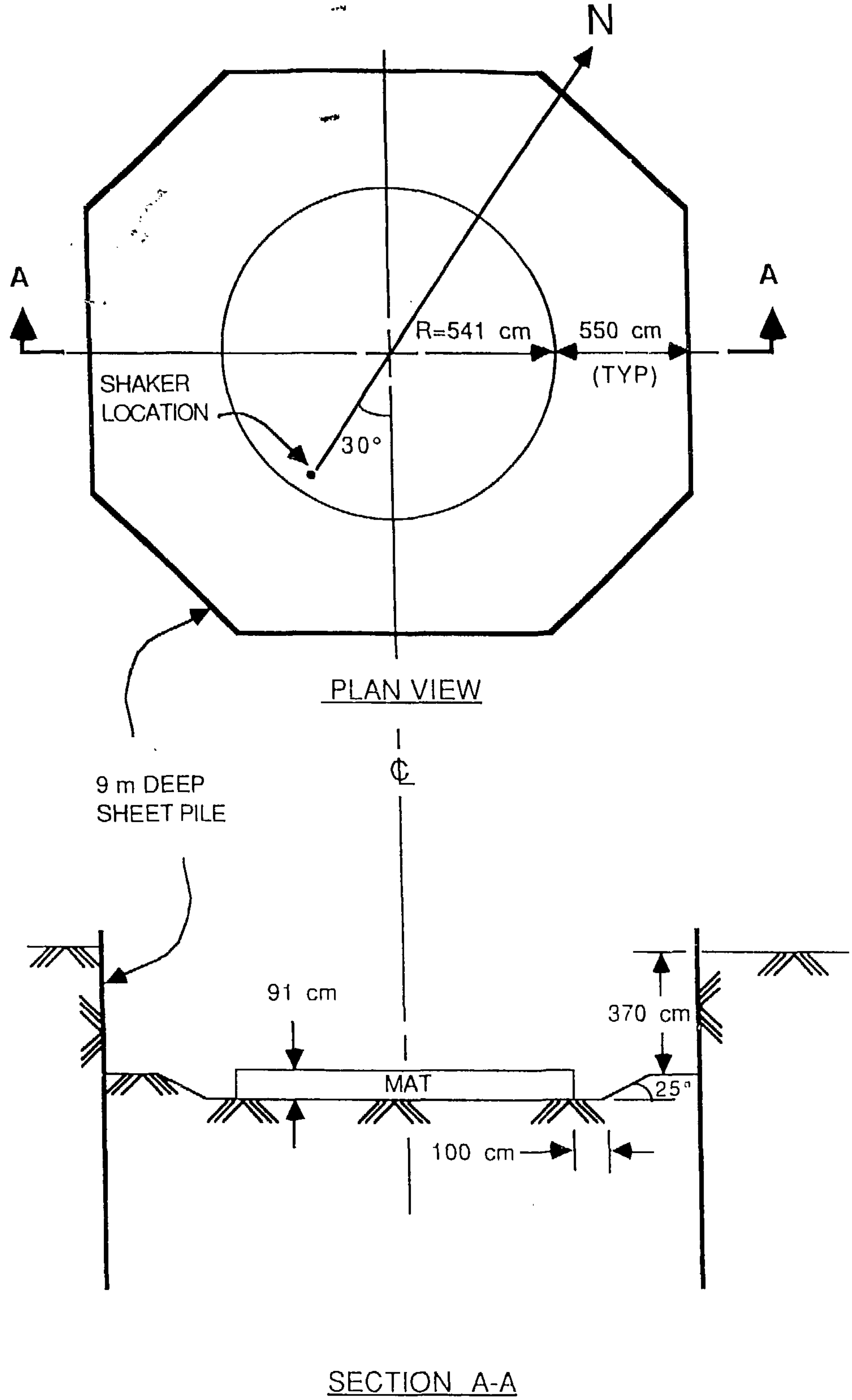
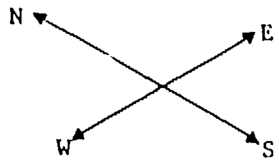


Figure 3. Configuration during Vibration Tests on Basemat



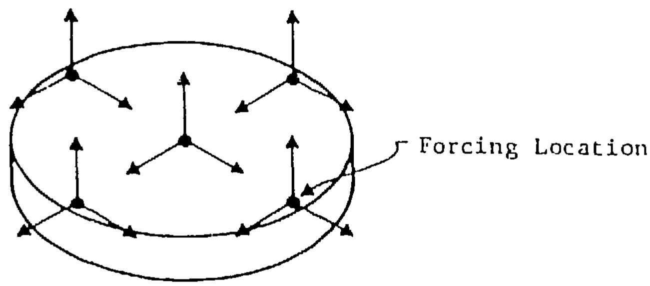
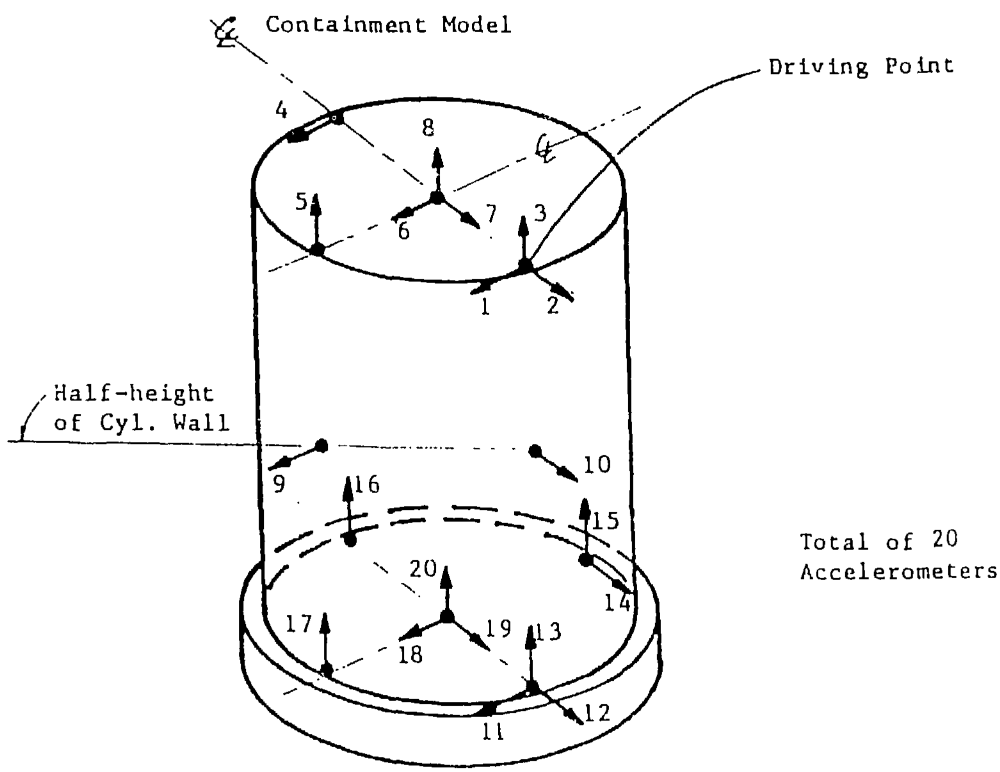


Figure 4. Vibration Test Instrumentation of Basemat



Figur 5. Vibration Test Instrumentation of Structure

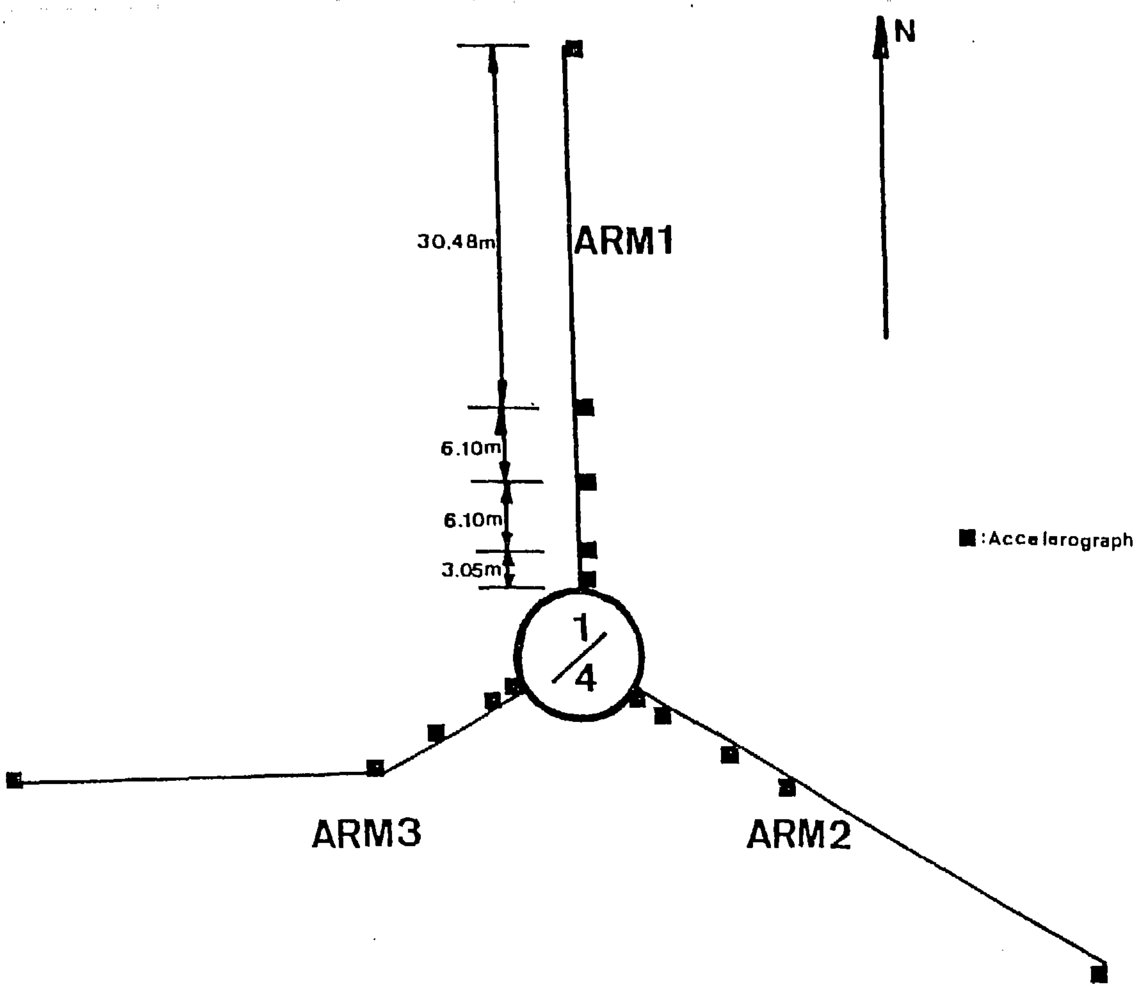


Figure 6. The Surface Instrumentation Array

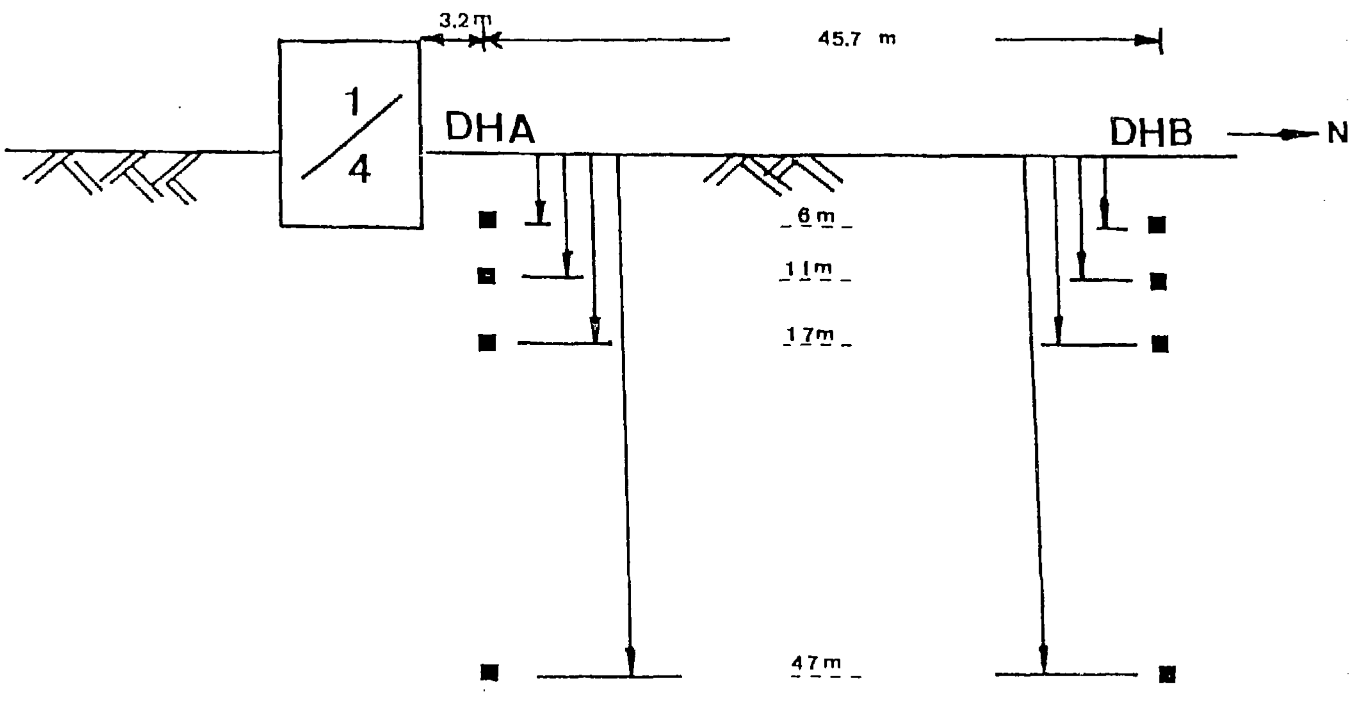


Figure 7. The Downhole Instrumentation

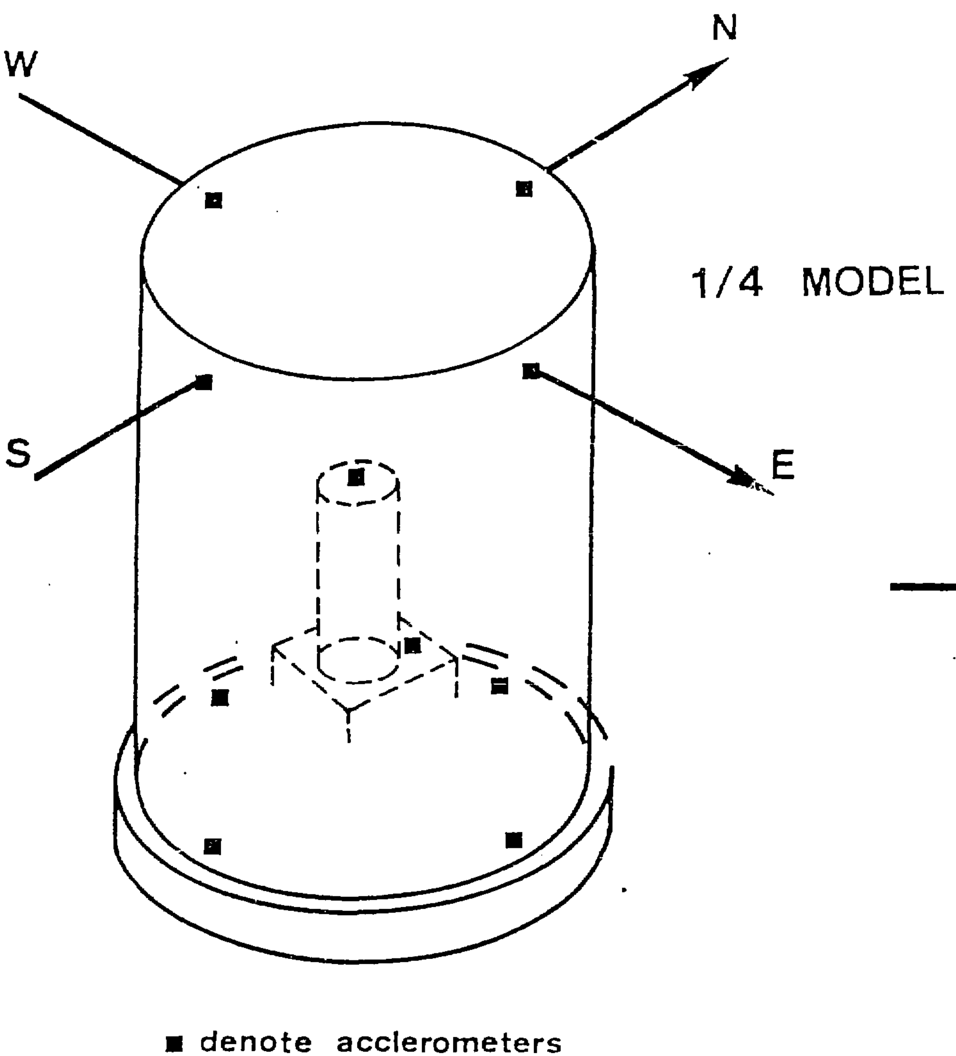


Figure 8. The Structural Instrumentation

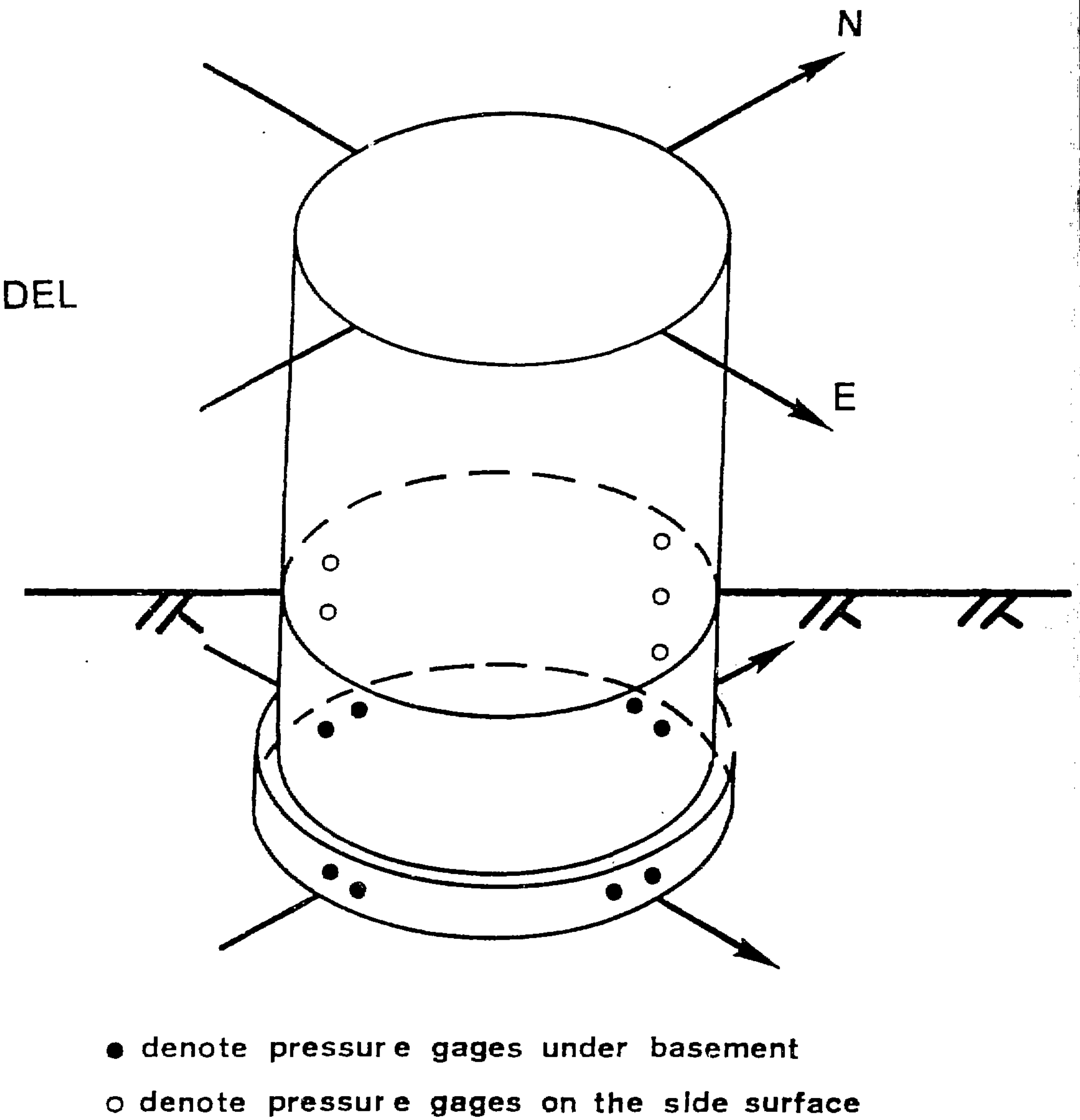


Figure 9. The Interfacial Instrumentation

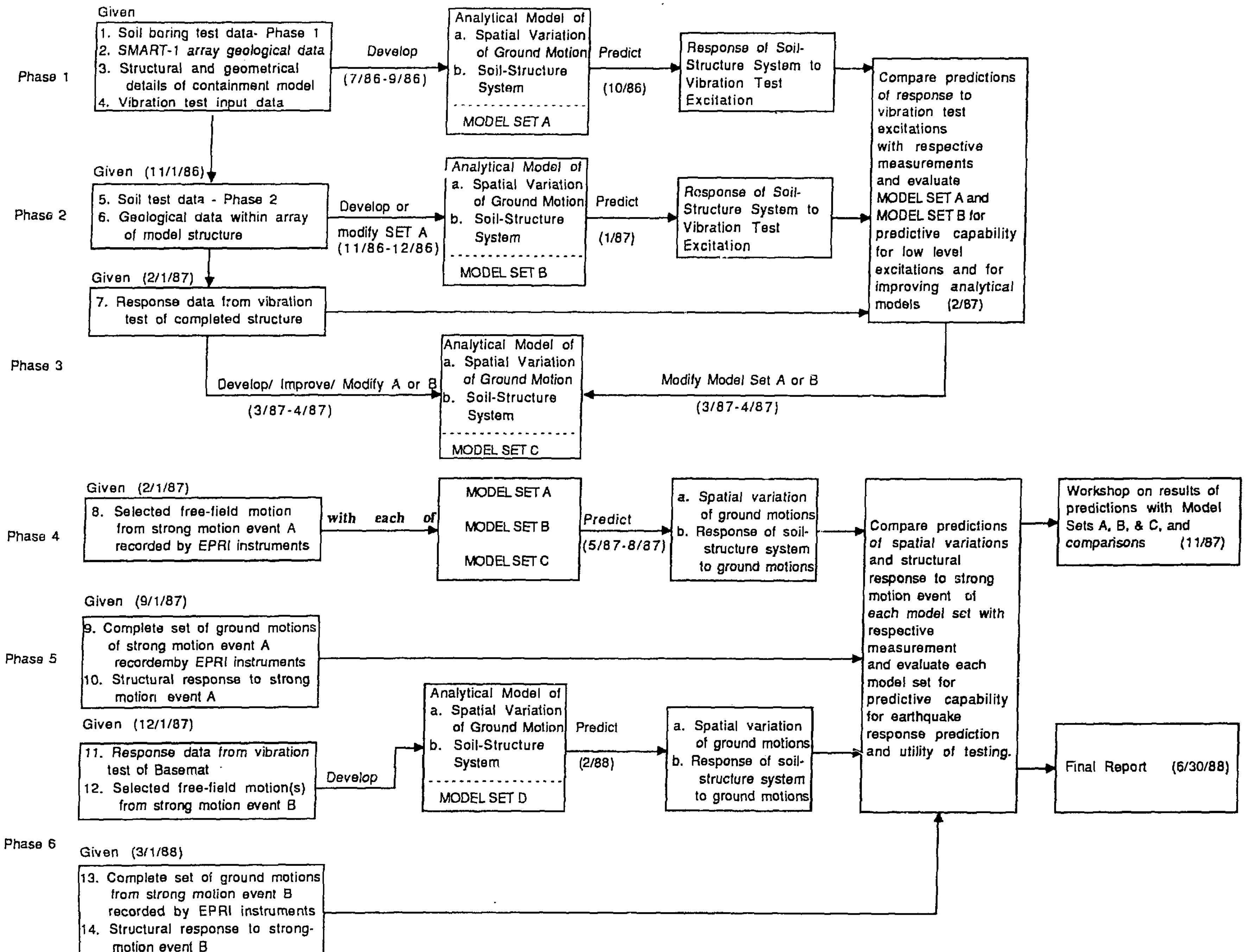


Figure 10. NRC/ANL Plan for Validation Program

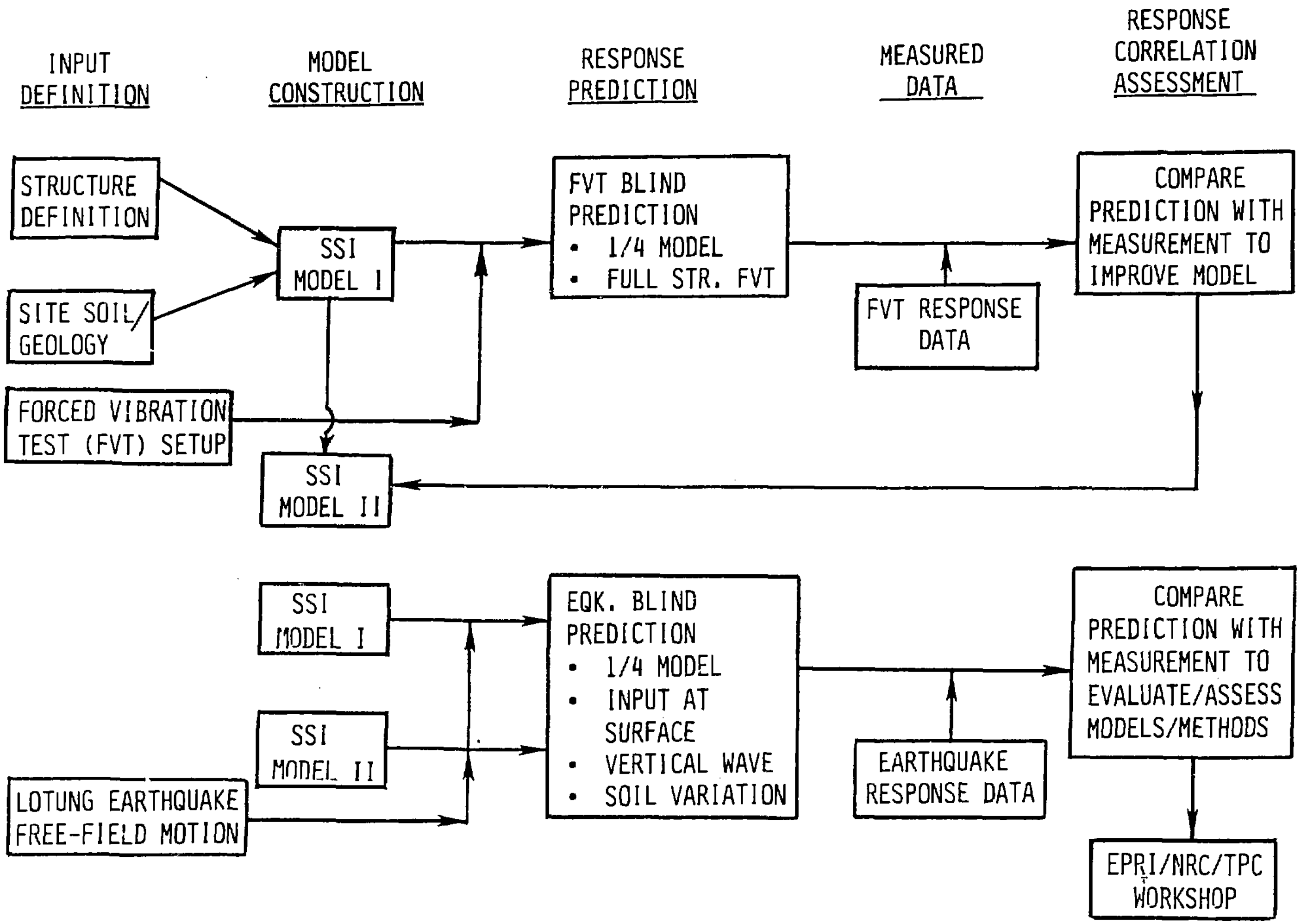


Figure 11. SSI Analysis for Lotung Seismic Experiment (EPRI Program)

Test No.	Run No.	Shaker	Eccentricity in Kg-m	Direction of Forcing	Starting Frequency, in Hz	Ending Frequency in Hz	No. of Freq.[4]	Force Amplitude, in N At Starting Frequency	At Ending Frequency
1	2	MK-12	0.545	R[1]	20.10	30.04	20	8693	19420
2	1	MK-12	0.545	T[2]	20.20	30.13	26	8779	19530
3	1	MK-12	0.545	V[3]	20.00	40.34	48	8606	35010
4	1	MK-13	2.00	R	9.00	20.11	55	6395	31930
5	1	MK-13	11.40	R	5.00	10.07	48	11250	45600
6	1	MK-13	28.50	R	1.00	6.063	88	1125	41360
7	1	MK-13	28.40	T	1.00	6.090	62	1121	41590
8	1	MK-13	11.36	T	5.00	10.07	48	1121	45440
9	1	MK-13	2.00	T	9.00	21.05	58	6395	34986
10	1	MK-13	2.00	V	9.00	21.09	43	6395	35110
11	1	MK-13	11.66	V	2.50	5.697	22	2877	14940
11	2	MK-13	11.66	V	5.00	9.423	33	11510	40870

1. V = Vertical
2. R = Radial (North-South)
3. T = Tangential (East-West)
4. The frequencies are not equally spaced.

Table 1. Basemat Excitation

Test No.	Run No.	Shaker	Eccentricity in Kg-m	Direction of Forcing	Starting Frequency, in Hz	Ending Frequency in Hz	No. of Freq.[4]	Force Amplitude, in N At Starting Frequency	At Ending Frequency
1	1	MK-12	0.55	R[1]	15.00	30.52	76	4885	19880
2	1	MK-12	0.55	T[2]	15.00	30.10	71	4885	19670
3	1	MK-13	2.00	R	9.00	18.06	71	6395	25760
4	1	MK-13	11.50	R	5.00	10.07	57	1135	46070
5	1	MK-13	28.50	R	1.00	6.007	97	1125	40600
6	1	MK-13	28.50	T	1.00	6.020	79	1125	40770
7	1	MK-13	11.50	T	5.00	10.11	47	1135	46400
8	1	MK-13	2.00	T	9.00	18.06	71	6395	25760

1. R = Radial (North-South)
2. T = Tangential (East-West)
3. The frequencies are not equally spaced.

Table 2. Excitation of Completed Structure