2.11 HUALIEN LARGE-SCALE SEISMIC TEST

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BACKGROUND

In nuclear plant regulatory practice, there are two types of approaches for soil-structure interaction (SSI) analysis: half-space (or substructure) and direct (or finite element). Because of known limitations of each approach and the lack of in-depth experimental validation, the Nuclear Regulator Commission (NRC) Standard Review Plan's guidelines (SRP 3.7.2) on SSI review prior to July 1988 recommended that SSI computations be carried out using both approaches and that the results be enveloped unless an acceptable alternative demonstration of conservatism can be given. In the absence of data or clearly defined NRC criteria for an acceptable alternative, most applicants chose to use the conservative enveloping procedure.

Motivated by the need to have a coherent SSI analysis practice with well-defined, realistic guidelines and acceptance criteria, Electric Power Research Institute (EPRI) initiated SSI research in 1977. Early into the research, it was recognized that the key element in pushing the state-of-the-art was to have an experimental data base from controlled and well-instrumented experiments, since advanced development of analytical models for a highly complex physical phenomenon requires comparing analysis to experimental data. Based on this recognition, EPRI's SSI research has had a major focus on experimental investigation. Between 1977 and 1984, three series of SSI experiments were conducted. To simulate earthquake motions (SIMQUAKE), vertical arrays of explosives were detonated to generate dynamic waves propagating through the ground to the model structures. Ground motion data in the free-field surrounding the small-scale model structures together with the structure response data of the models formed a basis for interpreting SSI behavior and evaluating analysis methodologies.

To supplement the inadequacies of SIMQUAKE, EPRI, in 1985, with the cooperation of the Taiwan Power Company (Taipower), initiated an SSI experiment by deploying reduced scale containment models and instrumentation in an active earthquake region in Lotung, Taiwan. Eighteen earthquakes with Richter magnitudes ranging from 4.5 to 7.0 were recorded at the experimental site between September 1985 and November 1986. Several earthquakes had peak accelerations in the neighborhood of 0.2*g*, furnishing significant strong-motion records, which provided a basis for quantitative evaluation of conservatism embedded in various SSI methodologies and uncertainties and sensitivities of SSI parameters and procedures.

The Hualien LSST program was initiated in January 1990 and began recording earthquake data in 1993, to continue until the end of 2001. The goal of this program was to collect real earthquake-induced SSI data in order to evaluate computer codes used in SSI analyses of nuclear power plant structures. In the program, observations will be made on the motions of the reactor building model and the surrounding ground during large-scale earthquakes. The expectation is that the test model will be shaken by numerous earthquakes in this seismically active area of Taiwan. To date, nearly 100 moderate earthquakes have been recorded at the facility.

Included in earthquake recordings are the September 1999, 9.1 Magnitude Chi-Chi and nearly 30 aftershocks resulting from the Chi-Chi earthquake. Instrumentation located on the scale model and in the field along a three-dimensional strong ground motion array recorded the earthquake data. The LSST program at Hualien, Taiwan, is a follow-on to the SSI experiments at Lotung, Taiwan.

The Electric Power Research Institute (EPRI) organized the Hualien LSST experiment and coordinated participation with the Taiwan Power Company (Taipower), the NRC, the Central Research Institute of Electric Power Industry (CRIEPI), the Tokyo Electric Power Company (TEPCO), the Commissariat a l'Energie Atomique (CEA), Electricite de France (EdF), Framatome, the Korea Power Engineering Co. (KOPEC), Korean Institute of Nuclear Safety (KINS) and Korea Electric Power Corp. (KEPCO).

RESEARCH SUMMARY

The Hualien LSST site is located along the east coast of Taiwan about 90 miles south of Taipei. It is located close to the coastal range fault on the meilun terrace, which is a seismically active region of Taiwan. A 1/4-scale cylindrical reinforced concrete containment model with radius of about 5.4 m was constructed at Hualien Veteran's Marble Plant. The Hualien LSST model is located within the so-called Strong Motion Array in Taiwan (SMART2) was completed in 1992.

The Institute of Earth Sciences (IES), Taiwan, performed preliminary characterization of the site. These studies indicate that the surface material consists of two layers. The top layer is shallow (about 18 ft) and consists of a silty sand with a small gravel content. The second layer is a gravely sand, and this layer ranges in depth from 330-660 ft. The gravel in this layer ranges in size from 1-1/4 in. to 2-3/4 in. The underlying material is a mudstone. Detailed site geotechnical investigation results and laboratory tested soil properties were synthesized to developed soil models to provide a basis for analytical prediction and correlation of forced vibration tests (FVT) and actual earthquake induced response. The final detailed geophysical characterization of the site was done by CRIEPI.

FVT test were performed to characterize the dynamic properties of the model. Two FVT tests were performed by TEPCO, one before placement of the backfill and the second after backfill. Each of the test series consisted of five parts, varying the location and direction of the applied shaker force as follows: roof in the N-S direction; roof in the E-W direction; basemat in the N-S direction; basemat in the E-W direction; and basemat in the vertical direction. The shaker used for these tests was a rotating eccentric mass type, all FVT tests were completed early in 1993.

The instrumentation for the FVT tests consisted of velocity type displacement meters and pressure cells. The pressure cells were placed to monitor wall/soil and basement/soil interface pressures during earthquakes. The displacement meters were placed in the model and in the free field. The placement in the model was on the roof, at mid-height, and on the basemat. The gages were generally placed around the model periphery at each of the elevations and recorded responses in the N-S, E-W, and vertical directions.

The instrumentation array placed after the FVT tests and remaining in place to record seismic events consist of accelerometers, pressure gages, pore water pressure gages and settlement gages. Accelerometers are located on the surface of the free field along three radial lines; the radial lines are separated by about 120 degrees.

Appropriate modifications were then made to the instrumentation and data recording system, and then the model was prepared to record responses during earthquake events. The model was placed in this mode in September 1993 and recorded seismic events through 2001.

In addition to the 1/4-scale containment model, a vertical ground mounted, thin walled, steel liquid storage tank, designed by the Korean participants was installed at the Hualien LSST site. The tank is 7 m in diameter and 8.3 m in height, and is located approximately 50 m away from the containment model; the tank was completed in October 1994 (see Figure 1).

RESEARCH RESULTS

The results of the Hualien LSST program are highlighted in three areas: a) the soils exploration; b) the forced vibration tests; and c) the seismic response studies.

Soils Exploration

A comprehensive site characterization program was conducted by CRIEPI between 1990 and 1994. This site characterization program paid particular attention to the soil conditions to a depth of about 12 m below the ground surface (GL-12m). In this regard, the site characterization was at least as thorough as those commonly used for actual nuclear power plant sites. A somewhat less detailed characterization was provided for the gravel between GL-12m and GL-20m.

Cross-hole logging results reveal shear wave speeds from GL-5m to about GL-12m that appear to be significantly different in two orthogonal directions both before excavation and after construction of the model. The logging results show considerable scatter, however, and the difference between the wave speeds in the two orthogonal directions is more apparent in terms of the averages of the measurements in each direction. Prior to the forced vibration tests, the possibility of anisotropic site conditions with two principal directions of shear wave propagation in the horizontal direction was not expected. The forced vibration test data and the recorded earthquake ground motion data; however, reveal that this anisotropy appears to be the actual site condition.

Forced Vibration Test

Forced Vibration Tests (FVT) was conducted in order to obtain data regarding the dynamic characteristics of the SSI system (resonant frequency, damping factor) that are necessary in analyzing SSI effects. Two sets of FVTs were performed, one before placement of the backfill soil and the other after placement of the backfill soil. Response displacements were measured on the model's roof, at the top of the foundation base mat, and on the soil surface. The test results indicated that both the resonant frequency and the damping factor increased and that the response amplitude decreased due to embedment of the structure with backfill soil. The model responses also indicated that the site is anisotropic.

Seismic Response

Earthquake observations included measurements of acceleration by a high-density accelerometer arrangement; earth pressure between the base and soil; pore water pressure and settlement; and inclination of the model structure during earthquakes. The predicted responses for the soil and structure compared reasonably

Figure 1. **Containment and steel tank models; top photograph is 1:10 -scale reinforced concrete model; bottom photograph is full-scale tank.**

well with the measured ones. For one sector of the Hualien site, however, the structural responses did not compare well; this can be attributed to the anisotropic site characteristics.

REGULATORY IMPLICATIONS

An extensive soils exploration program was conducted by CRIEPI over the duration of the project. It can be concluded that the Hualien site was at least as extensively analyzed as any nuclear power plant site. In spite of this, significant uncertainties still exist in the soil properties. Much of the measured response data indicates that the soil models may represent the soil as too stiff. Potential sources of these uncertainties have been attributed to nonlinear effects such as soil separation, and to the difficulty in conducting field and laboratory tests of gravelly soils, which are found at the Hualien LSST site. Many of the measured responses also point to the apparent anisotropic characteristics of the soil properties. Soil anisotropy was not considered in formulation of the soils exploration program and as a result the Hualien program sheds little light on the magnitude or source of the anisotropic effects.

After backfill, measured data showed that soil embedment reduced the structural response to seismic motion. To adequately account for soil embedment effects in nuclear plant structures where embedment is significant, such as a Pebble Bed Reactor where it was stated that up to one half the building structure would be below ground, soil properties, such as static and dynamic soil embedment properties, would have to be defined to determine the amount of reduction in the structural response.

Two types of computer codes were used to model the forced vibration tests and the response of the model to the seismic events. The first type of code, Computer Analysis for Rapid Evaluation of Structures (CARES), is considered as a half-space SSI analysis method [4]. The second type of code, such as System for Analyses of Soil-Structure Interaction (SASSI), is considered as a finite element SSI analysis method [5].

Predictions of the model response to the backfill shaker tests made with both types of codes were in good agreement with each other and with the measured data. The predictions of the response of the model to the seismic events were also made with both types of codes. Generally fair agreement was found between the predicted and measured results. This suggests that the current methods to calculate the effects of SSI can account for observed phenomena; however, for seismic events it is important that analytical codes properly model the soil layer boundary conditions and soil properties, especially for backfill material.

CONCLUSIONS

The research results indicate that for an anisotropic site, some model responses between a control point located in the free field and the structure cannot be adequately computed based on isotropic models. Tools are not available to treat the anisotropic soil condition. For nuclear plant structures where embedment is important, such as a pebble bed reactor, soil properties will be need to be defined to adequately evaluate the effects of embedment. To address these findings communication between industry, academia and regulatory bodies should continue.

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