June 25, 2001

MEMORANDUM TO: Samuel J. Collins, Director
Office of Nuclear Reactor Regulation

Martin J. Virgilio, Director
Office of Nuclear Material Safety and Safeguards

FROM: Ashok C. Thadani, Director Original signed by R. Zimmerman for
Office of Nuclear Regulatory Research

SUBJECT: RESEARCH INFORMATION LETTER RIL-007, “HUALIEN SOIL-STRUCTURE INTERACTION LARGE SCALE SEISMIC TEST"

Background

Probabilistic Safety Assessments (PSAs) indicate that earthquakes are important contributors to the risk of nuclear power plants (NPPs). In addition, earthquakes can challenge the defense-in-depth provisions that protect plants from most other potential initiators. Although the quantification of the risk contribution from earthquakes in PSAs did not begin until the early 1980s, the nuclear power community has recognized this threat from the beginning. An important regulatory requirement for NPPs going back to the 1960s includes the protection against the effects of earthquakes.

General Design Criteria (GDC) 2, "Design Bases for Protection Against Natural Phenomena," of Appendix A, "General Design Criteria for Nuclear Power Plants," to 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities," and GDC 4, "Environmental and Dynamic Effects Design Bases," of Appendix A to 10 CFR Part 50, require, in part, that structures, systems, and components (SSCs) be designed to withstand the effects of natural phenomena, and to accommodate the effects of, and be compatible with, the environmental conditions associated with normal operation and postulated accidents. Appendix S, “Earthquake Engineering Criteria For Nuclear Power Plants,” to 10 CFR Part 50, gives, in part, requirements for the implementation of GDC 2 with respect to earthquakes and soil-structure interaction (SSI), i.e. an exchange of energy between a structure and the surrounding soil during an earthquake.

In nuclear plant design practice, there are two types of approaches for SSI analysis: half-space and finite element. Because of known limitations of each approach and the lack of in-depth experimental validation, Section 3.7.2, Seismic System Analysis of the SRP (Reference 1) prior to July 1988 (before the latest revision), recommended that SSI computations be carried out using both approaches and that the results be enveloped unless an acceptable alternative demonstration of conservatism could 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 (Reference 2). This approach led to costly designs of nuclear power plant structures and their internal structures.

Motivated by the need to have a coherent SSI analysis practice with well-defined, realistic guidelines and acceptance criteria, the 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. However, good SSI test data is rare because the cost of installing and maintaining instrumentation is high; thus it would be more cost effective to collect data at sites where repeated earthquakes are likely to occur. In the mid 1980s, EPRI asked NRC and several organizations in other countries to join in an SSI experiment in Lotung, Taiwan, a seismically active region of Taiwan. Data at Lotung under the EPRI initiative, recorded from 30 earthquakes with Richter magnitude ranging from 4.0 to 7.0, were considered by the NRC along with public comments in the Resolution of Unresolved Safety Issue A-40, "Seismic Design Criteria," in 1989. In the resolution of USI A-40, NRC revised SRP 3.7.2 and no longer required applicants to use both SSI methods.

Although the experiment at Lotung produced a significant body of data on SSI, its application was limited since the Lotung site was considered a soft soil site. In 1990, EPRI and the Taiwan Power Company (Taipower) organized the Hualien Large Scale Seismic Test (LSST) experiment and coordinated participation with other organizations including NRC, Central Research Institute of Electric Power Industry (CRIEPI), Tokyo Electric Power Company (TEPCO), Commissariat a l'Energie Atomique (CEA), Electricite de France (EdF), Framatome, Korea Power Engineering Company (KOPEC), Korean Institute of Nuclear Safety (KINS), and Korea Electric Power Corp (KEPCO). The above named organizations formed the Hualien consortium. The Hualien site in comparison to Lotung is a stiff soil site and consists of sands and gravel which is more representative of soil sites in the United States.

Summary of Research

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 quarter scale reinforced concrete model of a containment structure was constructed in Hualien, Taiwan in 1992. Forced vibration tests were performed both before and after placement of the backfill soil in 1993. The structure and surrounding free field were then instrumented with accelerometers, pressure gages, and displacement gages. Recordings were taken when significant seismic events occurred at the site. To date over 100 earthquakes with Richter magnitude ranging from 4.5 to 7.3 have been recorded (including the September 1999 7.3 magnitude Chi-Chi earthquake) at the Hualien LSST facility.

The results of the Hualien LSST research are documented in NUREG/CR-6584, "Evaluation of the Hualien Quarter Scale Model Seismic Experiment," and are discussed as follows. Volume 1 describes the analytical studies that were performed to correlate the measured response with predictions. The Hualien LSST site characteristics are described in Volume 2 of NUREG/CR-6584. This includes a discussion of the field exploration program used to determine the site characteristics of the soil. The predictions for the forced vibration tests are compared with the measured data in Volume 3 of NUREG/CR-6584. Comparisons between the predictions and measured data for the earthquake responses are made in Volume 4 of NUREG/CR-6584.

Results of the Research

The results of the Hualien LSST program are highlighted below for: 1) the soils exploration, 2) the forced vibration tests, and 3) the seismic response studies.

1. 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. However, the logging results show considerable scatter 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.

2. Forced Vibration Test

Forced Vibration Tests (FVT) were 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.

3. 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 well with the measured ones. However, for one sector of the Hualien site the structure 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. It should also be noted that current SRP (Section 3.7.2.II.4) guidance does not specifically mention or discuss the need to evaluate a site for soil ansiotropy.

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 ½ 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, CARES (Computer Analysis for Rapid Evaluation of Structures), is considered as a half-space SSI analysis method (Reference 4). The second type of code, such as SASSI (System for Analyses of Soil-Structure Interaction) is considered as a finite element SSI analysis method (Reference 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.

Closure

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 a meeting should be held among cognizant NRC staff and any recommendations/conclusions should be processed using the planning, budgeting, and performance management (PBPM) process.

RES believes that this international cooperative program has been cost-effective, helped advance the state of the art, and has provided experimental data to confirm current seismic requirements and validate recently developed SSI methods. Also, this work supports the strategic goals of maintaining safety, improving regulatory effectiveness, efficiency and realism, reducing unnecessary burden, and increasing public confidence. This research supports the strategic goals as noted in Attachment A.

Earlier findings of this research were shared with NRR and NMSS staff in project review meetings and other technical discussions. One member of NRR/DE/EMEB, Dr. Thomas Cheng, participated in technical review meetings held in Taiwan and made a site visit to the Hualien LSST facility in 1996. Our current plans are to update Regulatory Guide 1.60 and to evaluate the need to recommend revisions to the Standard Review Plan.

Based on a comparison of the theoretical results, using appropriate soil and structural models with the observed response, confidence has been gained in the ability of current analytical codes to account for the effects of SSI. Finally, data has been collected that will be available for future studies and that will be used to update current regulatory guidance in Regulatory Guide 1.60, “Design Response Spectra for Seismic Design of Nuclear Power Plants,” which is scheduled to be released for public comment later this year.

Please contact Herman Graves (415-5880) for any questions on the enclosed RIL and NUREG/CR-6584.

REFERENCES

1. U.S. Nuclear Regulatory Commission, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plant LWR Edition," NUREG-0800, July 1981.

2. Philippacopoulus, A. J., "Recommendations for the Resolution of Public Comments on USI A-40, Seismic Design Criteria," NUREG/CR-5347, June 1989.

3. Graves, H. L., Tang, H. T., and Liao, Y. C., “Large Scale Seismic Test Program at Hualien Taiwan,” Nuclear Engineering and Design, Netherlands, Volume 163, 1996, pp. 323-332.

4. Xu, J., Philippacopoulus, A. J., Miller, C. A. and Costantino, C. J., "CARES (Computer Analysis for Rapid Evaluation of Structures) Version 1.0," NUREG/CR-5588, Volumes 1-3, USNRC, Washington, D.C., July 1990.

5. Lysmer, J., Tabatabie-Raisi, M., Tajirian, F., and Ostadan, F., “SASSI - A System for Analysis of Soil-Structure Interaction,” Report No. UCB/GT/81-02, University of California, Berkeley, 1981.

Attachments: As stated

cc: W. Travers
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Attachment A

The international cooperative program, “Hualien Soil-Structure Interaction Large Scale Seismic Test,” is consistent with the NRC strategic performance goals in the areas of maintaining safety; making NRC activities and decisions more effective, efficient, and realistic; reducing unnecessary regulatory burden; and increasing public confidence as follows:

Maintaining Safety - The Hualien experimental data will increase our base of knowledge in a key safety area, seismic, for which risk assessments indicate its risk contribution may be large and the uncertainties great. This knowledge will make seismic analyses and design more credible because the data has been gathered as a result of the test structure being subjected to real earthquakes not simulated ones. This in turn will lead to more realistic seismic requirements and ultimately enhance safety.

Improving Regulatory Effectiveness, Efficiency, and Realism - The results, findings, conclusions, and data collected by RES and the other program participants in this study will support several regulatory activities. These activities include the technical review of proposed license amendments and the revision of Regulatory Guides 1.60, “Design Response Spectra for Seismic Design of Nuclear Power Plants,” and 1.132 “Site Investigations for Foundations of Nuclear Power Plants.” Any future regulatory products resulting from this work will be more realistic and technically sound because they will be based on actual earthquake response data.

– *Technical reviews of proposed license amendments*. The results of this study were used to benchmark and update a personal computer based program, Computer Analysis for Rapid Evaluation of Structures (CARES), that was originally developed under a different research program in 1990 and made available to technical reviewers. The CARES program has been used by NRR reviewers in their review of SSI analyses for the Westinghouse AP-600 advanced reactor design, Palisades site amplification studies for plant areas outside the reactor boundary for verifying the location of independent spent fuel storage installations, and for performing other parameter studies for SSI.

– *Revision of Regulatory Guides 1.60 and 1.132.* In the revision of Regulatory Guide 1.60, plans are to make a recommendation to use a process to convolve bedrock ground motions up a soil column to arrive at design surface spectra. In order to implement this process, data are needed from vertical array measurements (such as those made at the Hualien LSST facility) to ensure that the process leads to realistic assessments of the surface spectra. The knowledge gained during the field exploratory phase of the Hualien experiment will be factored into the final revision of Regulatory Guide 1.132 for which public comment expired in May 2001.

Reducing Unnecessary Burden - Data collected at the Hualien facility have provided NRC with an opportunity to improve and confirm the Standard Review Plan (SRP) guidelines on SSI. The existing guidelines in Section 3.7.2 of the SRP published in 1989 were based in part on data collected at the Lotung LSST site in the mid 1980s. The Hualien soil is composed of gravelly layers and is a stiffer soil in comparison to Lotung, making the Hualien site SSI effects more characteristic of those for prototypical U. S. power plants. The Hualien data should be used to determine if the current SRP guidelines that require licensees to perform SSI analyses using a variety of soil properties to reflect uncertainties is still justified.

Increasing Public Confidence - Since SSI is such an important issue within the realm of seismic design, NRCs technical credibility has been enhanced by participating in the Hualien LSST experiment. The Hualien LSST facility is one of the largest in the world for SSI research. Five different countries: Japan, Taiwan, Korea, France, and the United States, representing 15 organizations have been involved in this effort to collect actual seismic response data. Examination of this issue has been thorough, disciplined, and timely, evidenced by the peer review provided at regularly scheduled technical meetings where pre-test predictions, interim analysis, and preliminary conclusions of the data were reviewed and discussed by all participants. Knowledge gained from this research effort has been made available to the public through published technical papers, participation in widely attended conferences and publication of the attached NUREG/CRs.