2.3 RECOMMENDATIONS FOR SOIL STRUCTURE INTERACTION (SSI) INSTRUMENTATION

M. ÇELEBI
U.S. Geological Survey

C. B. CROUSE
URS Corporation

ABSTRACT

A workshop held in 1992 resulted in a set of recommendations to define the needs for and the parameters essential for implementation of a soil-structure interaction (SSI) experiment. During the workshop, beneficial and adverse effects of SSI were discussed. The recommendations and the current status of the SSI experiment are presented herein.

INTRODUCTION

The objectives of this paper are to:

- introduce the recommendations of a workshop held in 1992 that aimed to define the background information in establishing a special purpose array in a seismically active region of the United States to study specifically the effect of SSI and define the parameters and details of a SSI experiment;
- summarize two recent workshops that in general discussed the SSI subject
- describe the current state of implementation in the United States and Japan

The objectives of the 1992 workshop were: (a) to bring together a panel of experts to reach a consensus on the benefits and feasibility of instrumenting a building in a seismically active region of the United States to study specifically the effect of SSI, and (b) to discuss and determine the details of such a SSI experiment.

WORKSHOP OF 1992

Background

In the past, during design/analysis processes of engineered structures, it was assumed that the foundation of a structure was fixed to a rigid underlying medium. In the last four decades, however, it has been recognized that SSI alters the response characteristics of a structural system. In important engineered structures, detailed numerical and closed-form-solution methods are applied to perform soil-structure analyses. To date, the strong-motion data from instrumented buildings are insufficient to confirm the validity of the soil-structure interaction analysis methods and procedures as applied to structures other than nuclear power plant structures. SSI was introduced in the ATC-3 tentative provisions, and has been incorporated into the NEHRP provisions).

Since 1978, during several workshops and technical meetings, specific recommendations have been repeatedly made to instrument a building for soil-structure interaction studies [e.g., Lee, 1978; Iwan, 1978; Iwan 1981]. As recently as 4-5 November 1991, during the NSF workshop on "Experimental Needs for Geotechnical Earthquake Engineering," held in Albuquerque, New Mexico, strong-motion instrumentation for soil-structure interaction was given a high priority. Of particular significance is the high-priority recommendation in the recent USGS Circular 1079 titled "Goals, Options, and Priorities for the USGS Earthquake Hazards Reduction Program" [Page et al., 1992]. "Priority should be given to deploying both special-purpose arrays and networks designed to provide data for a wide variety of purposes. These deployments should include near-fault dense arrays and networks to determine earthquake source processes, regional arrays to determine seismic-wave propagation characteristics between the source and the site, downhole arrays to study the effects of local geologic conditions on modifying ground motions, special deployments to study soil-foundation interaction and the response of structures, and instrumentation of carefully chosen sites with the potential for liquefaction or landsliding."

Recent Meetings on the Subject

There have been no meetings to directly discuss the detailing of a soil-structure interaction experiment except the ones related to the nuclear power industry (e.g., the Lotung array). Since the subject matter of this workshop is related to those buildings that are not critical structures (such as nuclear power plants) but are significant from the point of view of reducing earthquake hazards, only the following meetings will be cited:

- Workshop on "Research Needs and Priorities for Geotechnical Earthquake Engineering Applications," University of Texas, Austin, Texas, June 1978 (Proceedings edited by K. Lee, W. Marcuson, K. Stokoe and F. Yokel).
- International Workshop on "Strong-Motion Earthquake Instrumentation," Honolulu, Hawaii, May 1978 (Proceedings edited by W. Iwan, 1978).
- U.S. National Workshop on "Strong-Motion Earthquake Instrumentation," Santa Barbara, California, April, 1981 (Proceedings edited by W. Iwan).
- Workshop on "Experimental Needs for Geotechnical Earthquake Engineering," Albuquerque, New Mexico, November 1991 (Proceedings to be compiled by C. Higgins).

MOTIVATION

Although, currently, there are over 150 instrumented structures in the United States, there is no instrumented structure that will allow detailed calibration and/or confirmation of the validity of the soil-structure interaction analysis methods. The significant sets of data acquired during the 1987 Whittier, 1989 Loma Prieta, and 1994 Northridge earthquakes provide insight into structural responses and clearly show that soil-structure interaction took place in several instrumented buildings; however, the data set is insufficient to calibrate soil-structure interaction methods or to quantify the significant parameters related to it. That is, to date, there are no strong-motion response data from instrumented structures complete enough to carry out detailed studies of the methods and procedures used in soil-structure interaction analyses, and, in turn, assess their impact on design codes and related analysis procedures. Examples of deficiencies in existing instrumented building systems are as follows:

- The strong-motion instrumented structures do not have pressure transducers and accelerometers around the periphery of the foundation system (a) to check the horizontal and vertical dynamic pressures and the variation of the forces, and (b) to quantify rocking and uplifting during strong-motion events.
- There are no downhole arrays[3] below the foundation or in the vicinity of a building to carry out studies related to vertical spatial variation of motions to calibrate convolution and deconvolution processes and applications. (The only building with a tri-axial downhole instrument is in Norwalk, California, see Fig. 1; however, the downhole instrument is within a caisson only 30 feet below the basement level and recent data shows that its motion is same as the basement of the building; [Çelebi, 1992][3].)
- There are no horizontal spatial arrays in the vicinity of a building to specifically study free-field motions and how these motions are altered by interaction with the foundation of a building structure.

Such an experiment will enhance the chances to record several aspects of the SSI phenomenon.

Ideal Soil-Structure Interaction Experimental Scheme

An ideal layout of arrays that includes soil-structure interaction instrumentation is provided in Figs. 2a and b [Çelebi et. al., 1977; Çelebi and Joyner, 1978]. As shown schematically in Figs. 2a and b, such a layout should have four main arrays:

1) superstructure array
2) soil-structure interaction array
3) vertical spatial array
4) horizontal spatial array

Workshop Discussions

The following major topics were discussed during the workshop:

1) Significance of strong-motion instrumentation for soil-structure interaction in relation to the earthquake hazard reduction programs;
2) Logistics (type of structure, type of foundation system, type of geotechnical site and type of seismic region that will optimize the chances of getting the best soil-structure interaction data);
3) Details of instruments (types of instruments---accelerometers, pressure transducers, recording systems, etc.); and
4) Recommendations of the workshop.

[3]This was the situation in 1992. Now there are a few structures around which there are downhole accelerometers.

Lotung and Hualien Experiments

The most detailed soil-structure interaction (SSI) experiment to date was implemented in 1985 by EPRI at Lotung. The purpose of the Lotung experiment was to facilitate the study of SSI for a 1/4- and 1/12-scale, reinforced-concrete, cylindrically-shaped nuclear power plant containment models under strong ground motion earthquakes [EPRI, 1989; Tang et. al., 1987a, b, c, 1990]. With this aim in mind, the Lotung experiments provided insight into the SSI response of a very stiff structure (fixed-based frequency on the order of 7--10 Hz and SSI frequency of 2.7 HNeez) on an extremely soft soil condition (shear wave velocity of the top layer between 300--1000 ft./sec. (100-330 m/s). The results of the Lotung experiment showed that the response of the structure was mainly in the rocking mode (rigid-body rotation) and that the SSI effect in structural deformation and seismic wave spatial variation under stiffer soil conditions were not addressed. To remedy those shortcomings, another experiment at a stiffer soil site, Hualien, was implemented [Tang, 1991]. The shear wave velocity of the top layer at this site is approximately 1200 ft./sec. (~400 m/s). The experiment is called the Hualien Large-Scale Seismic Test for Soil-Structure Interaction Research. Some of the lessons learned from the Lotung experiment and from the instrumentation schemes of both the Lotung and Hualien arrays can be used in the study of SSI for regular building structures. However, the natural frequencies of the containment structures of both the Lotung and Hualien experiments are much higher than those of regular buildings, the subject of the SSI experiment discussed herein.

RECOMMENDATIONS OF THE WORKSHOP

Recommendation 1

Needs and Motivation

A field experiment should be implemented to observe the structural behavior of and the SSI effects for a typical (and regular) building (hereto after referred to as typical building) during strong-motion earthquakes. A similar recommendation has been made in a recent USGS/EHRP document on research goals for the 1990s [USGS Circular 1079, 1992].

To date, there is still great uncertainty as to the significance of seismic soil-structure interaction (SSI) for ordinary structures. There may be both beneficial and adverse effects of soil-structure interaction; however, in many cases, SSI is simply ignored in design without establishing whether it will increase or decrease the response of the structure. The additional detailed recommendations to follow provide guidelines for the design of an experiment, which, if activated by a strong earthquake, will remove some of the above uncertainties.

First, what is currently known about SSI effects and what can realistically be observed and analyzed by current methods? For example, it is known that a major manifestation of SSI is a contribution to the rocking motion of the structure and, perhaps, to local deformations of the foundation of the structure. Thus, the instrumentation should be designed to observe these effects. Observations that can be checked against the results of numerical calculations are much more valuable than observations for which such comparisons cannot be made. Thus, the building, its foundation system, and the site configuration should be relatively simple--thus the need for a typical and regular building.

The motivations for an SSI experiment can be itemized as:

1) To improve the state-of-the-art of formulations and procedures for the evaluation of SSI effects;
2) To provide a clear and useful guidance as to when SSI should be incorporated in the analysis of a building, and, when necessary, how it should be done: and
3) To check the accuracy of numerical prediction of SSI and, in particular, of the rocking of the foundation since there is not yet great confidence in specific numerical predictions of the amount of rocking which is a major contributor to SSI.

Recommendation 2

Site Location and Soil Conditions

The test site should be located in an area with relatively high seismicity and should be easily accessible for installation and maintenance of the instrumentation. The following areas are identified in the publications USGS Open-File Report 88-398 and USGS Circular 1053 as having the highest earthquake probabilities:

1) The San Francisco Bay Area: (Faults: San Andreas, Hayward and Rogers Creek); and
2) Southern California—Upland, Redlands, San Bernardino Areas: (Faults: San Jacinto and San Andreas).

Several existing buildings in the San Bernadino area are already heavily instrumented.

In order for the SSI effects to be significant the test site should be a soil site rather than a rock site. Also, the geometry and ground water conditions of the site should be relatively simple such that the incident wave field can be well-defined and analyzed. This leads to the following recommendations:

1) The site should not be too shallow, i.e., rock should be located at an appreciable depth (e.g., more than 50 ft below the foundation level of the candidate structure);
2) A firm alluvial site is preferable. Such a site would consist of sands and gravels with shear-wave velocities V_s in the range of 500-1000 fps (~150-300 m/s) within the upper 50 ft of the site;
3) The site should be level and essentially horizontally layered. This is a critical requirement if observations are to be compared with analytical results:
4) The site should not be liquefiable and should have a stable ground water level:
5) A detailed site investigation should be performed before the site is selected. The investigation should include several borings to establish stratigraphy, *in situ* shear-wave velocity measurements, laboratory tests on undisturbed samples, and ground water observations;
6) Permanent open space around the building must be ensured for long-term observation of free-field motions. This requirement is a "must"; the chances of it being satisfied are probably highest if a public building is chosen for the experiment.

Recommendation 3

Foundation

The foundation system of the candidate structure should be as simple as possible and should not inherently minimize SSI effects. Thus:

(a) The preferred foundation type is a stiff box or mat foundation. The contact surface with the underlying soil should be approximately plane;

(b) A 1- or 2-story basement is acceptable; however, the foundation system should not be fully compensated since this will tend to minimize the inertial SSI effects, one of the effects that are desirable to observe. (A fully compensated foundation system is one for which the weight of the displaced soil is equal to the weight of the entire structure including the basement); and

(c) The initial experiment should exclude pile-supported structures.

Recommendation 4

Superstructure

It is preferable that a new building (before construction starts) be identified for instrumentation as part of the SSI experiment rather than using an existing building. It is further recommended that the building (to be instrumented for an SSI experiment) have the following general characteristics:

(a) The candidate structure should be a typical office building that falls within the scope of current seismic design codes. It should also be amendable to accurate analysis. Thus, the geometry and load-carrying system of the structure should be as simple and regular as possible. A building symmetrical about two axes is preferable;

(b) It is desirable that the structure has different stiffnesses in its two principal directions; however, the aspect ratio of its plan dimensions should not exceed 3 to 1 (preferably 2 to 1). Furthermore, to insure that there is reasonable radiation damping, the building should not be too slender;

(c) The structure should not be too light, since this would minimize SSI effects. A reinforced concrete structure or a steel structure with concrete walls is preferable;

(d) The fixed-base natural period of the superstructure should be of the order 0.5 seconds. This corresponds to a 5- to 10-story building, depending on the building type; and

(e) If at all possible, a new, yet-to-be-constructed, building should be chosen. With access to the structure during construction, the load-carrying system of the structure can be clearly defined and instrumentation can be more easily installed. This is especially important if pressure cells or other instruments are to be installed on the external basement walls or in the backfill.

Recommendation 5

Instrumentation

Several types of instrumentation should be employed to record forces, motions and local deformations in the structure and the surrounding soil.

Superstructure Instrumentation: The main instrumentation in the superstructure should be digital accelerometers with a common time base. Enough instruments should be installed to determine the translational, torsional, and rocking motions at least at three levels of the structure, including the base level and the top floor. The exact location of the instruments should be determined only after extensive analytical response studies and ambient and forced vibration tests of the structure.

If acceptable to the owner of the structure, the ambient and forced vibration tests should be repeated after significant seismic events to determine if the seismic experience of the structure has changed its dynamic characteristics. Additional sensors should be installed within the structure to measure story drifts and slab deformations at several levels.

Foundation Instrumentation: In addition to accelerometers, other sensors (linear variable displacement transducers [LVDT] or other instruments) should be installed to record local deformations of the foundation system. This is especially important if the foundation mat is flexible or if shear walls are founded on independent foundations.

It is also desirable to be able to record dynamic contact pressures on basement walls and the foundation slab. Unfortunately, currently available pressure cells are not reliable for observations that extend over several years. Also, they are virtually impossible to install in an existing backfill. Direct recording of contact pressures may therefore not be practical. It may, however, be possible, and it is certainly desirable, to install rugged instruments that can record wall/soil separation or foundation uplift.

Free-field Instrumentation: A minimum of three boreholes should be instrumented to record free-field motions. The boreholes should surround the instrumented building and should be located far enough away from all existing and planned structures to ensure that SSI effects do not contaminate the records obtained. The boreholes should not be so far away from each other, however, that incoherency effects destroy the coherency between the motions observed in the different boreholes. At least three triaxial accelerometers should be installed in each borehole: at the surface, at mid-depth, and at a depth deeper than the foundation level of the candidate building. If the bedrock is within a depth of 300 ft (~100 m) an additional instrument should be installed at the soil/rock interface in each boring.

The surface instruments in the three borehole sets will double as a surface array; however, it is recommended that additional surficial instruments be deployed closer to the building to detect any changes in motion due to SSI and/or due to the presence of the backfill.

NEW DEVELOPMENTS

Status of SSI Experiment

Selection of Hardware

USGS has acquired partial hardware for an SSI experiment. These are:

- Downhole accelerometers: Triaxial downhole accelerometers have been selected and purchased.The intent is to deploy these immediately below the foundation of the building at least at two but preferably at three vertical locations. In addition, at a distance away from the building, another downhole array containing 2-3 downhole accelerographs will be deployed:
- Pressure Transducer System: In selecting pressure transducer system, consultations with technical staff at USGS and other institutions led to use of combinations of flatjack and differential pressure transducer system. In this way, it will be possible to record the average differential pressure over a larger area than the usually smaller area that pressure transducer covers. Furthermore, it will be easier to deploy the flatjacks below the foundation and the sidewalls of the basement. Figure 3 depicts a conceptual schematic of the deployment of the flatjack and the differential pressure transducer combination system:
- Flatjack; and
- Differential Pressure Transducers.

Other Requisite Hardware to be acquired:

- Recording System; and
- Structural Array hardware.

Selection of Site

To date, a suitable site on which a building suitable for SSI experiment is being planned, but has not yet been satisfactorily identified.

TWO NEW (US-JAPAN) WORKSHOPS ON SSI (1998 and 2001)

Workshop of 1998

Under the auspices of Panel on Wind and Seismic Effects of the United States-Japan Natural Resources Development Program (UJNR), two workshops on “Soil-Structure Interaction “ (SSI) were organized.

(a) The first workshop was held in Menlo Park, California, on 22-23 September 1998. U.S. Geological Open-File Report 99-143 was issued as the proceedings of that workshop; and

(b) The second workshop was held in Tsukuba, Japan on 6-8 March 2001.

Both workshop presentations covered:

- Current methods of SSI used in design/analyses processes in both Japan and the United States
- Recent research being carried out
- Experimental SSI research arrays and/or facilities developed and that are in the process of being developed
- Searching ways to cooperate on future SSI research. The aim of the workshop was to cover the following topics:
  1. Current Methods of Practice of SSI in the US and Japan
     a. Geotechnical Point of View
     b. Structural Point of View
  2. Code Provisions and Limitations.
  3. Observed Data.
  4. Observational Arrays and Testing Facilities - Current Status and Future Needs.
  5. Recent Research Results and How To Implement Them Into Practice.
  6. Additional Research Needed.
  7. Additional Observational Arrays and Testing Facilities Needed.

During the 2001 workshop, a paper outlined eight different special seismic arrays in Japan that are earmarked for verifying SSI effects [Yamagishi, 2001].

CONCLUSIONS

Given the lack of observations related to SSI phenomenon, it is necessary to plan for an experiment that could yield data to validate or improve analytical methods that are used for assessing SSI effects on structures during strong shaking. The recommendations developed during the 1992 workshop and repeated herein could serve as a basis to develop a much needed SSI experiment in the United States.

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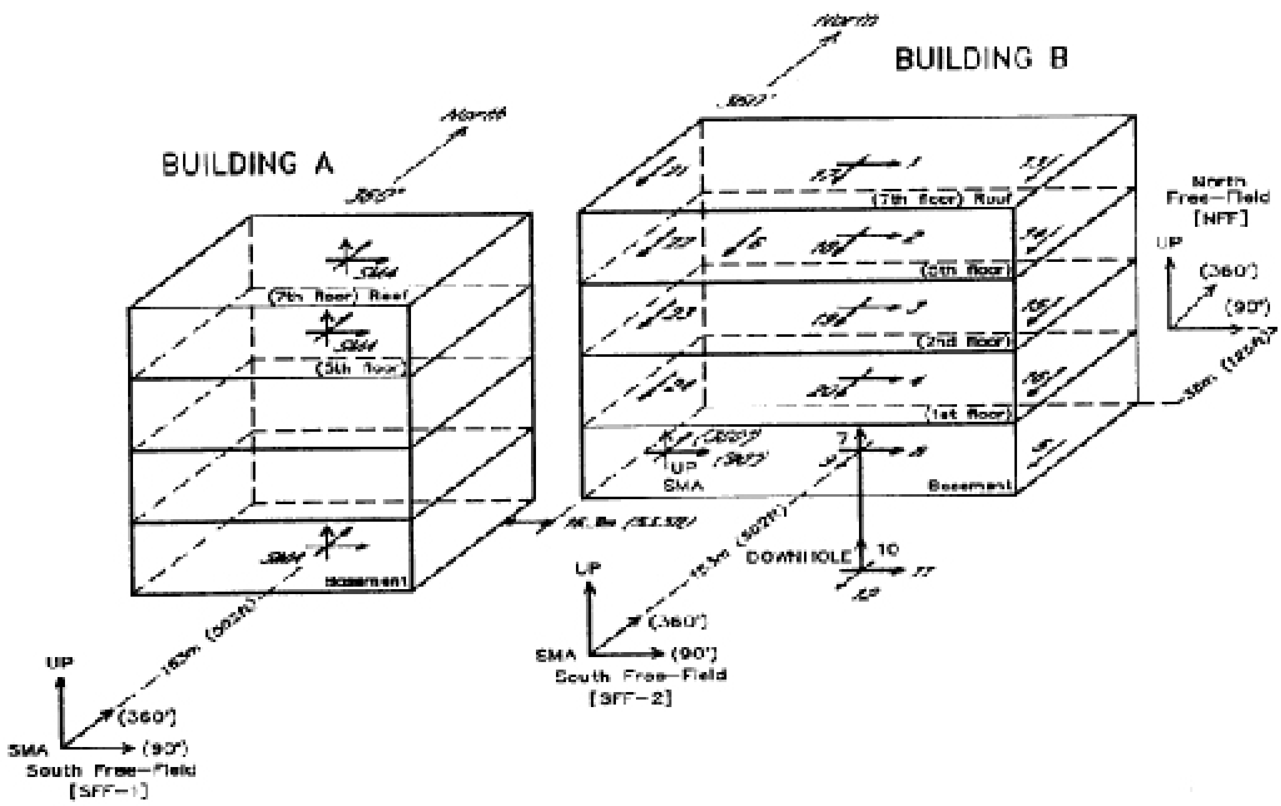
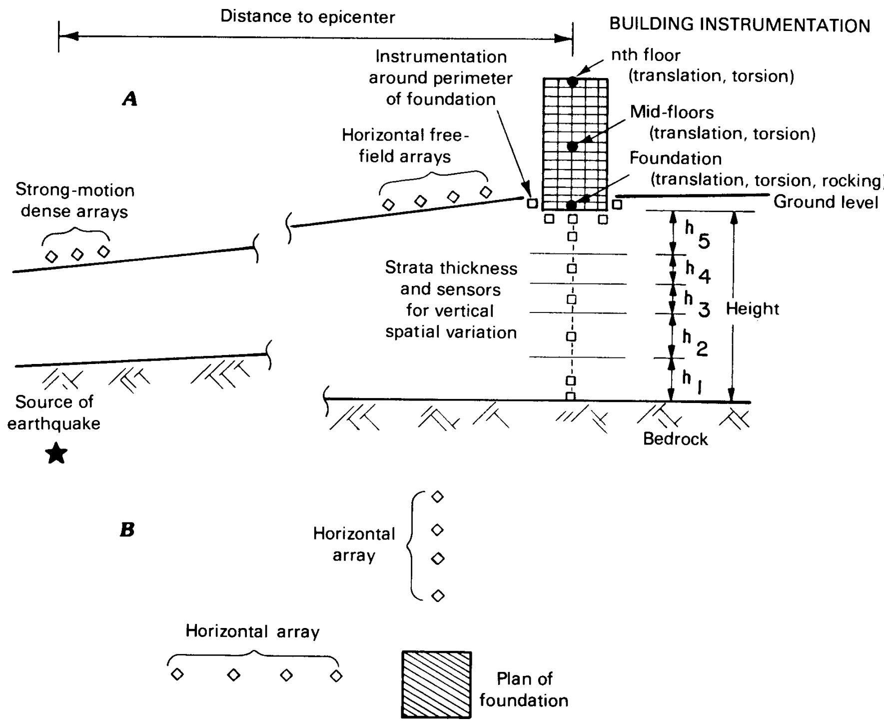


Fig. 1. Two instrumented buildings in Norwalk, Calif. Building B has a downhole instrument within a caisson.



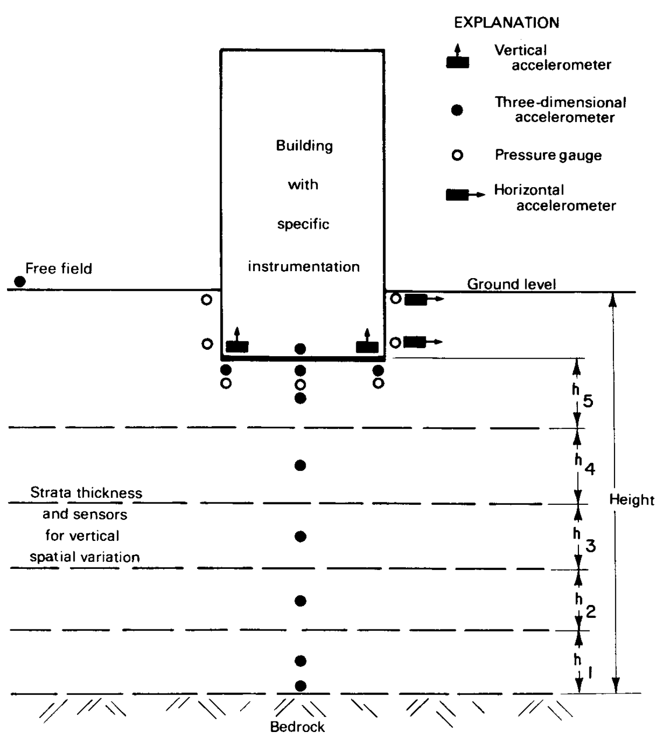


Fig. 2. Schematic of essential instrumentation for an SSI experiment

APPENDIX A. Summary of Discussions and Recommendations of 1992 Workshop

Soil -structure-interaction (SSI) effects may be either beneficial or detrimental to the performance of structures. When beneficial, by incorporating SSI effects in the seismic code calculations, more cost-effective designs are possible. For some situations, such as the design or retrofitting of bridges, dams or buried structures, etc., an appropriate inclusion of SSI effects in seismic calculations may bring large design cost savings to our society. There is an urgent need for performing comparative cost-benefit reviews for different types of constructions with and without considering rigorously the SSI effects. On the other hand, when it is determined by calculations that SSI effects can be detrimental to the performance of structures, by mere recognition and taking effective measures, safety and better performance can be achieved.

Present Status of SSI:

- To promote practical application of SSI evaluation procedures, practicing engineers must first be convinced of the need for SSI evaluations. To render such evaluations a necessity, SSI evaluation procedures must become an integral part of the total seismic analysis and design process. Current building, codes, which are based on SSI response behavior of a single-degree-of-freedom (SDOF) SSI system and have incorporated only the SSI effects of period elongation and damping increase for the fundamental mode of a structure system, do not address the total effect of SSI (such as the additional effects of "scattered" seismic input motions, and global as well as local soil non-linearity); as such, they do not promote the use of proper SSI evaluation procedures in the design process;
- In the past, SSI research has concentrated on solutions for gross dynamic response behaviors of simple linear SSI systems. Recent research also tends to focus on studying the SSI problems that can be solved with simple linear theories. To further the SSI research, it is time that the research be advanced beyond the studies of simple linear SSI systems and should start to develop realistic SSI evaluation procedures needed for practical design purposes, e.g. evaluations of nonlinear soil-resistance behaviors and soil-foundation interface pressures;
- To date, evaluation of seismic SSI effects has placed emphasis on seismic system demand, i.e., seismic SSI system response behavior. It is time to extend evaluation to SSI system performance, which requires the evaluation of not only the system demands but also the corresponding (strength and ductility) capacities. In the context of SSI, the system capacities of interest are the capacities of the soil-foundation interaction system. In fact, any realistic evaluation of the SSI system demand must incorporate realistic constitutive behavior of the soil-foundation system up to its allowable capacity limit;
- Experimental research should not be limited to the confirmation of SSI system response behavior. It must be designed and conducted in a manner in order to improve the SSI system modeling and to facilitate assessment of the SSI system performance up to its performance limit;

- To facilitate practical applications, SSI researchers must also develop and make available to practicing engineers a set of reliable and easy-to-use computer software for them to conduct realistic SSI evaluations;
- The number of papers on SSI both in Japan and United States has been steady during the last few years. This implies that support for SSI research has not increased in recent years;
- SSI is interdisciplinary (geotechnical and structural) and hence tends to be poorly understood by both sides. There is a big gap between state-of-the-art and the knowledge of practicing engineers;
- SSI is too complex to define exactly. We can define conditions where SSI is not important, however. Let's define what we know, where contributions can be made, and improve our knowledge transfer. We should not emphasize code-oriented research too much; we need to communicate to practitioners the essential aspects of the problem;
- There is a need to distinguish between heavy nuclear power plants and ordinary buildings. Nuclear plants are already being designed with consideration of SSI. For some buildings SSI is not important; these cases should be identified;
- Our knowledge of ordinary building structures is limited, so there is a need to emphasize SSI research for ordinary types of buildings;
- There are virtually no full-scale experiments on buildings;
- Single-degree-of-freedom (SDOF) structure with rigid foundation is the most common type of research topic. Much research has been done on this subject;
- Flexible foundations with multi-degree-of-freedom (MDOF) structures are difficult to analyze and there is very little research done on this topic;
- Individual footings beneath each column are also difficult to analyze, and there is very little work done on this subject;
- There is virtually no field performance data on SSI. Existing data is inadequate. Interpretation of field data from earthquakes is important to verify methodologies;
- Although there is a lot of research on pile foundations, there is great need to translate that accumulated knowledge into practice;
- We need more detailed experiments;
- In general, linear elastic analysis is good for:
  - (a) buildings on surface foundations
  - (b) building-soil-building interaction
  - (c) single building with embedded foundation;
- Linear analyses is not so bad. Past experience shows linear models are here to stay. They've been around for a long time, despite some nonlinear alternatives, and they will remain. Linear elastic analysis has shortcomings, however, for building-soil -building interaction when the foundations are embedded;

- The standpoint of practitioners: Is SSI a necessary aspect of the design process? We think it is, but how do we demonstrate that? Need more than period lengthening and foundation damping; these are not useful to practicing engineers. We need to translate our research results into better demand predictions for structures. SSI enters the design process through pressure on foundations. Further research is needed;
- SSI is significant in the context of performance-based design;
- Community studying SSI is shrinking due to limited funding priority place on SSI by NSF. If we speak as one voice, we can make an impact on the NSF (like the structural control and tsunami people). Let's create a web site to advance the issue (post research findings, etc.);
- Design of nuclear power plants was a major stimulus to SSI. Since practically no new nuclear plants are being design, such stimulus has vanished;
- Recent earthquakes show that there is a high level of nonlinearity in soil over broad area. This nonlinearity may have lead to SSI effects, which saved these buildings. We need to investigate this; and
- Need dialogue between experimentalists and analysts.

Additional SSI Research:

- Seismic earth pressures against retaining walls, considering nonlinear aspects such as gapping;
- Comparative studies of nonlinear vs. linear SSI to evaluate where non-linear analysis is important;
- More work is needed on pile foundations. For example, observed damage of piles due to soil displacement suggests that we need to consider soil displacement, not just structural inertia, when designing piles. How the two actions can be superimposed is of vital importance;
- More work is needed for underground structures such as tunnels and pipelines;
- How do we estimate the degree of nonlinearity in soil and its effects on structural response?;
- Need more work on flexible foundations;
- More work needs to be done on seismic soil pressures against wall;
- SSI is more involved than just the first mode period lengthening ratio (T_{SSI} / T_{FIXED}) due to interaction and ground motion variability. The load paths for inertial load, especially near the ground line need to be considered;
- Nonlinear SSI may be very important for severe earthquakes. Need simple models for nonlinear SSI;

- We are only recently getting accustomed to > I g ground motions. Pushover is becoming more common, need to properly account for SSI in such analyses, especially near the failure state;
- If the movement is towards Performance Based Design, then we need to understand the uncertainties;
- There is a need for SSI research for near field ground motions. Such effects may be very localized;
- From the geotechnical point of view, an important issue is the damage in piles at soil boundaries significantly below the ground surface due to lateral flow. Before liquefaction, soil is fairly elastic and strains are important in determining soil properties. After liquefaction, soil behaves as liquid. Need to distinguish between liquefied and non-liquefied soil in our SSI formulations;
- Energy absorption by liquefied soil is significant, adds extra damping;
- Level of energy dissipation depends on when liquefaction occurs in the time history. Liquefaction doesn't help much if it occurs late. There is evidence of this from Wildlife Liquefaction Site [see Holzer et al., 1989, Dynamics of liquefaction during the 1987 Superstition Hills, California, earthquake, *Science*, 244:56-69];
- We need to be concerned about 5-10 story buildings subjected to near-field pulses. The long period energy content of these motions means that period lengthening would increase the base shear; and
- There is a need to address in future engineering activities the large uncertainty associated with SSI. We know that the earthquake motions are random, the soil properties are random, local motion spatial variation is random, etc. So, there is an objective need in the future to approach these aspects more consistently using probabilistic models. In addition, for improving a seismic design or for a costly retrofit of a highway concrete bridge, it is essential to do some probabilistic SSI analyses and try to calibrate the deterministic design based on risk assessment comparisons. Therefore, it is important that NSF envisions this need for future.

Better Field Observations:

- In general, there have been some successes in experimental work and use of observed data. These can be summarized in three ways: (a) Lotung-type of experiment with very good instrumentation for a specific type of structure, lots of comparisons between theory and experiment, (b) in-depth studies of typical building structures and (c) studies of many buildings, look at trends that can be easily understood by many engineers (e.g, Stewart, Ph.D. thesis, Stewart, J. P., and Stewart, A. F., 1997, Analysis of soil-structure interaction effects on building response from earthquake strong motion recordings at 58 sites, Report No: UCB/EERC 97/01, Richmond, Calif.). There is still great need, however, for developing and/or improving the current field observation systems such that these systems will better enable:

(a) experimental verification of analytical procedures (e.g., in Europe, the research is on verifying SSI provisions in Eurocode.);

(b) interpretation of available field data;

(c) additional instrumentation to obtain proper SSI response data (e.g., most instrumented buildings have inadequate vertical sensors to calculate rocking effects, and in some cases, if physically possible, additional free-field instruments and downhole accelerographs should be deployed);

(d) evaluation of the influence of free-field displacements on piles; and

(e) understanding the soil pressures against foundation elements such as basement walls. More work needs to be done on seismic soil pressures against walls.

- We need reliable experimental data for verification of simple analysis schemes.

Transfer of Knowledge:

- There is a big gap between state-of-the-art and the knowledge of practicing engineers. Therefore,

(a) it is necessary to simply be able to demonstrate to the practicing engineers when and if SSI is important;

(b) simple and practical tools and procedures are needed for transfer of knowledge to practicing engineers;

(c) efforts should be made to include SSI in building codes;

(d) efforts should be made to incorporate SSI methodologies in favorite computer software such as SAP; and

(e) efforts should be made to demonstrate to the profession the usefulness in incorporating SSI in their designs. The design engineers should be appraised of the fact that incorporation of SSI procedures can be, in some cases, financially beneficial;

- There is considerable research on pile foundations; however, there is great need to translate that accumulated knowledge into practice;
- There is a significant need for knowledge transfer on the issue of damping;
- Graduate students need to be taught SSI, which will help to bridge that gap between researchers and practitioners. All graduate student qualifying exams should have SSI questions;
- Need practical tools and agreed-upon computer codes; and
- The data should not be used to calibrate a design code. Rather, we need to understand simple problems well, and then develop good code formulations for design based on the insight gained from these simple models. Instrumentation needs to be detailed enough to guide us through the process.

Data Exchange Between the United States and Japan

- This is of vital importance for researchers on both sides. For example, Professor Iguchi wrote a book (along with 21 authors) on SSI. Two-thousand copies of this book were distributed in Japan through lectures to engineers. The United States side may desire to have the book translated;
- There are impressive experiments in Japan for SSI, we need to become more familiar with them; and
- We should recommend that there be better information exchange between the United States and Japan. Japanese experimental data is extremely valuable - must relate it to available theoretical models. Perhaps here in the United States we could contribute our expertise to such an effort.

Other Issues:

- SSI practices should be pushed into the codes. In that case, the industry will use it, making necessary to teach it. Under these conditions, funding agencies will have to fund such activities. The code committees are receptive now to SSI; this should be followed to fruition.