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RECOMMENDATIONS FOR A SOIL-STRUCTURE INTERACTION EXPERIMENT (REPORT BASED ON A WORKSHOP HELD AT SAN FRANCISCO, CALIFORNIA ON FEBRUARY 7, 1992)

compiled by

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OBJECTIVES OF THE WORKSHOP

The objectives of the 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 soil-structure interaction, and (b) to discuss and decide on the details of such a soil-structure interaction experiment.

INTRODUCTION

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 soil-structure interaction 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. Soil-structure interaction is now included in various codes (*e.g.,* ATC–3, NEHRP–1985).

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 November 4–5, 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, Boore, Bucknam and Thatcher, 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:

1. 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).

2. International Workshop on "Strong-Motion Earthquake Instrumentation," Honolulu, Hawaii, May 1978 (Proceedings edited by W. Iwan, 1978).
3. U.S. National Workshop on "Strong-Motion Earthquake Instrumentation," Santa Barbara, California, April, 1981 (Proceedings edited by W. Iwan).
4. 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 100 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 and 1989 Loma Prieta 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, we do not have 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:

1. 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.
2. There are no downhole arrays 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. 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 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 is necessary and overdue because its results can be used in earthquake hazard mitigation efforts. With such an experiment, the capability to record real-life soil-structure interaction will be greatly enhanced.

IDEAL SOIL-STRUCTURE INTERACTION EXPERIMENTAL SCHEME

An ideal layout of arrays that includes soil-structure interaction instrumentation is provided in Figures 1 and 2 (Çelebi *et al.*, 1977; Çelebi and Joyner, 1978). Such a layout should have four main arrays:

1. Superstructure array
2. Soil-structure interaction array
3. Vertical Spatial array
4. Horizontal Spatial array.

These arrays are depicted schematically in both Figures 1 and 2.

MANAGEMENT AND OTHER BENEFITS OF THE EXPERIMENT

When implemented, the experiment will be managed and maintained by the USGS strong-motion program. Therefore, the experiment will have the backing of a stable institution that has been engaged in monitoring and maintaining strong-motion networks in the United States during the last four decades.

The data acquired through the experiment will be open to all investigators. It is anticipated that the data will be used as key research material related to soil-structure interaction methods. Future workshops may be held to discuss the data and related researches.

It is anticipated that low-level amplitude tests will also be conducted once the subject building is instrumented with the essential hardware. Comparison of soil-structure interaction effects during low-level amplitude motions and during strong-motions will constitute another worthwhile benefit of the future experiment.

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 geo-technical 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.).
4. Recommendations of the workshop.

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 Hz) 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, is currently being 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 soil-structure interaction 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)

The workshop participants recommend that a field experiment be implemented to observe the structural behavior of and the soil-structure interaction (SSI) effects for a typical (and regular) building (heretoafter 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]).

This principal recommendation is motivated by the fact that 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.

In making these recommendations, the participants of the workshop considered 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. Also considered was the fact that observations which 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.
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 OFR 88–398 and USGS CIRCULAR 1053 as having the highest earthquake probabilities:

a. The San Francisco Bay Area.
   Faults: San Andreas, Hayward and Rogers Creek

a. 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:

a. The site should not be too shallow, *i.e.,* rock should be located at an appreciable depth (*e.g.,* more than 50 feet below the foundation level of the candidate structure).
b. 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 feet of the site.
c. The site should be level and essentially horizontally layered. This is a critical requirement if observations are to be compared with analytical results.
d. The site should not be liquefiable and should have a stable ground water level.
e. 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.

f. Permanent open space around the building must be ensured for long-term observation of free-field motions. This requirement is a "must" and 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 is 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).

c. The initial experiment should exclude pile supported structures.

RECOMMENDATION 4: (SUPERSTRUCTURE)

The consensus of the participants is that it would be preferable if a new building (before construction starts) can 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:

The candidate structure should be a typical office building which falls within the scope of current seismic design codes. It should also be amendable to accurate analysis. Thus:

a. The geometry and load-carrying system of the structure should be as simple and regular as possible. A building which is symmetric about two axes is preferable.

b. It is desirable that the structure have 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.

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.

1. 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.

2. 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.

3. 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 the records obtained are not contaminated by SSI effects. However, the boreholes should not be so far away from each other 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 feet ($\sim$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.

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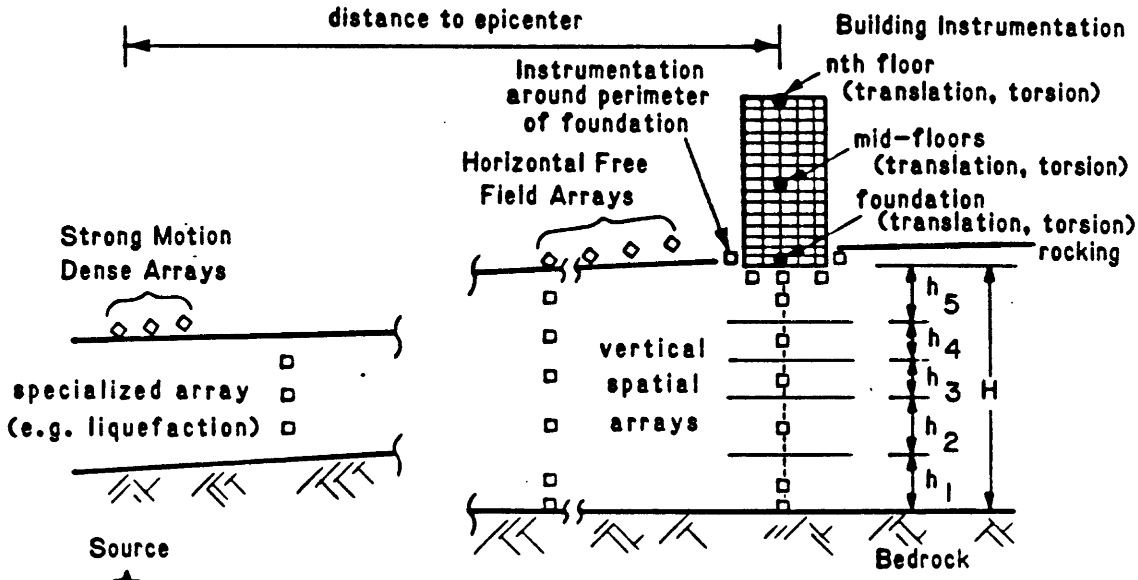
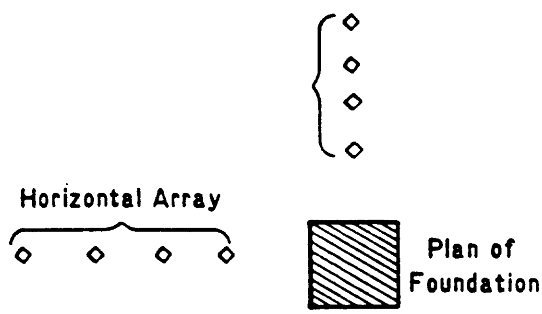


(a) VERTICAL CROSS SECTION



(b) PLAN VIEW OF HORIZONTAL FREE FIELD ARRAY AROUND THE BUILDING

Figure 1. General sketch of an integrated array depicting strong-motion instrumentation starting from the source zone to the area around a test structure and the structure itself.

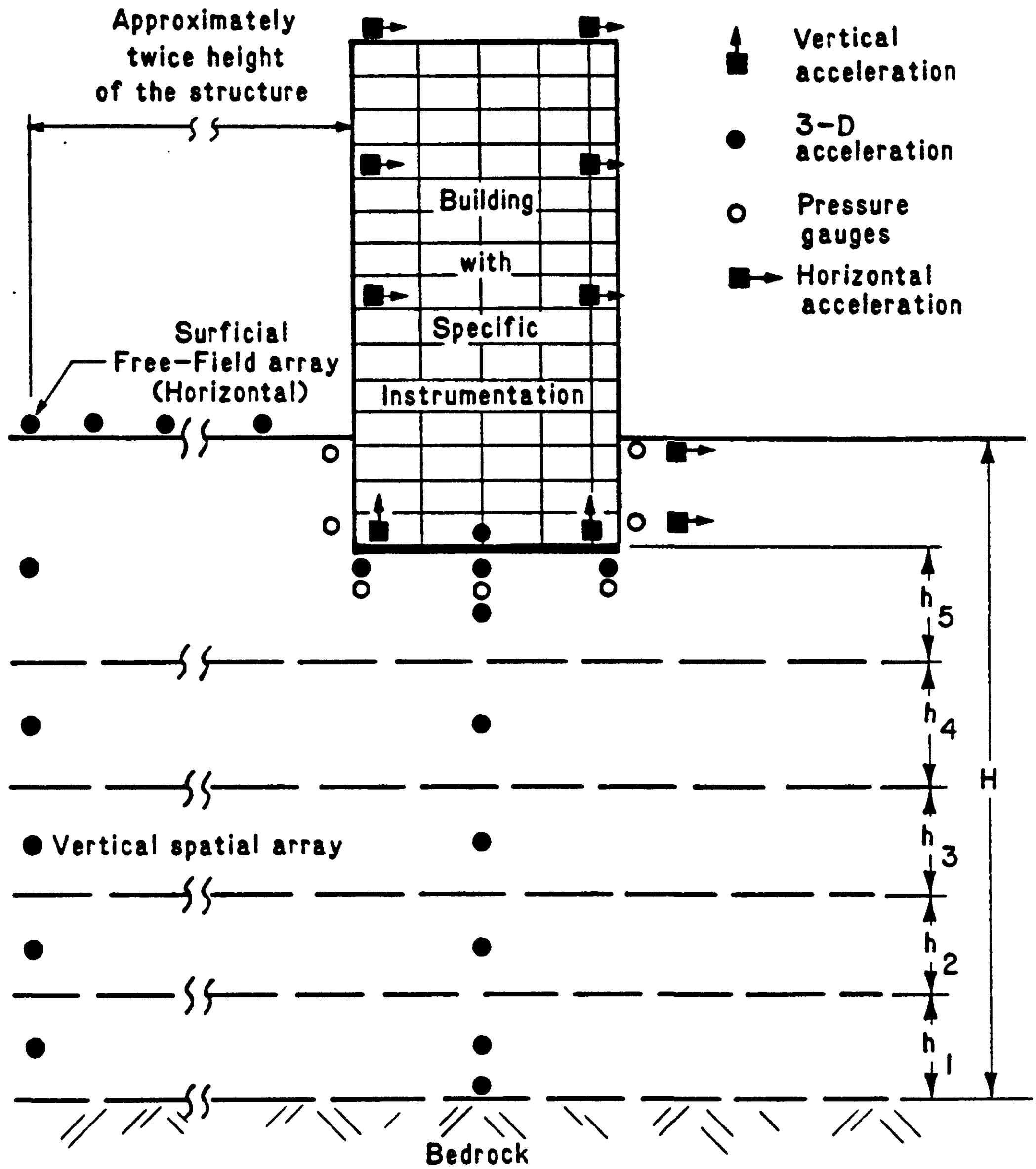


Figure 2. Specific instrumentation around and in the test structure. Depicted are the instrumentation to define vertical and horizontal spatial variation of motions as well as specific instrumentation to define the variation of motions and forces at the foundation and the superstructure.