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SYNOPSIS A workshop held in 1992 (Çelebi *et al.*, 1992) brought together a panel of experts (a) 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 (SSI), and (b) to define the parameters of a SSI experiment. The recommendations of the workshop and the current status of the SSI experiment are described herein.

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. However, in the last four decades, it has been recognized that interaction between soil and structure alters the response characteristics of a structural system. Some codes now include provisions to reflect this effect (ATC-3, NEHRP-1985). For important engineered structures, detailed methods are applied to perform soil-structure interaction (SSI) analyses. To date, the strong-motion data from instrumented buildings are insufficient to confirm the validity of the SSI analysis methods.

Since 1978, during several workshops and technical meetings, specific recommendations have been repeatedly made to instrument a building for SSI studies (*e.g.* Lee *et al.*, 1978; Iwan, 1978; Iwan 1981). During the recent NSF workshop on "Experimental Needs for Geotechnical Earthquake Engineering," held in Albuquerque, New Mexico, strong-motion instrumentation for SSI was given a high priority (Higgins, 1992). U. S. Geological Survey Circular 1079 spells out priority recommendations for special purpose arrays including those that will facilitate soil-foundation interaction studies (Page *et al.*, 1992).

MOTIVATION

Although, there are now 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 SSI 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 and quantify the significant parameters related to SSI. Examples of deficiencies in existing instrumented buildings 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 variation of the horizontal and vertical dynamic pressures, 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.

(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.

IDEAL SSI EXPERIMENTAL SCHEME

An ideal SSI experiment should have four main arrays (Çelebi *et al.*, 1987; Çelebi and Joyner, 1987):

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. 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 SSI methods.

LOTUNG AND HUALIEN EXPERIMENTS

The most detailed (SSI) experiment to date was implemented in 1985 by EPRI at Lotung to facilitate the study of SSI for a 1/4- and 1/12-scale, reinforced concrete, cylindrically shaped nuclear power plant containment models

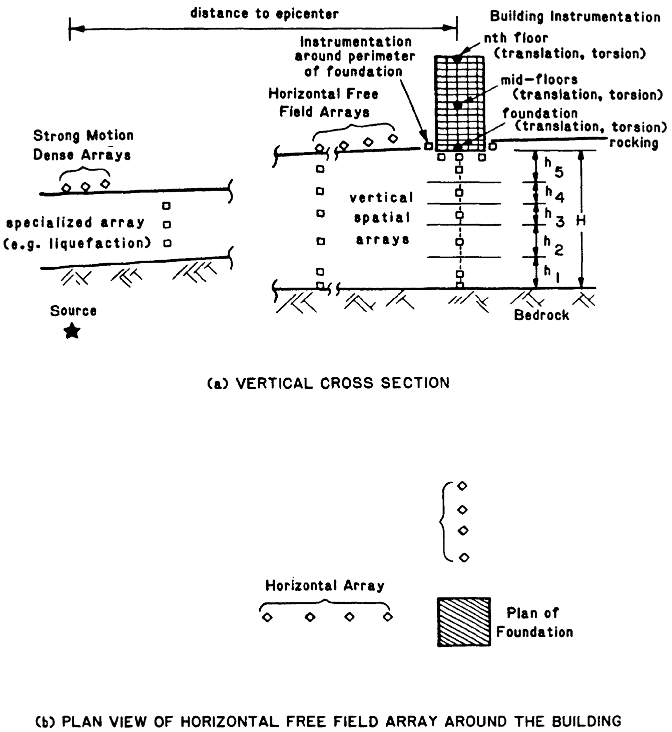

Figure 1. Schematic Plan of an SSI Experiment

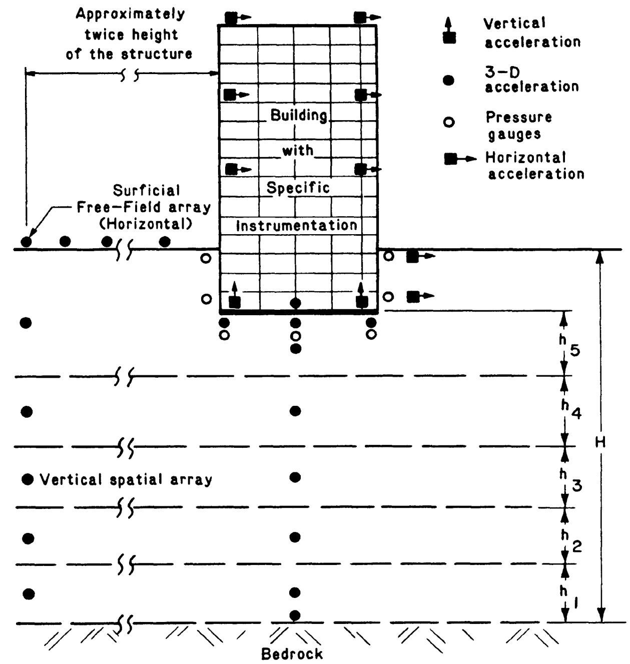

Figure 2. Instrumentation Around Building

under strong ground motion earthquakes (EPRI, 1989; Tang, 1987, Tang *et.al.*, 1987a, b, 1990). 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 and that the SSI effect in structural deformation and seismic wave spatial variation under stiffer soil conditions were not addressed. To remedy these 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). 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.

RECOMMENDATIONS OF THE WORKSHOP

RECOMMENDATION 1: NEEDS AND MOTIVATION

A field experiment be implemented to observe the structural behavior of and the SSI effects for a typical (and regular) building (hereinafter referred to as typical building) during strong-motion earthquakes. This principal recommendation is motivated by the fact that there is still great uncertainty as to the significance of seismic SSI for typical 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.

It is necessary to consider 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 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 guidance as to when SSI should be incorporated in the analysis of a building and how it should be done.

(3.) To check the accuracy of numerical prediction of SSI. In particular, at present, there is not great confidence in specific numerical predictions of the amount of rocking of the foundation - a major contributor to SSI.

RECOMMENDATION 2: SITE 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 by the USGS as having the highest earthquake probabilities (WGCEP, 1988, 1990):

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

(b.) Southern California (Upland, Redlands, San Bernardino Areas): Faults: San Jacinto and San Andreas.

In order for the SSI effects to be significant the test site should be a soil site rather than a rock site. 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:

(a.) The site should not be too shallow. Rock should be located at an appreciable depth (*eg* more than 50 feet below the foundation level of the candidate structure).

(b.) A firm alluvial site is preferable. The site would consist of sands and gravels with shear-wave velocities 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

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

(a.) The candidate structure should be a typical office building which falls within the scope of current seismic design codes and be amenable to accurate analysis. Furthermore, the geometry and load-carrying system of the structure should be simple and regular. 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 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 accelerometers in the superstructure should be connected to digital recorders 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. 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, 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.

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 location: 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 (~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.

CURRENT STATUS

While selection of the site and prospective building is being pursued, necessary hardware that will be deployed before the construction of the building is being defined and purchased. It is anticipated that implementation will start within 1-2 years.

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