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FULL-SCALE EXPERIMENTAL STUDIES OF SOIL-STRUCTURE INTERACTION

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ABSTRACT

This paper presents a review of the full-scale experimental studies of soil-structure interaction. It briefly reviews the early research on soil-structure interaction, starting from the 1930s, the studies of the Hollywood Storage Building in the U.S. (the first structure in California where earthquake strong motion was recorded in 1933), selected research on soil-structure interaction and full-scale testing from the 1970s to present, and experimental work on large model tests. It also presents examples of full-scale tests in actual structures, and an analysis of the trends in full-scale experimental studies of soil-structure interaction via the number of published journal and conference papers. It is concluded that monitoring of earthquake response in and around buildings and comprehensive full-scale tests of structures are the best experimental methods for investigating scil-structure interaction, because they are most complete, the boundary conditions are satisfied exactly, and the problems related to scaling and similarity laws are eliminated.

KEYWORDS: Soil-Structure Interaction, Full-Scale Testing, Large-Scale Tests, Hollywood Storage Building

INTRODUCTION

Soil-structure interaction is a collection of phenomena in the response of structures caused by the flexibility of the foundation soils, as well as in the response of soils caused by the presence of structures. In general, it lengthens the apparent system period, increases the relative contribution of the rocking component of ground motion to the total response, and usually reduces the maximum base shear (Todorovska and Trifunac, 1990a, 1991, 1992a, 1992b, 1993; Gupta and Trifunac, 1991). This reduction results from the scattering of the incident waves from the foundation, and from radiation of the structural vibration energy into the soil. When the soil surrounding the foundation experiences small to moderate levels of non-linear response, the soil-structure interaction can lead to significant absorption of the incident wave energy, thus reducing the available energy to excite the structure (Trifunac et al., 2001a).

The simplest soil-structure interaction models are those in which the structure is supported by a rigid foundation (Abdel-Ghaffar and Trifunac, 1977; Werner et al., 1977, 1979). These models require only six additional degrees-of-freedom (three translations and three rotations), but may be too simple for practical applications. Models with flexible foundations are rare (Iguchi and Luco, 1982; Hayir et al., 2001; Liou and Huang, 1994; Todorovska et al., 2001a, 2001b; Trifunac and Todorovska, 1999c; Wong et al., 1977) and difficult to validate against data (Trifunac et al., 1999).

Recorded strong motion in structures indicates that destructive shaking is often accompanied by non-linear response of the foundation soils (Luco et al., 1986; Trifunac and Todorovska, 1998; Trifunac et al., 1999, 2001b, 2001c), and that the time-dependent changes of the apparent frequencies of the response are often due to significant contribution of soil-structure interaction (Udwadia and Trifunac, 1974).

Contributions to the subject of soil-structure interaction have been reviewed on numerous occasions, during conferences devoted specifically to this subject (e.g., International Symposium on Soil-Structure Interaction, 1977), symposia following World Conferences on Earthquake Engineering (Ergunay and Erdik, 1981), and workshops (Celebi and Okawa, 1999). The subject has been reviewed in specialized reports (Luco, 1980) and researched in numerous doctoral dissertations (e.g., Merritt, 1953; Luco, 1969a; Lee, 1979), and books (Wolf, 1985, 1994).

Experimental studies of soil-structure interaction are best conducted in full-scale in actual buildings, during microtremors (Trifunac, 1970a, 1970b, 1972a), forced vibrations (Blume, 1936; Hudson, 1970), and earthquake excitation (Luco et al., 1987; Stewart and Stewart, 1997). The difficulties of conducting experiments in the laboratory are not only due to the similarity laws that have to be satisfied, but are mainly due to modeling the (semi-infinite) half-space boundary condition.

Experimental studies of soil-structure interaction have also been conducted in the laboratory, e.g., static and dynamic (shaking table) tests of soil structure interaction, and centrifuge experiments of soil-pile and soil-structure interaction. Since 1970s, the number of papers dealing with these subjects has grown steadily, producing a large volume of specialized research results (see, e.g., McLean and Ko, 1991, and Kimura et al., 1998), a comprehensive review of which would be more appropriate for a separate future paper, and is out of the scope of this paper.

This paper focuses on a review of the full-scale experimental studies of soil-structure interaction. First, it briefly reviews the early research on soil-structure interaction, starting from the early 1930s, and including the work of Suyehiro, Sezawa and Kanai, and Biot. This is followed by a review of studies of the Hollywood Storage Building in the U.S. (the first structure in California where earthquake strong motion was recorded in 1933), by a review of selected research on soil-structure interaction and full-scale testing from the 1970s to present, and by a review of experimental work on large model tests. Next, the paper reviews specific examples of full-scale tests in actual structures, to illustrate how such tests contribute towards formulation of models and assumptions. Finally, it presents an analysis of the trends in full-scale experimental studies of soil-structure interaction via the number of published journal and conference papers. The last section presents a discussion and the conclusions.

THE EARLY RESEARCH ON SOIL-STRUCTURE INTERACTION

We begin by reviewing the work of Suyehiro, Sezawa, Kanai and Biot – pioneers who contributed to the evolution of the concept of soil-structure interaction.

In the fall of 1931, Professor Kyoji Suyehiro visited the United States and presented a series of three lectures on Engineering Seismology (Suyehiro, 1932). His third lecture (III) entitled "Vibration of Buildings in an Earthquake" is of particular interest. In this lecture, Suyehiro discussed the response and observed damage of "rigid", "medium rigid" and "weak" buildings situated on "soft" (loose clay) and "rock" ground. He explained how the "rigid" building "moved as a rigid body on the ground-bed" and suffered little or no damage. In contrast, the "weak" buildings on "rock" ground were either damaged or destroyed. Searching for an explanation, Suyehiro states that "very probably the primary cause is the yielding of the ground-bed due to oscillation of the foundation…". He concluded, "such cushioning action of the ground at the time of an earthquake may serve more or less to relieve the destructive action of a strong earthquake in the case of masonry (i.e. rigid) buildings". These remarkable observations were confirmed many times by earthquake damage patterns seen since 1932. Suyehiro then describes microtremor measurements in the Earthquake Research Institute, in the building and on the adjacent ground. Professor Ishimoto performed these measurements in 1929 (see Figure 55 on Page 91 of Suyehiro's lectures). His investigation of the velocity of ripples on the ground is very useful in this connection. According to him, "on the surface of the ground where our Institute building stands, the P-wave has a velocity of above 120 m. per sec. and the S-wave about 65 m. per sec. Therefore, very probably, the wavelength of ripples having a period of 0.1 sec. is between 6.5 to 12.0 m.; hence, they are less than the linear dimensions of the building. Consequently, a building on soft ground is not sensitive to those quick and short ripples. It may also be mentioned that this fact may be attributed to a certain extent to another behavior of the vibration of soft ground, in which the amplitude of the component of a seismic vibration of very short period decreases quickly with depth. Therefore, foundations at some depth below the surface will be less affected by the rapid components of seismic vibrations."

It is fascinating to read how Suyehiro describes the scattering of short waves from a "rigid" foundation and the resulting averaging (smoothing) action of the foundation. "According to observations made by Professor Imamura on the vibration of the Diet Building during construction, some very rapid ripples, having a period of about 0.1 sec., disappeared in the motion of the foundation although the foundation moved about as much as the neighboring ground". In his published lectures, Suyehiro does not use the modern term "soil-structure-interaction", but it is obvious that one of the main topics of his lecture

III is in fact soil-structure-interaction. Of course, from today's viewpoint, his observations were intuitive and for the most part qualitative, but his insight and ability to interpret observations were remarkable.

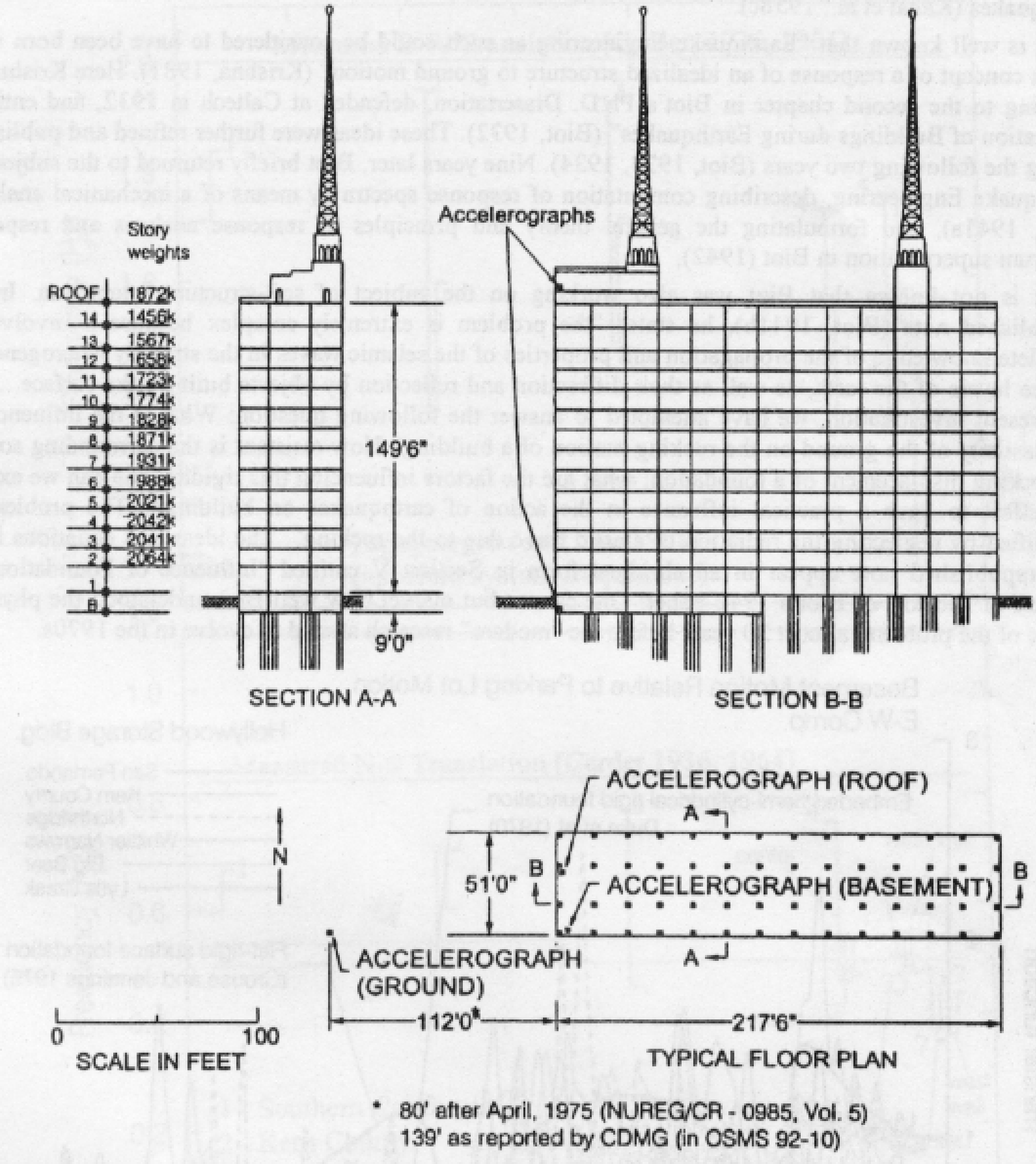

Fig. 1 A sketch of the Hollywood Storage Building in the early 1950s (the location of the strong motion accelerographs is indicated, one in the basement, one on the roof and one at a "free-field" site, 112 feet west of the south-west corner of the building) (after Duke et al., 1970)

Sezawa and Kanai (1935, 1936) also made pioneering studies of soil-structure-interaction. Their method was based on wave propagation, and even though they did not use the term "soil-structure-interaction", that is what they were studying. Their stated aim was to investigate the "decay of the seismic vibration of a simple or tall structure by dissipation of their energy into the ground". Summarizing this work and his observations over the span of 50 years, Kanai (1983) writes: "the excellent agreement between the calculated waveform and the observed seismograms seems to indicate that most of the vibrational damping of the buildings and dams during earthquakes occurred at the contact surface between the structure and the ground". To better appreciate the mathematical formulation and the physical insight of Sezawa's and Kanai's work, it is helpful to begin by reading Luco (1969b) and Trifunac (1972b).

During the 1950s, Kanai and co-workers carried out numerous tests on full-scale structures. They studied the influence of the ground stiffness on the response of structures (Kanai et al., 1953, 1955a, 1955b), using excitation by microtremors, vibration generators (Kanai et al., 1958a, 1958b), and earthquakes (Kanai et al., 1958c).

It is well known that "Earthquake Engineering as such could be considered to have been born with Biot's concept of a response of an idealized structure to ground motion" (Krishna, 1981). Here Krishna is referring to the second chapter in Biot's Ph.D. Dissertation, defended at Caltech in 1932, and entitled "Vibration of Buildings during Earthquakes" (Biot, 1932). These ideas were further refined and published during the following two years (Biot, 1933, 1934). Nine years later, Biot briefly returned to the subject of Earthquake Engineering, describing computation of response spectra by means of a mechanical analyzer (Biot, 1941a), and formulating the general theory and principles of response analysis and response spectrum superposition in Biot (1942).

It is not known that Biot was also working on the subject of soil-structure interaction. In an unpublished note (Biot, 1941b), he states "the problem is extremely complex because it involves a complete knowledge of the propagation and properties of the seismic waves in the strongly heterogeneous surface layers of the earth, as well as their diffraction and reflection by objects built on the surface... In the present investigation, we have attempted to answer the following question: What is the influence of the elasticity of the ground on the rocking motion of a building? How resistant is the surrounding soil to the rocking displacement of a foundation; what are the factors influencing this rigidity, and can we expect this effect to have a practical influence in the action of earthquakes on buildings? The problem is simplified by neglecting the radiation of elastic wave due to the rocking". The ideas and equations from this unpublished note appear in an abridged form in Section V entitled "Influence of Foundation on Motion of Blocks" of Biot's 1942 paper. One cannot but marvel how well Biot understood the physical nature of the problem, almost 30 years before the "modern" research started to evolve in the 1970s.

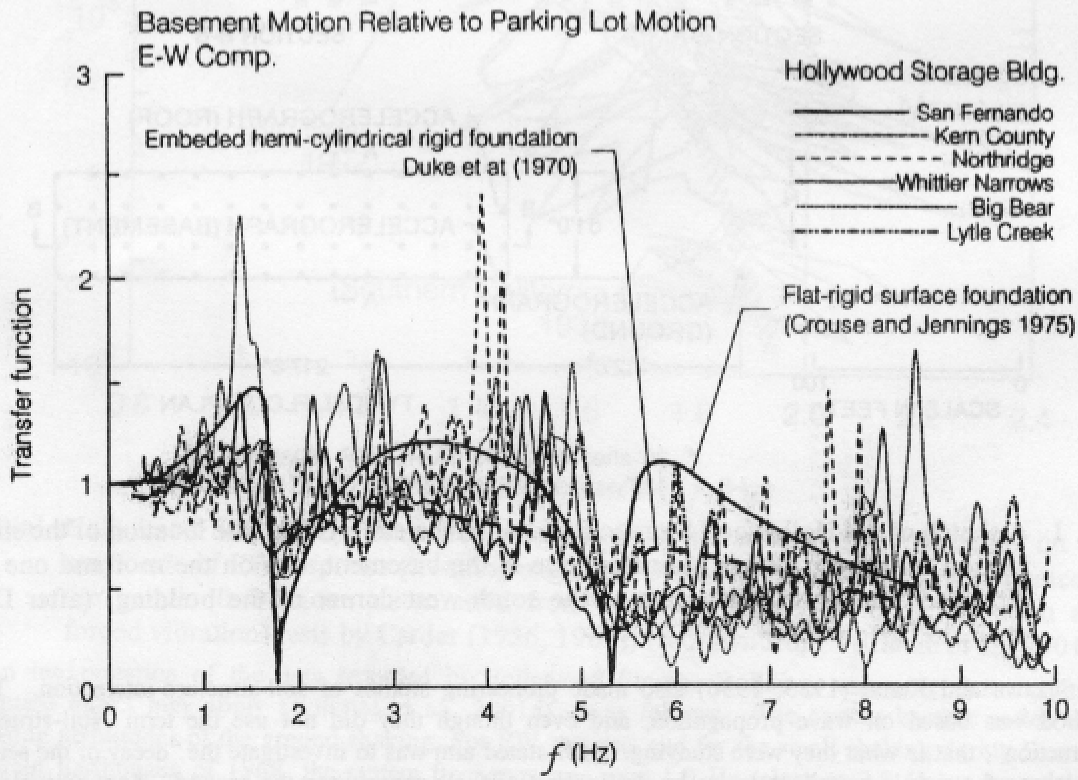

Fig. 2 E-W acceleration transfer-function between motion recorded at the basement of Hollywood Storage Building and at the "free-field" site (in the parking lot, about 100 feet west of the building, see Figure 1) during six earthquakes (the heavy solid and dashed lines correspond to two examples of theoretical transfer-functions (Crouse and Jennings, 1975))

STUDIES OF THE HOLLYWOOD STORAGE BUILDING

The Hollywood Storage Building (HSB, located at 1025 North Highland Ave. in Los Angeles, Figure 1) was the first structure in California equipped with permanent strong motion accelerographs in 1933 (the instrument in the parking lot was installed in December 1939; see Trifunac et al., 2001d). It is also the first building in California where strong motion was recorded (October, 1933), and also the first building for which it could be shown that both theoretical analysis and observation of soil-structure interaction are consistent (Figure 2; Duke et al., 1970). This building served as a testing ground for intuitive (Housner, 1957) and theoretical and quantitative (Duke et al., 1970) studies of soil-structure interaction. The data recorded in and near this building was also used in several other related studies, for example, on scattering of waves by a "rigid" foundation, the associated "filtering" of high frequency motions, and on the associated torsional excitation of the foundation (Cloud, 1978; Gupta and Trifunac, 1990; Shioya and Yamahara, 1980; Whitley et al., 1977). Since 1933, there were numerous triggers of the strong motion accelerographs in this building, but only a few, so far, have been processed and are available for analysis. This building was also studied using ambient and forced vibration tests (Carder, 1936, 1964).

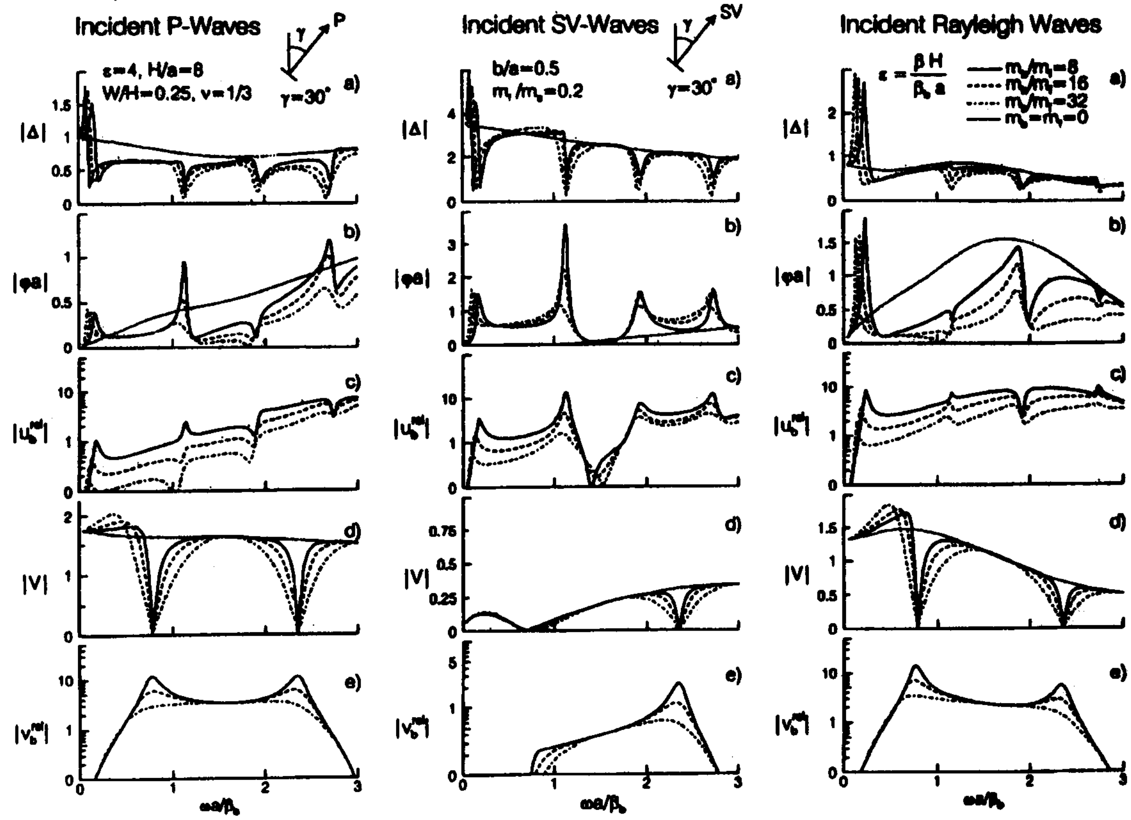

Fig. 3 Transfer-function amplitudes for (a) horizontal foundation motion, Δ, (b) foundation rocking, φa, (c) building relative horizontal motion, u_b, (d) vertical foundation motion, V, and (e) building relative vertical motion, v_b, versus dimensionless frequency, $\omega a/\beta_b$, for incident P-waves (left), SV-waves (center) and Rayleigh waves (right) (after Todorovska and Trifunac, 1990a) (W and H represent the width and height of the building, h and $2a$ represent embedment and width of the rigid foundation respectively, β and β_b are shear wave velocities in the soil and in the building, m_b is mass of the building, m_f is mass of the foundation and m_s is mass of soil replaced by the foundation, all per unit length of the 2D models)

Housner (1957) performed visual comparison of the accelerations recorded in the basement of this building and in the parking lot during the 1952 Kern County earthquake, as well as of the corresponding response spectra (spectral velocity) computed by an analog computer (Housner and McCann, 1949). He concluded that, for this "relatively large, heavy and stiff" building, "there was not significant amount of ground coupling," and that "in order for the ground coupling to be significant, in engineering sense, the ground would have to be much softer than the so called soft alluvium on which the building rests." This often cited conclusion, as well as the inference made about differences in the stresses in the building along its long and short axes, should be taken with great caution, as they are based on inaccurately processed data, using the limited data processing technology available at that time, and on intuitive reasoning limited by the lack of analytical solutions for this problem at that time, which would have provided deeper insight into the problem and helped interpret the empirical data. More specifically, a recent comparison of the spectra that Housner (1957) used in his analysis revealed that there were significant errors in the response spectra he computed, for the longer periods for all components, and for all periods for the EW component of the motion recorded in the basement (approximately by a factor of two, see Trifunac et al., 2001d, which reviews data on nine earthquakes recorded in this building during the past 61 years of observation). These errors lead to an erroneous inference that there was a significant difference between the components of motion along the long axis recorded in the parking lot and in the basement, while there was no significant difference for the components along the short axis (see Figure 1). The conclusion that there was no significant coupling between the motion of the ground and of the building was based on the intuitive reasoning that "if the horizontal coupling were strong… the spectrum curve for zero damping would have a peak at the fundamental period of vibration (of the building)." Analytical solutions showed later that the transfer-function for the horizontal motion of the base actually has a zero or a local minimum at the natural period of vibration of the building (see Figure 3).

As illustrated above, studies of the effects of soil-structure interaction may be based on comparison of the motions recorded in the structure with those recorded at a "free-field site" (typically several hundred feet away from the structure). It is usually assumed that the "free-field" record approximates the motions in the absence of the structure (Trifunac, 1972b). The transfer-functions between the foundation motion and the corresponding motions at the "free field site" are then used in the analysis (Lee et al., 1982; Moslem and Trifunac, 1987). The first successful interpretation of observed data, using analysis of this type, was presented by Duke et al. (1970). They interpreted the EW recorded motions (along the longitudinal building direction, see Figure 1) of the Hollywood Storage Building in terms of an analytic solution of soil-structure interaction, with a rigid semi-cylindrical foundation, and for vertically incident SH waves (see the dashed line in Figure 2, Luco, 1969b). Duke et al. (1970) did not interpret the soil-structure interaction for NS (transverse) response, because at that time, a theoretical solution did not exist for in-plane motion. Figure 3 shows results for in-plane motion of a model similar to the two-dimensional model of Luco (1969b) and Trifunac (1972b), i.e. a shear wall supported by a cylindrical foundation embedded into an elastic homogeneous half-space, redrawn from Todorovska and Trifunac (1990a). It shows the foundation horizontal displacement, Δ, rocking angle, φ, relative horizontal displacement of the top of the shear wall, u_b^{rel}, foundation vertical motion, V, and relative vertical displacement of the top of the shear wall, v_b^{rel}, for incident unit amplitude P- and SV-waves with incident angle $\gamma = 30°$ and Rayleigh waves with unit horizontal amplitude on the surface, and for different model parameters ($\varepsilon = \beta H/\beta_b a$, H/a, W/H, m_s/m_f, m_b/m_f, where a is the half width of the foundation, H and W are the shear wall height and width, and m_b, m_f and m_s are the mass of the shear-wall, foundation and soil replaced by the foundation). It is seen that, as for the solutions of Luco (1969b) and Trifunac (1972b) for SH wave excitation, Δ has minima at the natural frequencies of the building. However, for all other frequencies, the transfer-functions for Δ are complicated and different for different incoming waves and angles of wave incidence. Thus, selecting a simple model and formulating an interpretation in terms of transfer-functions of recorded horizontal motions only, is difficult. In contrast, transfer-functions for vertical motion (V) are simpler and more similar for all incident waves and incident angles. The transfer-functions of rocking motions are very dependent on the type of incident waves. Since actual strong motion consists of all body and surface waves, the observed transfer-functions for in-plane motion (assuming linear behavior of the foundation soils), would be more complicated and different from any of the Δ transfer-functions illustrated in Figure 3.

In the analysis of Duke et al. (1970) and Todorovska and Trifunac (1990a) (see Figure 3), it was assumed that the building foundation can be represented by a semi-cylindrical rigid mass. Clearly this is a very rough approximation for the foundation system of the Hollywood Storage Building, which is on Raymond concrete piles 12 ft to 30ft long (Figure 1). Thus, if this foundation is to be modeled by a rigid equivalent foundation, it would be good to select some more representative embedment ratios, as this affects the nature of the waves scattered from the foundation (Wong and Trifunac, 1974). It is more likely however that this foundation does not behave like a rigid body, especially for intermediate and high frequency waves (Trifunac et al., 1999). How to represent soil-structure interaction with flexible three-dimensional foundations has not been studied so far in sufficient detail to allow any definite interpretation, and so we leave this interesting topic for a future analysis. So far, there have been no dense arrays in building foundations that have recorded earthquake motion.

An example of an early analysis of the rocking period of a rigid building on flexible soil can be found in Biot (1942). Merritt and Housner (1954) also investigated the rocking motions, from which Housner (1957) concluded "significant effects could be expected only with exceptionally soft ground". It is interesting to note that Housner (1957) and Duke et al. (1970) papers appear to have left an impression on subsequent researchers, who state for example that the "evidence of soil structure interaction can be quantitatively detected in the frequency domain by the ratio $\left|\Delta + u_g^H\right| \,/\, \left|u_g^h\right|$" (e.g., Hradilek et al., 1973). Rocking and torsional contribution to interaction are rarely addressed in papers which aim to interpret earthquake accelerograms recorded in buildings.

Duke et al. (1970) concluded, "soil-structure interaction produced marked change in the horizontal base displacements, in the east-west direction...", with little or no rocking in this direction. For the north-south direction, the soil-structure interaction did not affect drastically the horizontal base displacements, but produced rocking of the foundation, as can be observed by analysis of the roof motion.

Other studies of Hollywood Storage Building were presented by Crouse and Jennings (1975) who compared strong motion records of the 1952 Kern County earthquake with a new set of records from the 1971 San Fernando earthquake, and by Serino and Fenves (1990) and Papageorgiou and Lin (1991), who analyzed its response after the Whittier-Narrows earthquake of 1987. Serino and Fenves (1990) used substructuring method (Chopra and Gutierez, 1973) and estimated the reduction of base shear, overturning moment and roof displacement of 3, 7 and zero percent for transverse direction, and 17, 15 and 19 percent for longitudinal direction, respectively. The studies of Crouse and Jennings (1995) and Papageorgiou and Lin (1991) are discussed in more detail in Trifunac et al. (2001d).

RESEARCH ON FULL-SCALE TESTING OF SOIL-STRUCTURE INTERACTION AFTER 1970

Journal and conference papers explicitly dealing with analysis of soil-structure interaction, in full-scale and in terms of recorded earthquake response, are rare. Examples include studies of a three-story long building founded on soft soil (Muria-Vila and Alcorta, 1992), a study of free-field motions surrounding a building, and of the motions of the building (Kashima and Kitagawa, 1988), creation of a database of earthquake records for response of a concrete tower (Ganev et al., 1993), and earthquake response analyses of simple bridges (Goel and Chopra, 1994; Werner et al., 1994), and of a caisson–type foundation of Sasame bridge (Kaino and Kikuchi, 1988). Analysis of earthquake records and identification of soil-structure interaction from recorded accelerograms in buildings is discussed in Safak (1992).

Full-scale tests of soil-structure interaction using periodic force excitation of structures are more common. The examples include tests of bridges (Crouse et al., 1987; Maragakis et al., 1996; Ventura et al., 1995), buildings with prefabricated panels (Petrovski, 1978; Erdik and Gulkan, 1984), a steel frame building (Shinozaki et al., 1994), tall concrete silo tower (Ellis, 1986), nuclear reactor buildings (Erdik et al., 1985; Mizuno and Tsushima, 1975; Casirati et al., 1988; and Iguchi et al., 1988), and foundations supported by piles (Urao et al., 1988; and Yahata et al., 1992). Wave motion resulting from soil-structure interaction during forced vibration tests of a nine-story reinforced concrete building (Luco et al., 1986, 1988) is described in Luco et al. (1975). Vibrations of a full-scale bridge structure excited by quickly released horizontal loads are described in Douglas et al. (1990) and in Richardson and Douglas (1993).

Non-linear response of the soil may cause significant changes in the apparent frequencies of the building-soil system (Trifunac et al., 2001a, 2001b), and this may lead to different results for small and large amplitudes of response (Luco et al., 1986). These differences can be quantified and interpreted by comparison of experimental results for small and large amplitudes of response (Trifunac, 1972a; Fukuoka, 1977; Ueshima, 1988; and Tobita et al., 2000).

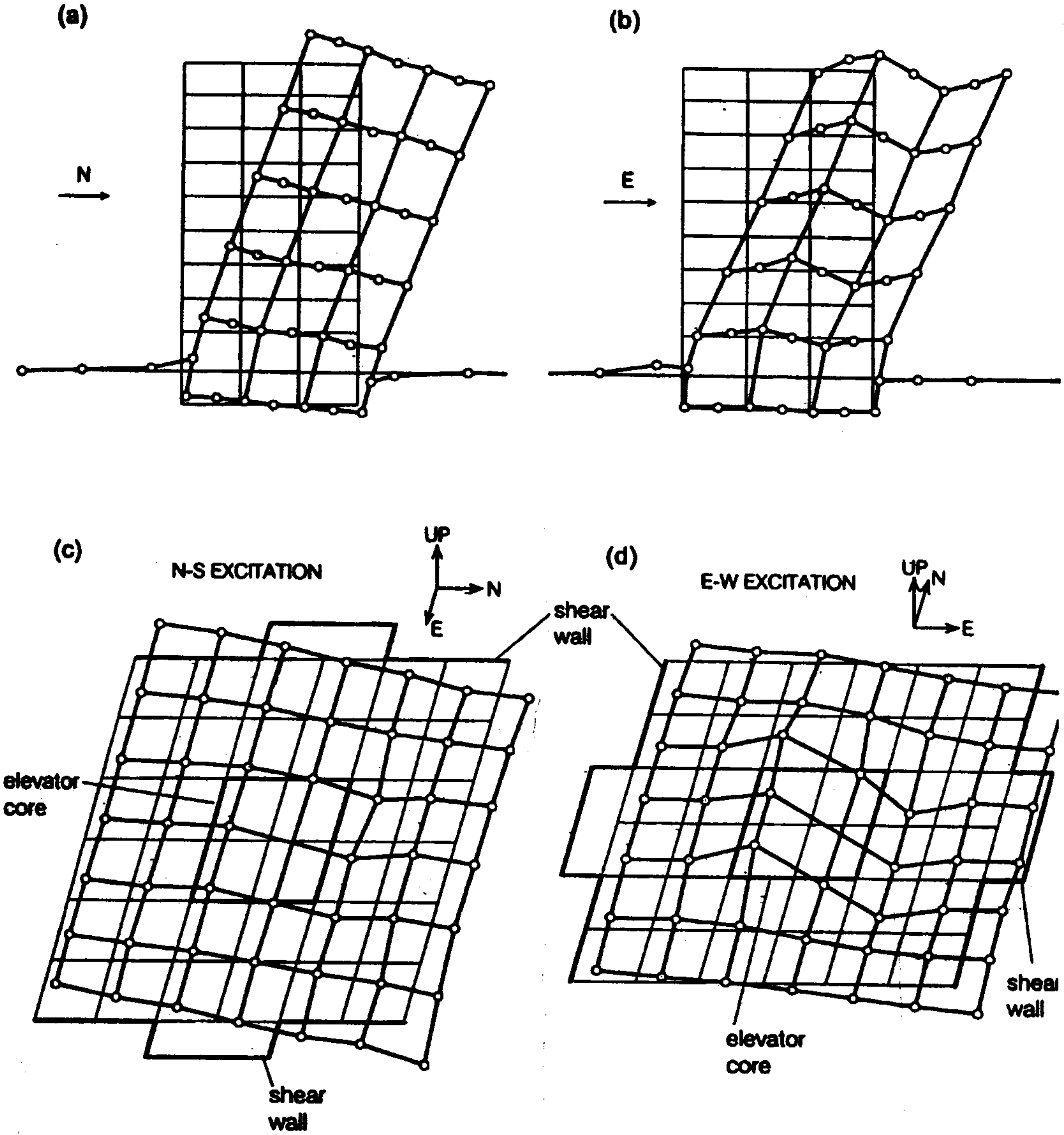

Fig. 4 Deformation of Millikan Library, a nine-story reinforced concrete building, excited at the roof by a shaker with two counter rotating masses (a) along the west shear wall during NS excitation, (b) along a section through the elevator core during EW excitation, (c) of the basement slab during NS excitation, and (d) of the basement slab during EW excitation (from Foutch et al., 1975)

LARGE MODEL TESTS

To understand soil-structure interaction and to validate different modeling and analysis methods, in-situ experimental investigations are essential. Because it is difficult to simulate half-space conditions in small specimens on shaking tables, a viable alternative is to construct scaled down models in seismically active areas. This approach offers numerous other advantages: choice of embedment depth, control of backfill soil material, possibility to install detailed instrumentation, ability to control the surroundings of the site, etc. (Tang et al., 1989).

As the full-scale structures, large-scale models can be excited by periodic actuators or shakers (e.g., Petrovski, 1975; Mizuno, 1978; Hadjian et al., 1990; Luco and Wong, 1990; Fujimori et al., 1992; Inukai et al., 1992; Ohtsuka et al., 1992; Tuzuki et al., 1992; Uchiyama, 1992; de Barros and Luco, 1995), earthquakes (Iguchi et al., 1988a, 1988b; Wong and Luco, 1990), or by both (Tohma et al., 1985; Toki and Kiyono, 1992; Ganev et al., 1996; Ohtsuka et al., 1996). Small amplitude measurements during microtremor excitation can also be compared with results from forced vibration tests, and with response to earthquake excitation (Mizuno, 1980). Kitada et al. (1999) present a recent summary of large model testing in Japan.

A special category of full-scale experiments deals with soil-structure interaction characteristics of foundations for strong motion accelerographs. Because of their small dimensions, studies of these full-scale foundations give results analogous to those from in-situ tests of scaled models mentioned above (Crouse and Hushmand, 1990; Crouse et al., 1984; Ramirez-Centeno and Ruiz-Sandoval, 1996).

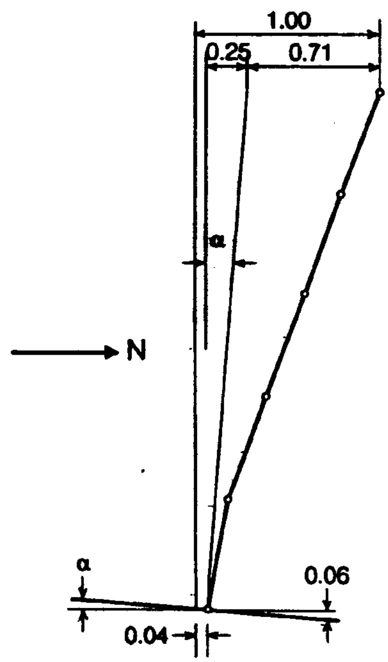

Fig. 5 Contributions of foundation translation and rocking to the roof motion of Millikan Library, for N-S shaking (from Foutch et al., 1975)

EXAMPLES OF FULL-SCALE TESTS IN ACTUAL STRUCTURES

In the following, we review several examples of full-scale tests in actual structures to illustrate how those tests can contribute towards formulation of realistic models and model assumptions.

1. Rigid versus Flexible Foundation Models

In dynamic analyses of soil-structure systems, it is convenient to assume that the foundation is rigid. This simplifies the analysis, and reduces the number of additional degrees-of-freedom required to include the soil-structure interaction, and thereby the number of simultaneous equations to be solved. However, the validity of this assumption must be carefully investigated, as it depends not only on the relative rigidity of the foundation and of the soil, but also on the type of structure and its overall rigidity, lateral load-resisting system and orientation. This can be illustrated by comparison of the NS and EW vibrations of Millikan Library in Pasadena, a nine-story reinforced concrete structure, studied by Luco et al. (1986). Even though the foundation system of this building is relatively flexible, for NS vibrations, the two symmetric shear walls at each end of the building (east and west) act to "stiffen" the foundation slab, which allows rigid foundation representation (Figure 4, a and c). For EW vibrations, the building carries the lateral loads by an elevator core, which deforms the foundation slab in the middle, while the shear walls act as membranes providing axial constraints, but little bending stiffness (Figure 4, b and d), and thus, the foundation slab cannot be approximated by a rigid foundation model. The three-dimensional deformation shapes in Figure 4 show how this structure deforms while vibrating in NS and EW directions. These were measured during forced vibration tests of this building (Foutch et al., 1975), and were essential for this interpretation. Figure 5 shows schematically the relative contributions of the horizontal deformation of the soil (4 percent), the roof displacement resulting from rigid body rocking (25 percent), and the relative deformation of the building (71 percent), during steady state forced-vibrations in the NS direction (as in Figure 4a).

Recent ambient vibration tests in a seven-story reinforced concrete moment resistant frame building in Van Nuys, California showed that the foundation supported by piles deforms during passage of microtremor waves. It can be inferred that the same happens during the passage of strong motion waves that have much larger amplitude. A detailed ambient vibration survey of this symmetric structure on symmetric pile foundations showed that the center of torsion for this structure is outside the building plan, close to its south-east corner (Trifunac et al., 1999). Subsequent examination of the strong motion records in this building showed that this eccentricity may have been present in all post-1971 responses, and is due either to some asymmetry in the soil-pile system from the time of its construction in 1966, or to some partial damage from the 1971 San Fernando earthquake (Trifunac et al., 1999), or may be, to a large lateral heterogeneity in the soil.

Differential motions of building foundations (Trifunac, 1997) may reduce the translational response at the upper floors, but may lead to large additional shear forces and bending moments in the columns of the first floor, depending on the foundation design. The response spectrum method can be modified to include the consequences of such differential motions (Trifunac and Todorovska, 1997), but it is necessary to study this further via full-scale measurements during future strong earthquakes, and to correlate the theory with observations.

The assumption that foundations can be represented by rigid "slabs" seems to be implicit in most full-scale instrumentation programs for buildings where strong motion has been recorded so far. Technically, it should be easy to supplement the existing instrumentation to provide data on differential motion of building foundations. Ideally, this should be done first in instrumented buildings where strong motion has already been recorded during many past earthquakes, so that additional value can be added to the existing data, interpretation and analyses.

2. Surface versus Embedded Foundation Models

Following many ambient, forced vibration tests of and earthquakes recorded in Millikan Library (Figure 4) and apparent inconsistencies in the data and its interpretation, Luco et al. (1986) decided in the mid-1970s to develop a comprehensive theoretical model that includes the soil-structure interaction. When this model was completed, the comparison of the recorded motions with those predicted by the model showed that the foundation impedances, available at that time only for rigid surface foundations, were not adequate. This initiated work on refinement of the (rigid foundation) impedance functions to include explicitly the embedment. With the new impedance functions, there was an excellent agreement between the theoretical predictions and the measurements for the NS response. The report on this study could finally be completed, 10 years later (Luco et al., 1986).

3. Experimental Estimates of Impedance Functions

Let H_s and M_s be the horizontal force and moment with which the foundation and the soil interact, resulting from the flexibility of the soil, and let Δ and φ be the corresponding horizontal displacement and rocking angle of the foundation. These four variables are related by

$$H_s = GL(K_{HH}\Delta + K_{HM}\,L\varphi) \tag{2a}$$

$$M_s = GL^2(K_{MH}\Delta + K_{MM}\,L\varphi) \tag{2b}$$

where K_{HH}, $K_{HM} = K_{MH}$ and K_{MM} represent the normalized, complex, frequency-dependent impedance functions for the foundation assumed rigid, G is the reference shear modulus of the soil, and L is a characteristic length, which depends on the shape of the foundation.

Numerous analytical and numerical procedures have been developed for computation of frequency-dependent impedance functions. These procedures require simplified representation of the soil medium, usually in terms of parallel homogeneous layers and of infinite extent horizontally. Also, equivalent dynamic soil moduli must be specified on the basis of standard field and laboratory geotechnical tests. Carefully and well-designed full-scale experiments on structures are therefore invaluable to verify those methods and to evaluate the adequacy of the theoretical approximations and selection of the governing parameters.

Luco et al. (1986, 1988) and Wong et al. (1988), for example, have described forced vibration tests of Millikan Library, in which the response at the top of the structure and the translational and rocking response at the base can be used to calculate the force and the moment the foundation exerts on the soil. When the coupling impedances K_{MH} and K_{HM} are small, K_{HH} and K_{MM} can be approximated from experimental measurements. They found excellent agreement between theoretical and experimental estimates of rocking impedance functions, and not so good agreement for the corresponding horizontal impedance functions, particularly for the EW response. They concluded, "These discrepancies in the E-W direction are associated with the failure of the simple foundation model to account for the flexibility of the actual foundation and for the large radiation damping in horizontal vibrations obtained experimentally. It seems then, that if the foundation acts as a rigid body it is possible to predict quite accurately the effects of soil-structure interaction during forced vibration tests by use of simple models. Analytical models more complex than those used in this study may be required for highly flexible foundations" (Wong et al., 1988).

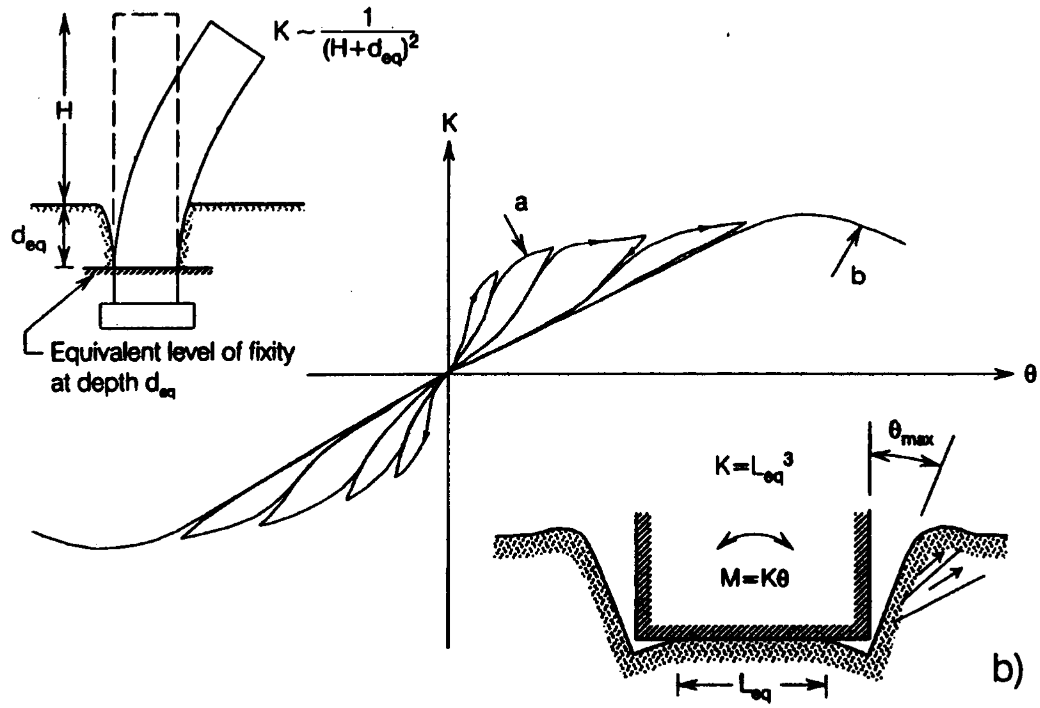

Fig. 6 (a) Non-linear changes in the rocking stiffness caused by passive soil pressure on the sidewalls of the building and variable equivalent depth of fixity d_{eq} (b) A schematic representation of "permanent" soil deformation after large rocking response (from Trifunac et al., 2001c)

4. Torsion

The torsional response in non-symmetric structures is caused by geometrical separation of the centers of mass and of rigidity. For symmetric structures, torsional response may occur because of asymmetry of the foundation system, the wave passage effects (Luco, 1976; Trifunac et al., 1999), accidental torsion (buildings are rarely perfectly symmetric), or from all of the above. Long and narrow symmetric buildings, for example, can experience significant torsional response and whipping (Todorovska and

Trifunac, 1989, 1990b), when excited by earthquake waves propagating along the longitudinal axis of the structure-soil system.

Full-scale measurements of torsional response and of torsional components of soil-structure interaction cannot be performed directly, because, at present, there are no rotational strong motion accelerographs installed in buildings. It is possible to estimate only the average rotations from the differences in translational motions, when there are multiple recorders in the structure arranged accordingly.

The following illustrates thus computed rotations for the Hollywood Storage Building (Figure 1). The locations and orientations of the strong motion accelerographs since 1976 are shown in Figure 1 (bottom). For this instrument configuration, processed strong motion data are available only from four earthquakes: 1987 Whittier-Narrows, 1992 Landers, 1992 Big Bear, and 1994 Northridge. By suitable combination of displacements computed from the recorded accelerograms after double integration, it is possible to estimate the average torsion in the west side of the building. Trifunac et al. (2001d) show that, most of the time, the relative motions of the west side of the roof were about one-half of the motions of the center of the roof (respectively channels 12 and 10 in Figure 3.1 of Trifunac et al., 2001d), and that the two motions were in phase. An exception to this is the response to the 1994 Northridge earthquake, 8 to 12 s after trigger time (see Figure 5.1d in Trifunac et al., 2001d). Thus, most of the time, this building is twisting about a point west of the center of symmetry of the base. A similar behavior was reported by Trifunac et al. (1999) for a seven-story reinforced concrete building in Van Nuys, California, also supported by a pile foundation. For the Hollywood Storage Building, such a behavior may have been caused in part by the non-symmetry of the foundation (the building has a basement only beneath its western half, see Figure 1). Such torsional eccentricity thus causes whipping of the eastern end of the building, particularly for EW arrivals of SH and Love waves (e.g., during Whittier-Narrows, 1987, Landers, 1992, and Big Bear, 1992 earthquakes; see Figure 17 in Todorovska and Trifunac, 1989). Unfortunately, there are no strong motion instruments along the eastern end of Hollywood Storage Building to verify this interpretation.

5. Time and Amplitude-Dependent Response

Trifunac et al. (2001a, 2001b) reported on systematic and significant amplitude-dependent changes of soil-structure system frequency $\tilde{f} = 1/\tilde{T}$ of a seven-story reinforced concrete frame building supported by piles, in Van Nuys, California, damaged by the 1994 Northridge earthquake. They used the conceptual model in Figure 6 to explain the observed changes. This model consists of a building with height H and an embedded foundation. In the initial stages of the response when the amplitudes are small and the soil stiffness is "linear", as the building begins to "push" the soil sideways, its effective depth of "fixity" (indicated by d_{eq} in Figure 6a) changes as a function of the response amplitudes and history. Larger d_{eq} leads to smaller stiffness $K \sim 1/(H + d_{eq})^2$ and smaller $\tilde{f}$. While the building pushes the soil, d_{eq} decreases and K increases ("hardening" behavior). When the direction of motion reverses and the building moves away from the soil, a gap forms between the two, d_{eq} increases and K decreases ("softening" behavior). This results in non-linear system behavior, which can be modeled by a non-linear spring or by a group of springs with gap elements. As the amplitudes of motion increase further, the soil begins to yield and material non-linearity is introduced into the system, reducing or canceling the "hardening" part of the cycle. This behavior repeats as long as the successive amplitudes of vibration increase and the soil can be pushed sideways. At the time of the largest response amplitudes (θ_{max}), the gap between the building foundation and the soil sidewalls is the largest. By forcing it to yield, the soil can be "compacted" also below the corners of the "rigid" foundation (see Figure 6b), reducing the equivalent length, L_{eq} of the contact between the foundation and the soil, thus resulting in reduction of the system stiffness ($K \sim L_{eq}^3$; Luco et al., 1987) and reduction of $\tilde{f}$. Following the largest amplitudes of response, as the strong motion amplitudes begin to decrease, the depth of "fixity" d_{eq} and the contact length L_{eq} remain constant (many equivalent gap elements remain open). The building responds with smaller amplitudes, and the period of response is longer. Continued shaking, aftershocks and subsequent earthquakes may activate a "healing process". Through dynamic compaction and settlement of the soil material, which was loosened and pushed aside by the preceding strong motion, the soil is packed back around the piles, grade beams, and sides of the building, thus rebuilding or even increasing the previous system stiffness. It seems that this cycle may be repeated many times, depending on the sequence of aftershocks and earthquakes during the "quiet" intervals between strong motion events.

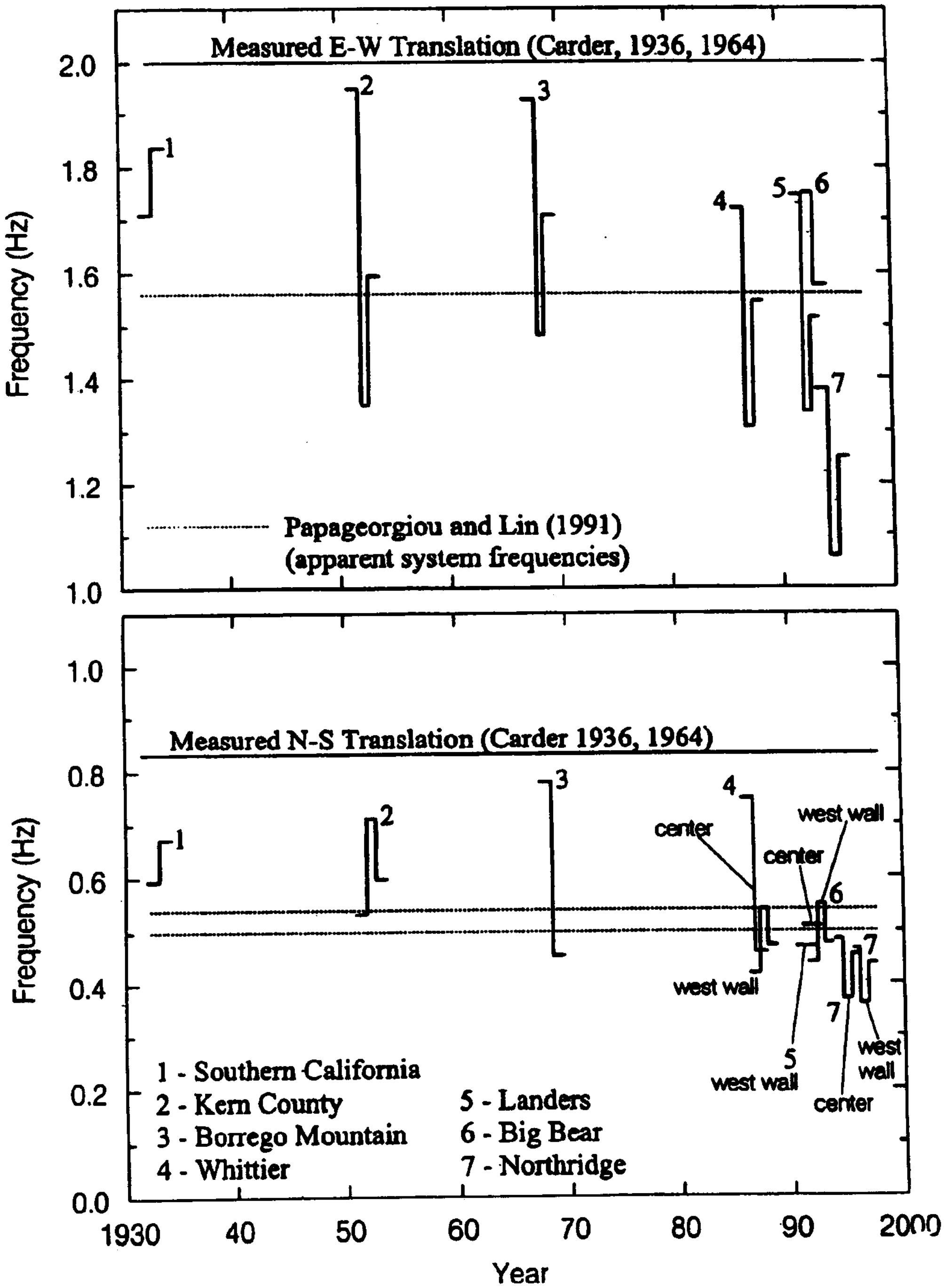

Fig. 7 Hollywood Storage Building: summary of the time-dependent changes of the system frequency during seven earthquakes, between 1933 and 1994 (the horizontal lines show the system frequencies determined from ambient vibration and forced vibration tests (EW and NS translations, light solid lines, Carder, 1936, 1964), and those identified by Papageorgiou and Lin (1991) (dashed lines); for each earthquake, the horizontal ticks represent pre- and post-earthquake estimates of the system frequencies) (from Trifunac et al., 2001d)

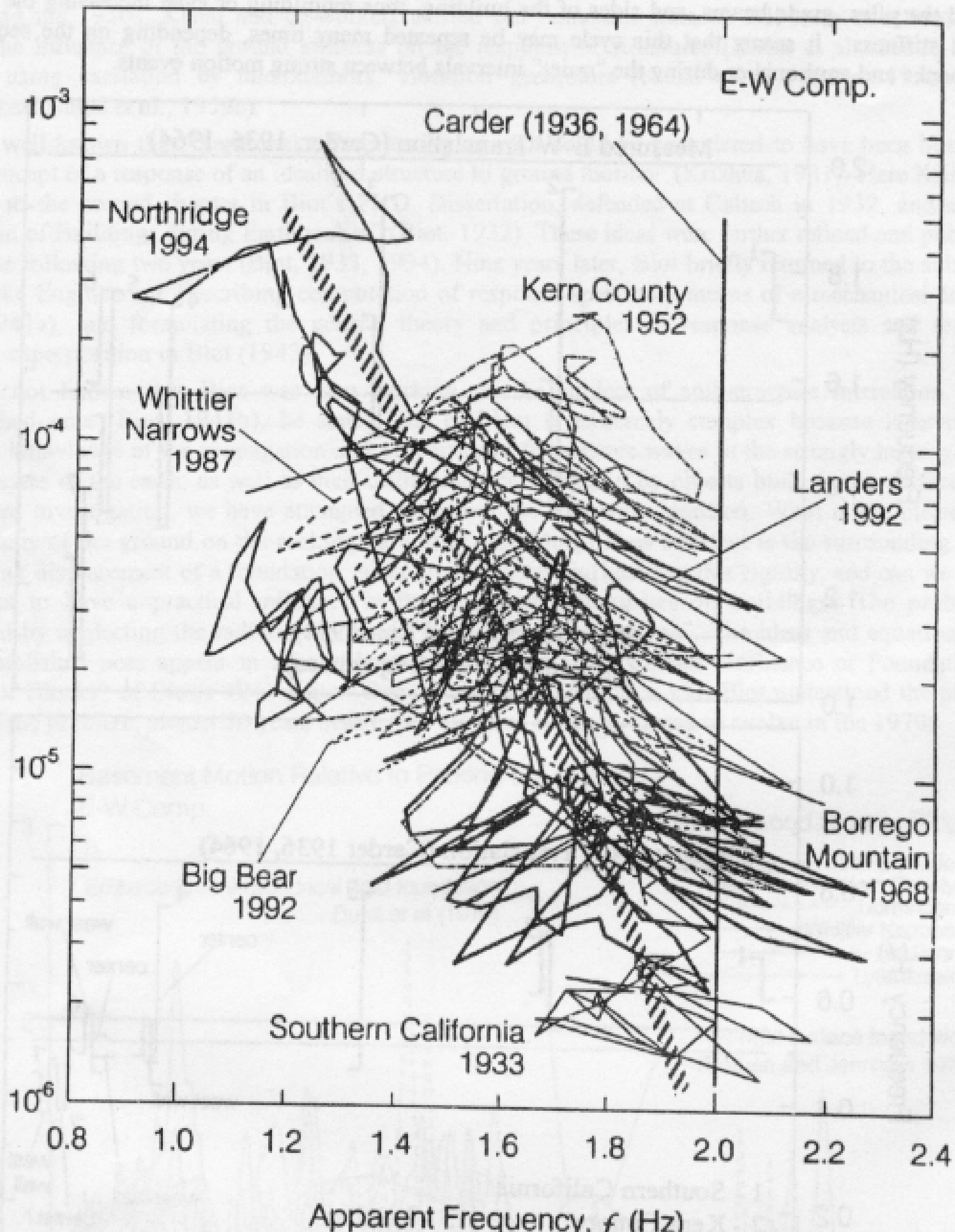

Fig. 8(a) Hollywood Storage Building: dependence of the apparent system frequency on the amplitude of EW response ("rocking angle") (the solid vertical lines show estimates of the system frequencies determined from small amplitude (ambient vibration and forced vibration) tests by Carder (1936, 1964)) (redrawn from Trifunac et al., 2001d)

An interpretation of the data recorded in Hollywood Storage Building, assuming that a similar conceptual model may apply (Trifunac et al., 2001d), is as follows. The system became softer with increasing amplitudes of the ground shaking. For EW motions and for the small shaking during Borrego Mountain Earthquake of 1968, the system frequency was near 1.9 Hz (close to 2.0 Hz as reported by Carder, 1936, 1964). For larger amplitudes of motion, the system frequency decreased, and was near 1.25 Hz for the larger shaking during the 1994 Northridge earthquake. For NS translational response, the system frequency was near 0.6 to 0.7 Hz for small ground shaking (Southern California earthquake of 1933), and fell to ~ 0.45 Hz during the largest recorded motions (Northridge earthquake of 1994). From ambient and forced vibration tests, this frequency was 0.83 Hz (Carder, 1964). The fundamental torsional frequency was reported by Carder (1964) to be in the range of 1.57-1.67 Hz. This frequency was as low as

1.1 Hz during the shaking from the 1992 Landers earthquake (waves arriving from the east). Figure 7 summarizes the above trends. It also shows the EW and NS translational frequencies observed by Carder (1936, 1964). The dashed lines show the apparent system frequencies identified by Papageorgiou and Lin (1991).

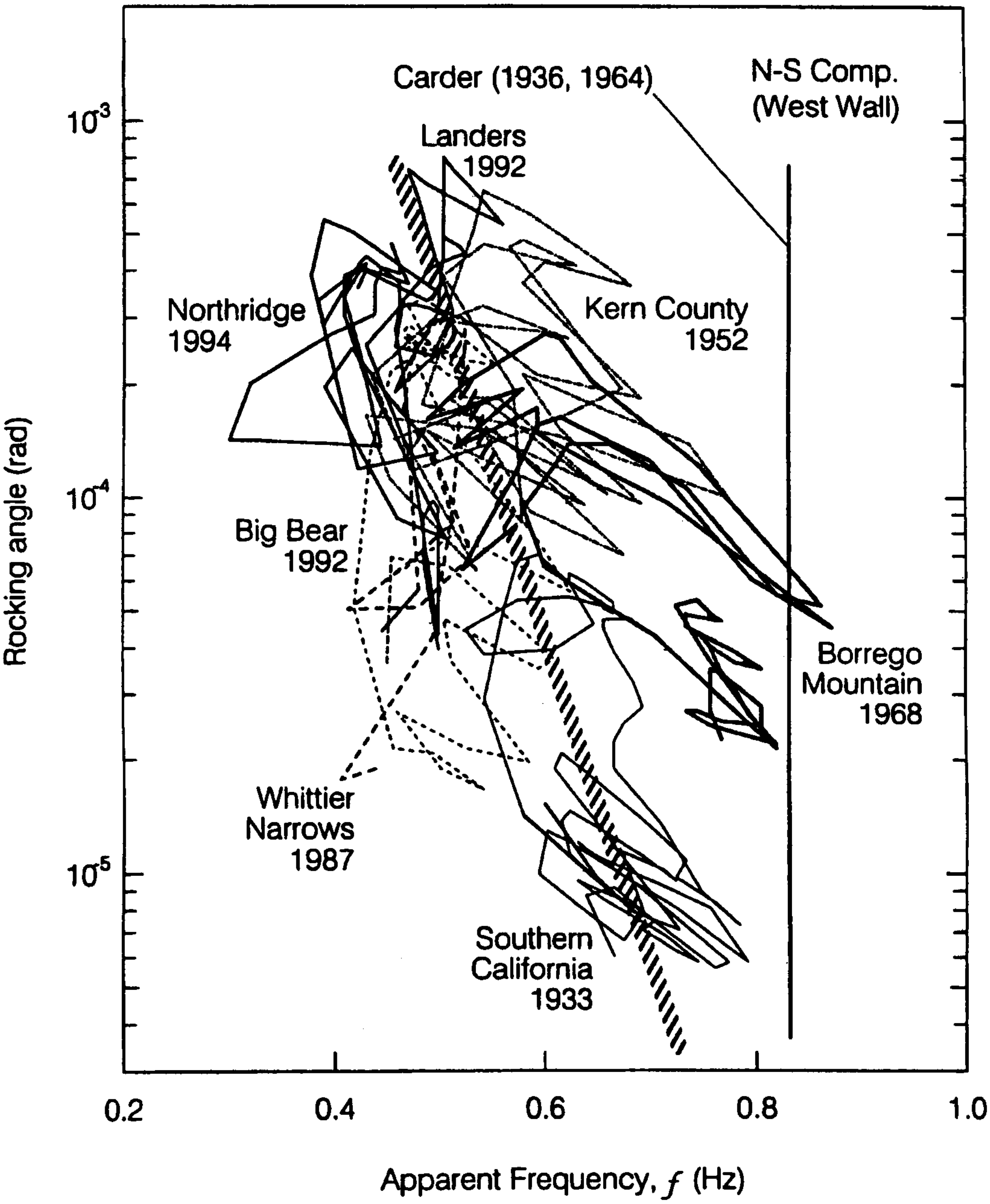

Fig. 8(b) Hollywood Storage Building: dependence of the apparent system frequency on the amplitude of NS response ("rocking angle") (the solid vertical lines show estimates of the system frequencies determined from small amplitude (ambient vibration and forced vibration) tests by Carder (1936, 1964)) (redrawn from Trifunac et al., 2001d)

Figures 8(a) and 8(b) compare the "rocking angles" (displacement at the roof minus displacement at ground level divided by the building height) versus the instantaneous apparent frequency computed for most half-period segments of the response of the Hollywood Storage Building to all seven earthquakes. It can be seen that the apparent system frequency depends on the amplitude of shaking, and for small amplitudes, approaches the frequencies from full-scale ambient and forced vibration tests measured by

Carder (1936, 1964). These trends are consistent with the non-linear soil structure model shown in Figure 6.

It should be noted here that, for the same building analyzed by Trifunac et al. (2001a, 2001b) (a seven-story reinforced concrete building in Van Nuys, California), there have also been more traditional interpretations of the lengthening of the period of the building. For example, De la Llera et al. (2001), Islam (1996), and Li and Jirsa (1998), who analyzed the 1994 Northridge earthquake data, completely ignored the effects of the soil-structure interaction and interpreted the lengthening of the system period to have resulted entirely from structural damage incurred during this earthquake. Both of these conflicting interpretations fit the Northridge response data, which are not adequate to separate uniquely the effects of the soil-structure interaction. In fact, much of the non-uniqueness problem in interpretation of non-linear response of soil-structure systems is due to the fact that most of the current instrumentation in buildings is inadequate to isolate the effects of the soil-structure interaction. For realistic modeling of soil-structure systems, it is very important that the hypotheses that fit earthquake response data are at least narrowed down to a consistent set. This would require much denser instrumentation in structures than currently deployed, deployment of rotational transducers, direct measurement of strain along the contact between the foundation and the soil, and many repeated measurements over a longer period of time and under different levels of excitation.

GENERAL TRENDS IN RESEARCH ON SOIL-STRUCTURE INTERACTION AND FULL-SCALE TESTING

After a brief and productive period, from 1965 to about 1975, when many informative and useful full-scale experiments were conducted (see Luco et al., 1986, for an example of a detailed study of a forced-vibration test, and Ivanović et al., 2000, for a review of ambient vibration tests), the Earthquake Engineering profession seems to have converged toward small-scale laboratory experiments. In 1996, "Earthquake Spectra" (Abrams, 1996) published a theme issue entitled "Experimental Methods". Interestingly, none of the nine papers mentioned or referenced full-scale tests of structures.

Papers dealing with experimental aspects of soil-structure-interaction do not exhibit major fluctuations, and since 1970, appear at an average rate of 3.3/year. Analysis of these papers shows that only about 1.2 papers/year deal with full-scale experiments, about 2/3 of the experimental papers being devoted to laboratory testing. The only year with five papers on full-scale tests involving soil-structure-interaction was 1975. During 1972–1974, 1976, 1979, 1982, 1995, 1997 and 1998 (or 45 percent of the time), there were no contributions in the leading Earthquake Engineering journals. Our search may have missed to identify some papers, but this finding is nevertheless alarming.

It is instructive to consider the trend of the number of papers presented at World Conferences on Earthquake Engineering (WCEE). During the first conference, in 1956 in San Francisco, 40 papers were presented, and during the last two conferences (Acapulco, 1996 and Auckland, 2000) about 1440 papers (each) were presented. The proceedings of the 10th World Conference in Madrid in 1992 were the last to be published in printed form, and the proceedings of the two most recent conferences (11th and 12th) are published on a CD-ROM. Analysis of the percentage of papers dealing with soil-structure interaction, relative to the total number, shows that the largest number of papers was presented in 1988, during the 9th conference, held in Tokyo and Kyoto. The largest percentage of papers devoted to soil-structure interaction was presented in 1973 during the 5th conference. It is seen that the general interest in soil-structure-interaction, at least among researchers and practitioners who publish in World Conference Proceedings, is decreasing.

A more detailed analysis of the above trends for the period 1988 to 1997 in Japan has been presented by Iguchi and Yasui (1999). They find that the number of papers dealing with piles has increased significantly after the 1995 (following Hyogo-Ken Nanbu earthquake).

It is interesting to note that there is a strong correlation between the percentage of papers in WCEE proceedings and the number of papers published in journals, other conferences, and reports, if percentage of papers devoted to soil-structure interaction during world conferences is plotted with a 7 year shift forward relative to the total number of journal papers on the same subject. An explanation may be that the world conferences contribute toward influencing the researchers on what is relevant and useful to work on. The process which begins with recognition that a subject or an idea is worth working on, organization (funding) and actual beginning of work, successful completion of work, submission of the finished papers to journals, peer review, revisions, and eventual publication, all appear to take, on average, about 7 years. If this is indeed so, it is interesting to contrast this with the typical 5 to 6 years probation period for tenure track assistant professors, or with duration of funding initiatives of the National Science Foundation in United States, for example. All of this is based on an old fashioned assumption that a recognized and true measure of successful completion of a research task is marked by publication in a respectable professional journal.

DISCUSSION AND CONCLUSIONS

1. State of Soil-Structure Interaction Research and Full-Scale Testing

Monitoring earthquake response in and around buildings and comprehensive full-scale tests of structures are the best experimental method for investigating soil-structure interaction, because the scaling and similarity laws problems are eliminated, and because the boundary conditions are satisfied exactly (Trifunac and Todorovska, 1999). Surprisingly, full-scale testing of structures and soil-structure interaction research in the United States (except for piles) has dropped to an alarmingly low level, and the reasons appear to lie in our educational programs. Small-scale laboratory tests and computer simulations are useful for understanding selected phenomena in soil-structure interaction. However, laboratory experiments lack the completeness of the full-scale tests, which is particularly true for investigation of soil-structure interaction phenomena (the semi-infinite soil boundary is practically impossible to model in the laboratory). Laboratory experiments are designed to measure what the researcher has decided to study and may help discover new physics only by accident. On the other hand, the as-built environment contains all the physical properties of reality, and the investigators only need to find ingenious ways to record and interpret them. Obviously, the priorities in earthquake engineering research are not properly balanced and precious time is being lost. If public safety is to be improved and financial losses from future earthquakes are to be reduced, an immediate action is needed to change these trends.

2. Difficulties in Interpreting Earthquake Response Data

The physical completeness and the reality of the full-scale structures are necessary but not sufficient conditions to guarantee correct end results. The discovery and understanding of the true nature of response tend to be born by the difficult labor involving reconciliation between our imperfect theories, modeling and analyses, with often incomplete data from measurements. Experienced experimentalists know that the first test rarely produces results, as we inevitably forget to measure something, or what we measure does not turn out to be useful. Thus, iterations are almost a rule, in both experiments and in the analyses (Trifunac and Todorovska, 1999).

Often, the difficulty in interpreting earthquake response data recorded in buildings lies in the non-uniqueness of the starting models and assumptions. For example, the transfer-functions of horizontal roof displacement of a fixed-base building, and of the same building on flexible soil, have very similar appearance near the first fixed-base frequency, or near the apparent frequency of the soil-structure system. Using a simple identification technique, it is easy to estimate the frequency and the associated fraction of critical damping from full-scale measurements during an earthquake, but it is not easy to identify the factors that control these peaks. The separation of the structure's fixed-base frequency from the rocking and translation frequencies associated with soil-structure interaction is less straightforward and can be performed only if additional instrumentation is available. The list of investigators who overlook this non-uniqueness is so long that it seems that this problem is ignored in most published work. Along the same lines, it is common to find papers presenting analyses of non-linear response of structural components, with discussions of structural ductility and how it relates to the observed changes in the response period, without including in their analyses the fact that, shortly after the earthquake, the apparent period of the soil-structure system was back at or near its pre-earthquake value, suggesting that an important source of non-linearity was not only in the structure, but also in the soil supporting it (Trifunac et al., 2001a, 2001b).

The non-uniqueness in future data can be eliminated in great part by placing additional instruments to measure the rotation of the building foundation (Luco et al., 1986; Moslem and Trifunac, 1986). It is interesting to note that in spite of the fact that transducers that record rotational acceleration and velocity have been constructed and tested (Shibata et al., 1976; Whitcomb, 1969), essentially no buildings are equipped with such instruments, and so far the earthquake engineers do not seem to request such data.

Rocking of the foundation can be calculated from the difference of recorded vertical motions at two points on a line perpendicular to the axis of rotation. The result represents the average rotations between the two points. To evaluate the actual point rotations, it is necessary to map the pattern of deformations of the building foundation, associated with the apparent frequency of the system prior to and following the earthquake (provided no damage occurred), by using forced vibration or ambient vibration tests, for example. This requires detailed full-scale testing, which has not been done for most buildings (Ivanović et al., 2000).

3. Practical Benefits from Full-Scale Testing

Soil-structure interaction can be used to reduce the structural response, by utilizing and increasing the effects of scattering of the incident waves from the foundation, radiation of the structural vibration energy into the soil, and (under controlled conditions) via non-linear response of the soil (Trifunac and Todorovska, 1999b). Namely, in presence of soil-structure interaction, the system damping depends on the damping in the building and in the soil, and on the scattering of wave energy from and through the foundation (Luco et al., 1986). Design of foundations to scatter efficiently high frequency (short) waves can increase the apparent system damping and can reduce the amplification of the system response near the first mode of vibration (Todorovska and Trifunac, 1992).

Studies of the dissipation of seismic wave energy by scattering of incident waves from the foundation, and by radiation of vibrational energy from the structure into the half-space, are among the oldest topics studied in the subject area of soil-structure interaction (Sezawa and Kanai, 1935, 1936). Modeling the dissipation of energy of a vibrating structure is constrained by the mathematical methods of analysis, and by the lack of comprehensive measurements, which would show the physical nature of this dissipation (Moslem and Trifunac, 1986; Crouse, 1999). Many linear response analyses use normal mode representation and, to maintain the advantages of working with decoupled equations, those approximate the damping matrix by a linear combination $\alpha[m]+\beta[k]$ of the mass and stiffness matrices, $[m]$ and $[k]$, where α and β are constants. For an n degree-of-freedom system, this allows one to choose the damping only for two modal frequencies, ω_i and ω_j, and the remaining $n-2$ modes then have equivalent damping ratios $\zeta = 0.5(\alpha/\omega_k + \beta\omega_k)$, which are not realistic. A common practice is to use constant damping ratios for all mode-shapes in the response analyses. This, of course, ignores the fact that the solution then violates the original differential equations, and can lead to erroneous responses.

Earthquake response records in combination with detailed full-scale testing of structures, before and after significant earthquake shaking, may be used to detect the location and extent of damage in the structure. However, this would require improved models and theory, which can be done through design of more detailed experiments and more detailed earthquake-monitoring instrumentation in building.

It is often assumed that symmetric buildings, supported by symmetric foundations on uniformly layered soil, will experience little or no torsional response. Also, most response analyses ignore torsional excitation caused by the passage of seismic waves across the finite horizontal dimensions of the foundation. Hidden asymmetries in the foundation and structural systems, coupled with the wave passage effects, can result in significant torsional response, which cannot be ignored (Lin et al., 2001). Such asymmetries can be detected only by full-scale tests of structures (using forced vibration, microtremors and recorded earthquake response). Systematic tests on different structures can be carried out to find how widespread these asymmetries are and to estimate them empirically for use in the design process, e.g., via accidental torsion eccentricities.

4. Recommendations

The bulk of processed earthquake response data recorded in buildings is for large amplitude response (e.g., rocking angles greater than 10^{-4} rad). This results in very different system frequency estimates from strong motion response, and from estimates based on microtremor excitation (e.g., see Figures 8(a) and 8(b)). These large differences have led investigators to conclude that the ambient vibration tests are difficult to interpret or are not reliable for inferences on strong motion response. However, as it is seen from Figures 8(a) and 8(b), both strong motion data and ambient vibration tests give mutually consistent results, and together help determine the expected changes of the system frequencies for a range of response amplitudes. Consequently, to develop sound mathematical models of soil-structure systems, such changes of the system frequencies must be modeled realistically, by incorporating geometric and material non-linearities into the representations of soil and structure. To enable this work, numerous intermediate and small amplitude earthquake recordings in structures must be processed and distributed to researchers. These data will enable researchers to quantify the changes in the system frequencies, and to define empirically how those depend on type of structure, foundation, and on the properties of the underlying soil. Correct estimate of the extent of the variability of the system frequency of structures is important in design as the seismic design coefficient $C(T)$ depends on the system period.

The significant changes in the system frequencies shown in Figures 8(a) and 8(b), for the Hollywood Storage Building are not unique to this building and to the soil at this site. Similar changes have been documented for other buildings with and without pile foundations (Luco et al., 1986; Trifunac et al., 2001a, 2001b). The range of system frequency variations, shown in Figures 8(a) and 8(b), is probably similar for many other buildings. This range may become broader for buildings on piles and on very soft soil, and narrower for buildings on stronger soil and on "rock". Thus, the dynamic response analyses of soil-structure systems must be based on models that can incorporate the observed non-linear mechanisms. This, coupled with the fact that most foundation systems of buildings cannot be assumed to be rigid (for purposes of soil-structure interaction analysis), implies that more complex and realistic models must be developed both in research and in design applications. Simple models using equivalent linear single-degree-of-freedom system, supported by rigid foundation on elastic soil, neither have adequate number of degrees-of-freedom, nor have the right physical properties to allow one to model the response of full-scale structures to moderate and strong ground shaking. Ignoring this and fitting simple models to the recorded response of full-scale structures, can only create confusion, erroneous interpretation, and misleading generalizations, all caused by the non-unique nature of the relationships between the hypotheses and the observed data.

The next generation of realistic models of soil-structure systems can be developed and refined only through full-scale studies of buildings and their response to excitations ranging from microtremors, to aftershocks, and all the way to large and destructive motions. To gather key new data and to support future work in full-scale studies of soil-structure interaction, rotational strong motion accelerographs must be added to the existing instrumented structures, or new accelerographs capable of recording three translations and three rotations simultaneously, must be deployed in place of the old instruments which record translation only. Also, the non-linear and time-dependent changes of the system behavior will require defining instantaneous system transfer-functions.

Finally, the above discussion and recommendations are consistent with the discussion and consensus recommendations by the participants of the 1st and 2nd UJNR (U.S.-Japan National Resources) Workshops on Soil-Structure Interaction, which took place in 1998 in Menlo Park, California, and in 2001 in Tsukuba, Japan (Celebi and Okawa, 1999; Building Research Institute, 2001). At both workshops, it was resolved that "research to advance soil-structure interaction methodologies be given high priority and that design provisions related thereto be introduced into the codes, thus enhancing the seismic safety of structures designed accordingly."

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