Proceedings, Third UJNR Workshop on Soil-Structure Interaction, March 29-30, 2004, Menlo Park, California, USA.

Opportunities for Soil-Structure Interaction Research Via ANSS

Mehmet Çelebi,[a] and Janise Rodgers[a]

The purpose of this paper is to introduce two integrated arrays each consisting of building and free-field arrays that can be used for soil-structure interaction (SSI) research. One of these arrays is funded by Advanced National Seismic Systems (ANSS), a new initiative managed by the United States Geological Survey. Through this new initiative, 6000 three-channel or equivalent accelerometers are aimed to be deployed in seismic urban areas of three United States. Of particular interest is the recommendation that SSI related deployment be given high priority. The two arrays serve as examples for further deployments in building structures to facilitate SSI research. Furthermore, limited data is available from both arrays to facilitate SSI research.

INTRODUCTION

State-of-the-art knowledge and analytical approaches require, when warranted, the structure-foundation system to be represented by mathematical models that include the influence of the sub-foundation media. Identification of beneficial and adverse effects of soil-structure-interaction (SSI) is a necessity. Adverse effects of SSI during the 1985 Michoacan (Mexico) earthquake were addressed by Tarquis and Roesset (1988), who showed that, in the lakebed zone of Mexico City, fundamental periods of mid-rise buildings (5-15 stories) lengthened due to SSI. Thus, such buildings became vulnerable because their lengthened periods were close to the now well known 2-s resonating site period of the lakebed zone.

Therefore, it is necessary to further study theoretically and verify through field experiments, the implications of soil-structure interaction effects on the dynamic behavior and performance of structures. To this end, 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, Marcuson, Stokoe and Yokel, 1978; Iwan, 1978

---

[a] United States Geological Survey, Menlo Park , Ca. 94025

and 1981). On 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."

Until 1992, 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) – which is outside the scope of this paper.

In 1992, a workshop specifically dedicated to the subject, recommendations were made to the effect that it is necessary to develop arrays for field conformation of soil-structure interaction (SSI) effects to improve current methodologies and develop new ones for analyses and design (Çelebi, Lysmer, and Luco, 1992). Recently, under the auspices of Panel on Wind and Seismic Effects of the United States - Japan Natural Resources Development Program (UJNR), two workshops on "Soil-Structure Interaction " (SSI) were organized.

(a) The first workshop was held in Menlo Park, CA on September 22-23, 1998. U.S. Geological Open-File Report 99-143 was issued as the proceedings of that workshop (Çelebi and Izuru, 1999).
(b) The second workshop was held in Tsukuba, Japan on March 6-8, 2001 (Proceedings, The 2nd UJNR Workshop on Soil-Structure Interaction, Tsukuba, Japan, March 6-8, 2001 – CD- ROM)

Both workshop presentations covered:

- Current methods of SSI used in design/analyses processes in both Japan and the United States,
- Recent research that is being carried out, and

- Experimental SSI research arrays and/or facilities developed and that are in the process of being developed and
- Searching ways to cooperate on future SSI research.

Another recent workshop identified evaluation of soil-structure interaction as one of the most important measurement objective for strong-motion instrumentation of buildings (COSMOS, 2001). Through recent Network for Earthquake Engineering Simulation (NEES) initiative by National Science Foundation, several large-scale testing and field facilities that can be used for SSI research (*e.g.* Youd et. al., 2004, this volume) are now funded. A new initiative, Advanced National Seismic System (ANSS[1]) managed by the U.S. Geological Survey (USGS) opens the door to opportunities to advance SSI research that can result in evaluation of current methods on real-life structures as it proposes to deploy 3000 (3-channel) instruments to monitor built environment in seismic urban areas of the United States.

Thus, it is fair to state that opportunities for advancing field deployment of seismic instruments in actual buildings for SSI research and assessment are being developed. In this paper, two such prototype cases of buildings instrumented are presented. These cases can provide opportunities for SSI research. The scope does not introduce results to date but rather provide information relevant for SSI research.

TWO ARRAYS FOR SSI RESEARCH

ARRAY 1 - ATWOOD BUILDING (ANCHORAGE, AK)

The Building and Site Conditions

The Atwood Building is 20 stories tall and is located in downtown Anchorage. The building is (1) a steel moment-resisting framed structure with only one level of basement, (2) 130’x130’ (39.6 m x 39.6 m) in plan and (3) 264’ (80.5 m) tall. The building foundation is without any piles and consists of 5’ (1.52 m) thick reinforced concrete mat below core and with 4’6” (1.37 m) thick reinforced concrete perimeter mat interconnected with grade beams.

---

[1] ANSS: Advance National Seismic System – an intiative to expand and upgrade the seismic network system in the United States, authorized by U.S. Congress and administered by the U.S. Geological Survey (USGS Circular 1188).

It is well known that downtown Anchorage is underlain by an approximately 100-150-feet (30.5 – 45.7 m) thick soil layer known as the Bootlegger Cove Formation, where considerable ground failures occurred during the 1964 Great Alaska earthquake. Thus, during earthquakes of various levels of shaking, recording the response and then assessing the behavior of structures at such sites and the sites themselves is of interest to the engineering community as the next large earthquake will most likely affect the performance of structures at such sites.

Instrumentation

For that reason, it is important to take measures in advance not only to design structures better with the best known methods but also to take it one step further by monitoring the shaking response of the structures in the most efficient way to capture data to enable (a) response studies, (b) assess the performance and (b) draw conclusions for future designs and/or retrofit or strengthening of similar structures. In this specific case, seismic instrumentation and monitoring of the Atwood Building is deemed to be important not only to shed light on the behavioral issues related to this particular building but also overall generic response issues related to such buildings on soft underlying geotechnical media such as that beneath downtown Anchorage. Therefore, interest in the performance of this particular building as well as similar buildings built on such a site and in a highly active seismic environment makes this a very desirable building to monitor during strong shaking events.

To meet the above objectives, the building instrumentation has two distinctive components integrated to provide answers to shaking response issues as they pertain to the particular building with its (a) specific structural system and foundation without any piles and (b) associated free-field and borehole array in close proximity to the building. General three-dimensional schematic of the building as well as the free-field surface and downhole array is provided in Figure 1.

The instrumentation within the building is designed to record (a) its lateral swaying, (b) twisting, (c) drifts (displacement between selected two consecutive floors) or average drifts between any two floors, and (d) rocking of the building which is related to interaction of the building with the underlying soil such that the shaking characteristics are altered due to such interaction. Quantification of this phenomenon is of utmost importance for defining the role of such soil-structure interaction in design and analyses of future structures.

The associated downhole array consists of surface and downhole instruments deployed at various depths to capture the response of varying layers of soil and how such layering affects the changes in the characteristics of earthquake motions as they travel and hit the surface and affect the shaking of the structures.

With the integrated downhole, surface and superstructure arrays, propagation of motions starting from the downhole to the roof of the building can be captured.

A Recorded Earthquake and Preliminary Analyses

Recorded acceleration and computed (double-integrated) displacements from the superstructure array of the building[2] during the December 15, 2003 (Ms=3.7) Point MacKenzie, Alaska earthquake are provided in Figure 2. The building is 18.8 km distance from the epicenter of the earthquake. The largest peak acceleration recorded in the building array is less than 0.02 g. The figure shows clearly the propagation of waves from basement to the roof of the building. Although at this low level shaking, clear SSI effects are not detected, Figure 3 shows the amplitude spectra of the two parallel NS motions, their difference and the EW motions at the roof and clearly identifies relevant structural frequencies. Figure 4 shows that the two basement motions are coherent for several frequencies one of which may be due to rocking. Further analyses on this subject is being carried out.

ARRAY 2 - PACIFIC PARK PLAZA BUILDING (EMERYVILLE, CA)

The Building and Site Conditions

Pacific Park Plaza Building is a thirty-story, 312 ft. (95.1 m) tall, ductile reinforced concrete moment-resisting frame building. The three wings of the building are constructed monolithically and are equally spaced at angles of 120 degrees around a central core. Shear walls in the center core and wings extend to the second floor level only, but column lines are continuous from the foundation to the roof. The foundation consists of a 5 ft. (1.8 m) thick reinforced concrete mat over friction piles driven beneath column lines.

---

[2] At the time of the earthquake, the surface and downhole free-field array was not activated.

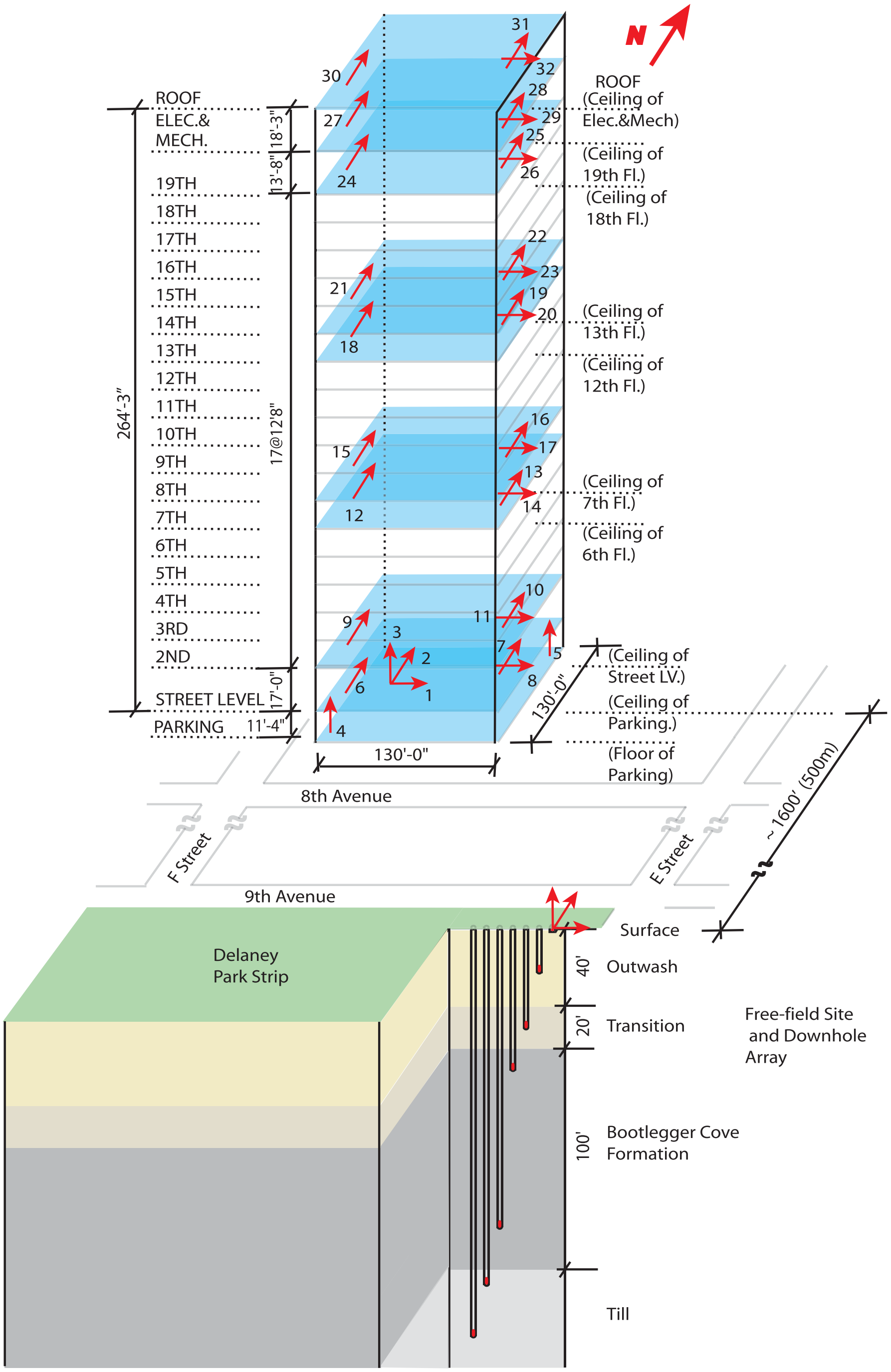

Figure 1. General three-dimensional schematic of the Atwood Building (Anchorage, AK) showing the general dimensions and locations of deployed accelerometers within the structure and at free field with tri-axial downhole accelerometers.

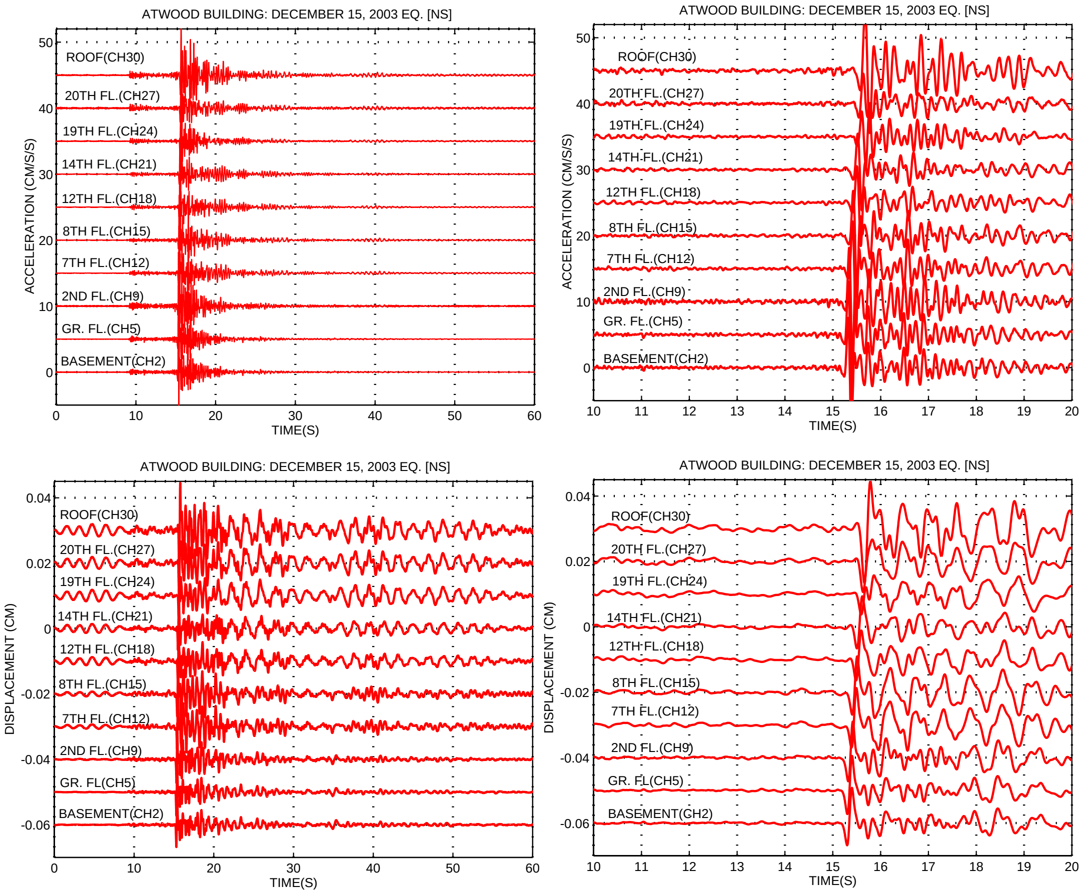

Figure 2. (top and bottom left) Sixty seconds of the responses recorded from the NS oriented accelerometers on the west end of the Atwood Building, (top and bottom right) Ten seconds of the acceleration and displacement responses showing propagation of waves from basement to the roof.

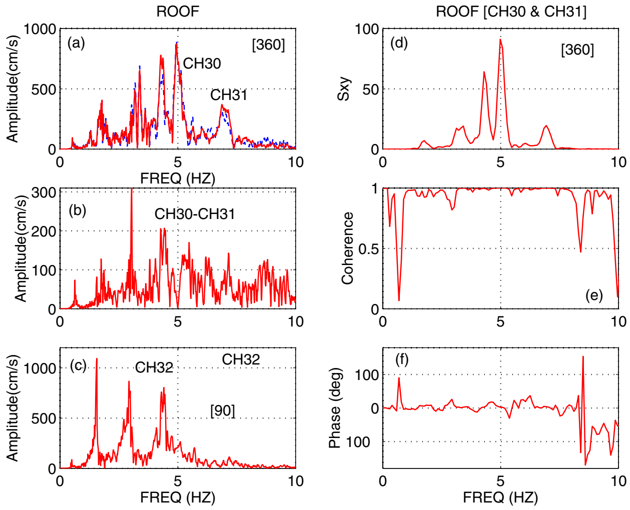

Figure 3. Amplitude spectra of accelerations recorded at the roof from the (a) two parallel translational accelerometers (Channels 30 and 31) in NS direction, (b) difference of Channels 30 and 31, (c) translational accelerometer (Channel 32) in the EW direction, and (d-f) the cross spectrum, coherence and phase angle plots of the two parallel motions (Channels 30 and 31).

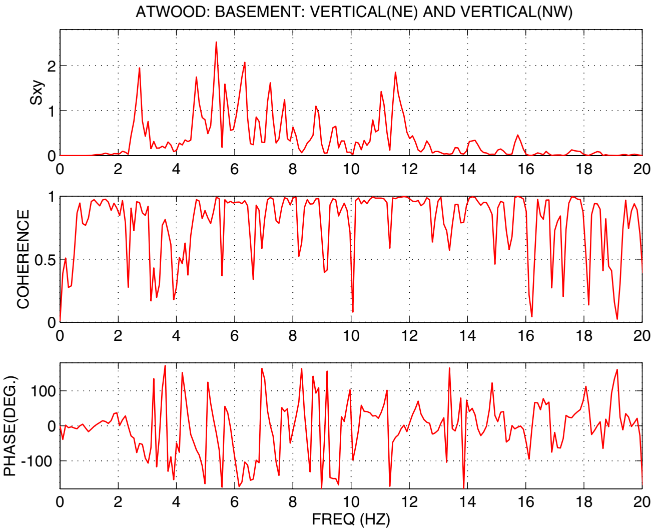

Figure 4. Cross Spectrum, coherence and phase angles of the two vertical motions at the basement.

Based on a relatively recent geologic log and shear wave velocity profile (Gibbs, et al., 1994), the soils at the site consist of artificial fill, soft silty clay (Holocene Bay Mud), and stiff to very stiff undifferentiated deposits composed of numerous layers of clay, loam, sand, and gravel. The layer of Holocene Bay Mud, clearly evident on the shear wave velocity profile shown in Figure 5a, begins at about 16 ft. (5 m) depth and is approximately 10 ft. (3 m) thick. Stiff deposits with shear wave velocity (V_s) of approximately 820 ft/s (250 m/s) extend from below the Holocene Bay Mud to a depth of approximately 80 ft. (24 m). Very stiff Pleistocene deposits with V_s approximately equal to 1300 ft/s (400 m/s) extend to a depth of about 155 ft (48 m). The site transfer function calculated using Haskell's shear-wave propagation method (Haskell, 1953, 1960) using the shear wave velocity profile in Figure 5a is plotted in Figure 5b, and indicates a site frequency at approximately 0.7 Hz.

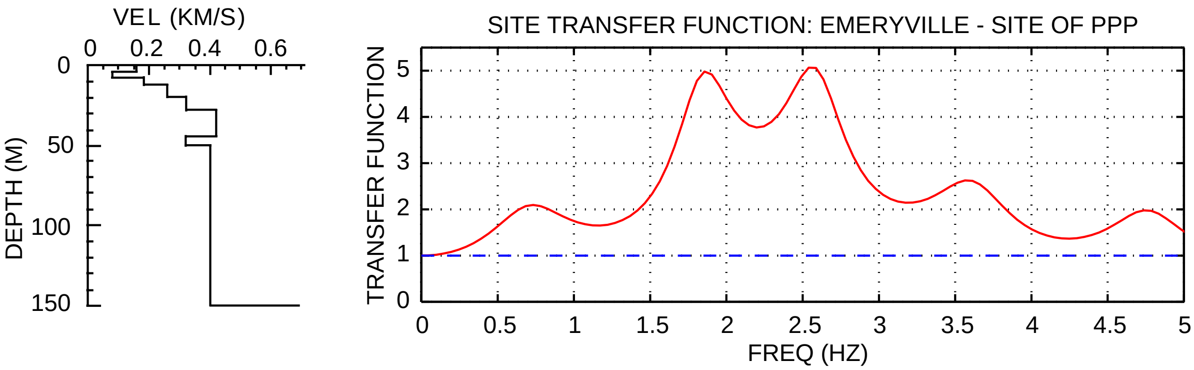

Figure 5. (a-left) Shear wave velocity profile and (b-right) Computed site transfer function

Instrumentation

A three-dimensional schematic of the Pacific Park Plaza Building and its integrated structure, surface, and downhole arrays is shown in Figure 6. The instrumentation scheme is uniquely designed to capture (a) the translational motions of the wings of the building relative to its core, (b) the vertical motions of the mat foundation slab at the ground floor level, and (c) free-field motions at the surface and at a downhole depth of 200 ft (61 m).

A Recorded Earthquake and Preliminary Analyses

The responses of the building and the surface free-field were recorded during the October 17, 1989 Loma Prieta earthquake. Significant research has already been done using these records.

Important features of the particular data set from the Loma Prieta earthquake includes amplified motions (Figure 7) at the site of the building as compared to the motions at Yerba Buena Island (both approximately 100 km from the epicenter of the Loma Prieta earthquake).

Figure 8 shows cross spectra of orthogonal horizontal accelerations at the core of the building roof and ground floor and SFF and their superimposed normalized spectra.

From the earthquake records, a building first mode frequency at 0.38 Hz is clearly identified. Also identified is the site frequency at 0.7 Hz (Safak,and Çelebi,1992 and Çelebi and Safak, 1992, Çelebi, 1998).

Extended data sets from this building include not only the Loma Prieta earthquake response data but also those from forced and ambient vibration tests performed by Stephen et. al (1985) as well as those by Marshall, Phan and Çelebi (1992) and Çelebi, Phan and Marshall (1993). Dynamic characteristics of the building extracted from the data sets are summarized in Table 1 and show considerable differences in the fundamental frequency extracted from strong shaking versus low-amplitude shaking. The differences are attributed to SSI effects during strong shaking (Çelebi, 1998, Kagawa, Aktan and Çelebi, 1993, Kagawa and Al-Khatib, 1993, Kambhatla, Aktan, Kagawa and Çelebi, 1992).

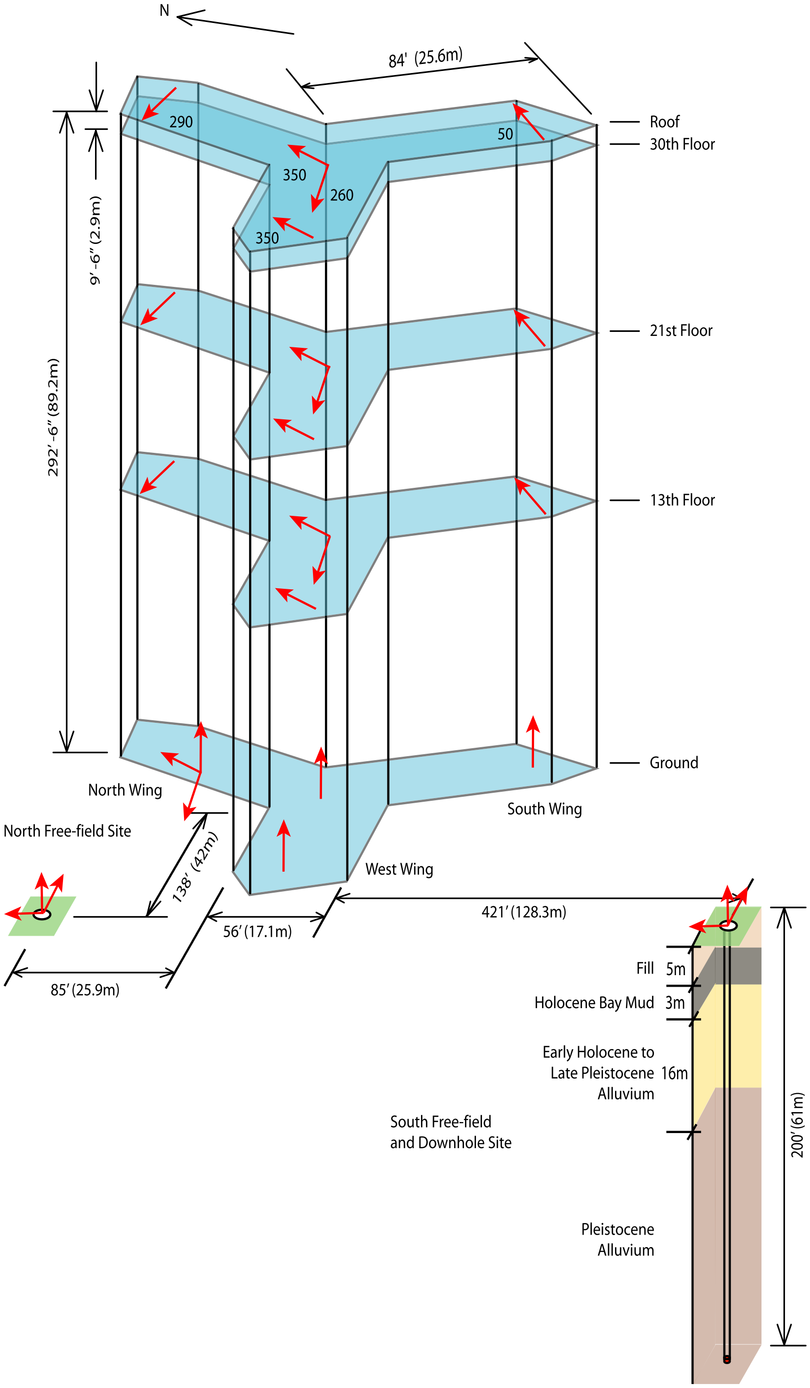

Figure 6. A three-dimensional schematic of the building array with integrated surface and downhole array [Note: The downhole accelerograph was added after the 1989 Loma Prieta earthquake).

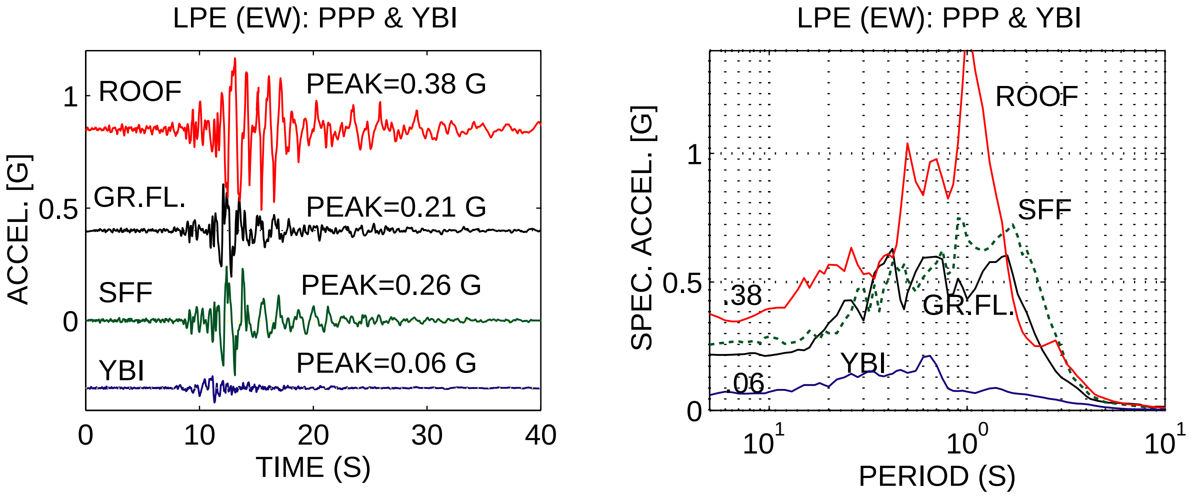

Figure 7. Amplified (EW) motions and their corresponding response spectra (5% damped) at the South Free-Field (SFF), ground floor and roof of the Pacific Park Plaza array as compared to the motions at Yerba Buena Island (YBI).

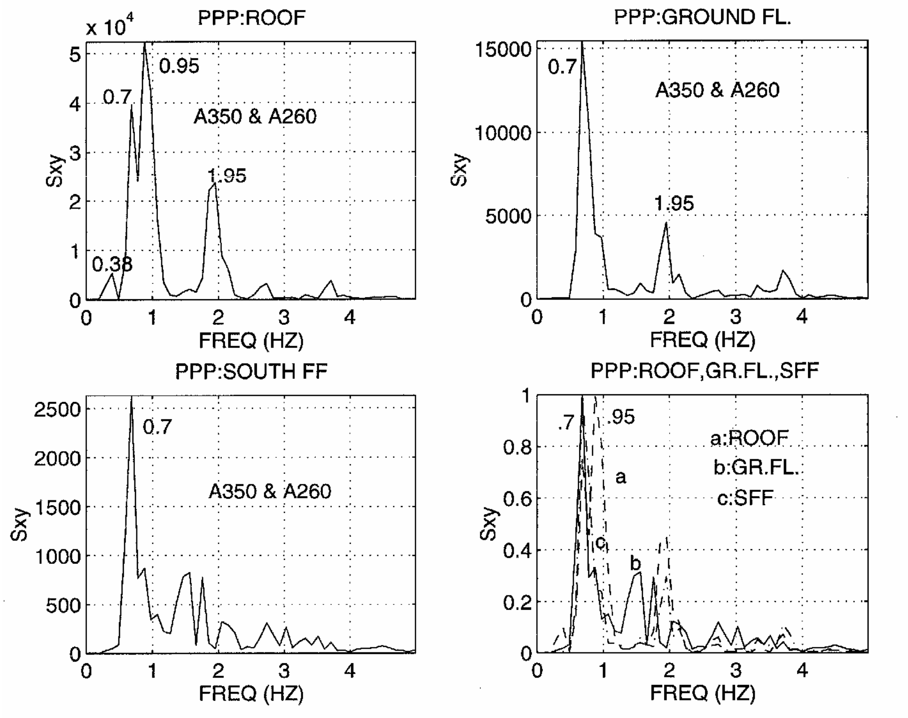

Figure 8. Cross-spectra of roof, ground floor and SFF motions and their superimposed normalized plot (lower right).

Table 1. Dynamic Characteristics of Pacific Park Plaza

		FREQUENCIES (HZ)			DAMPING (%)		
		MODE			MODE		
		1	2	3	1	2	3
1990 AMBIENT TESTS (from Çelebi, Phan and Marshall, 1992)							
N-S		0.48			0.6		
E-W		0.48			3.4		
1989 (LPE) STRONG-MOTION (from Çelebi, Phan and Marshall, 1992)							
N-S		0.38	0.95	1.95	11.6		
E-W		0.38	0.95	1.95	15.5		
1985 FORCED VIBRATION TESTS (from Stephen et.al, 1985)							
N-S		0.590	1.660	3.09	1.7	1.3	2.9
E-W		0.595	1.675	3.12	1.8	1.9	3.2
Torsion		0.565	1.700	3.16	1.5	1.32	1.7
1985 AMBIENT VIBRATION TESTS (from Stephen et.al., 1985)							
N-S		0.586	1.685	3.149	2.6	1.8	0.8
E-W		0.586	1.685	3.125	2.6	1.2	0.4
Torsion		0.586	1.709	3.125	3.8	1.4	1.0
MODAL ANALYSES (Rigid [R] & Flexible [F] Foundation) (from Stephen et.al. 1985)							
N-S	R	0.596	1.666	3.115			
	F	0.595	1.650	3.081			
E-W	R	0.596	1.666	3.115			
	F	0.595	1.650	3.081			
Torsion	R	0.565	1.711	3.275			
	F	0.562	1.686	3.220			

CONCLUSIONS

Two integrated arrays of building and free-field arrays that can be used for soil-structure interaction (SSI) research are introduced. One of these arrays is funded by the Advanced National Seismic System (ANSS), a new initiative managed by the United States Geological Survey. Through this new initiative, 6000 three-channel or equivalent accelerometers are intended to be deployed in seismic urban areas of the United States. In this initiative and numerous scientific meetings, strong recommendations for SSI related deployment were made. The two arrays can be an example for further deployments in building structures to facilitate SSI research. However, very limited data is available from both arrays to facilitate SSI research at this point.

REFERENCES

Çelebi, M., Phan, L. T., and Marshall, R. D., 1993, Dynamic characteristics of five tall buildings during strong and low-amplitude motions, Journal of the Structural Design of Tall Buildings (John Wiley & Sons), v. 2, 1-15, 1993.

Çelebi, M., 1998, Performance of Building structures - A Summary, in The Loma Prieta, California, Earthquake of October 17, 1989 - Building Structures (M. Çelebi, editor), USGS Prof. Paper 1552-C, p. c5-c76.

Stephen, R. M., Wilson, E. L., and Stander, N., 1985, Dynamic properties of a thirty-story condominium tower building, (EERC Report 85--03), Earthquake Engineering Research Center, University of California, Berkeley, Ca., April 1985.

Çelebi, M., and Şafak, E., (1992). ``Recorded Seismic Response of Pacific Park Plaza (Part I--Data and Preliminary Analysis)." ASCE (Journal of Structural Engineering), June 1992.

Şafak, E., and Çelebi, M. (1992). ``Recorded Seismic Response of Pacific Park Plaza (Part II--System Identification)." ASCE (Journal of Structural Engineering), June 1992.

Çelebi, M., Lysmer, J., and Luco, E., (compilers), 1992, Recommendations for a Soil-Structure Interaction Experiment (Report based on a workshop held at San Francisco, CA on February 7, 1992), USGS, OFR: 92-295, April 1992.

Çelebi, M., and Okawa, I. (eds.), 1999, UJNR Workshop on Soil-Structure Interaction - Proceedings of Workshop held on September 1999 at Menlo Park, CA., U.S. Geological Survey OFR 99-142.

COSMOS, 2001, Proceedings, Invited Workshop on Strong-motion Instrumentation of Buildings, Emeryville, Ca. November 2001, Cosmos Publication No: CP-2001/04.

Gibbs, J. F., Fumal, T. E., and Powers, T. J., 1994, Seismic velocities and geologic logs from borehole measurements at seven strong motion stations that recorded the 1989 Loma Prieta, California, earthquake: U.S. Geological Survey Open-File Report 94-222, 104 p.

Haskell, N. A., 1953, The dispersion of surface waves on multilayered media: Bulletin of the Seismological Society of America, v. 43, no. 1, p. 17-34.

Haskell, N. A., 1960, Crustal reflection of plane SH waves, Journal of Geophysical Research, v. 65, no. 12, p. 4147-4150.

Higgins, C. J., 1992 (editor), PROC. NSF Workshop---Experimental Needs for Geotechnical Earthquake Engineering, Albuquerque, New Mexico, November 4-5, 1991.

Iwan, W. D., ed., 1978, Proceedings of the International Workshop on Strong Motion Instrument Arrays, May 1978, Honolulu, Hawaii.

Iwan, W. D., ed., 1981, Proceedings of the U.S. National Workshop on Strong-Motion Earthquake Instrumentation, April 1981, Santa Barbara, California.

Kagawa, T., Aktan, H., Çelebi, M., 1993, Evaluation of soil and structure model using measured building response during the Loma Prieta earthquake: Report of the Dept. of Civil Engineering, Wayne State University, Detroit, Michigan, 169 p.

Kagawa, T., and Al-Khatib, M. A., 1993, Earthquake response of a 30-story building during the Loma Prieta earthquake, in Third Int'l Conf. On Case Histories of Geotechnical Engineering, Univ. of Missourin-Rolla, p. 547-553.

Kambhatla, A., Aktan, H. M., Kagawa, T. and Çelebi, M., 1992, Verification of simple soil-pile foundation-structure models, in Structures Congress '92, ASCE, NY, p. 721-724.

Lee, K. L., W. F. Marcuson, K. H. Stokoe, and F. Y. Yokel, editors, 1978, Research needs and priorities for geotechnical earthquake engineering applications, Workshop at the University of Texas, Austin, June 1978.

Marshall, R. D., Phan, L. T., and Çelebi, M., 1992, Measurement of Structural Response Characteristics of Full-Scale Buildings: Comparison of Results from Strong-Motion and Ambient Vibration Records." NISTIR 4884 (National Institute of Standards and Technology), Gaithersburg, MD.

Page, R., Boore, D. M., Bucknam, R. C., and Thatcher, W. R., 1992, Goals, Options, and Priorities for the USGS Earthquake Hazards Reduction Program: 1991-1995, USGS Circular 1079, February 1992.

Tarquis, F., and Roesset, J., 1988, Structural response and design response spectra for the 1985 Mexico City earthquake: University of Texas, Austin, Texas, Report No. GD89-1, 208p.

Youd, T. L., Steidl, J. H., and Nigbor, R. L., (this volume) , Ground Motion, Pore Water Pressure and SFSI Monitoring at NEES Permanently Instrumented Field Sites