11 WCEE
Copyright © 1996 Elsevier Science Ltd
Paper No. 371. (quote when citing this article)
Eleventh World Conference on Earthquake Engineering
ISBN: 0 08 042822 3

ANALYSES OF SITE LIQUEFACTION USING DOWNHOLE ARRAY SEISMIC RECORDS

Mourad ZEGHAL, Ahmed-W. ELGAMAL,
and Ender PARRA

Rensselaer Polytechnic Institute, Department of Civil Engineering
Troy, NY 12180, USA

ABSTRACT

Seismic downhole-array data provide a unique source of information on actual soil (and overall site) behavior over a wide range of loading conditions that are not readily covered by in-situ or laboratory experimentation procedures. In this paper, free-field downhole array seismic records are employed to identify and model the dynamic response at a Port Island (Kobe, Japan) site. At this site, a four-accelerometer downhole array recorded strong motion response during the recent 1995 Hyogoken-Nanbu earthquake. Actual seismic shear stress-strain histories are directly evaluated from the recorded downhole accelerations. These histories provide valuable insight into the mechanisms and properties of site liquefaction and associated loss of stiffness and strength. A computational simulation, performed based on the identified response properties, shed light on the site pore-pressure buildup mechanisms. The results of this study demonstrate that acceleration histories recorded by downhole arrays represent a valuable direct source of information on site response during seismic excitation.

KEYWORDS

Site, amplification, soil, liquefaction, cyclic mobility, dilation, downhole, Port Island.

INTRODUCTION

Damage due to seismic excitation is often directly correlated to local site conditions. This correlation was evident during recent earthquakes such as those of Mexico City (Seed *et al.* 1987), San Francisco (Seed *et al.* 1990), and Kobe (Bardet *et al.* 1995, Comartin *et al.* 1995, Sitar 1995). The associated mechanisms of ground response are being increasingly documented through a growing worldwide network of sites instrumented with downhole seismic arrays.

Laboratory experimentation on soil liquefaction has provided valuable information on the mechanisms associated with excess pore-pressure buildup (National Research Council 1985). However, for engineering applications, there remains a need to understand and identify the in situ characteristics of soil stiffness and strength degradation due to seismically-induced liquefaction. Downhole acceleration and excess-pore-pressure seismic records furnish direct insight into the response mechanisms of instrumented layers within the ground. In addition, these records offer a solid basis for calibration of in-situ and laboratory testing procedures, and refinement of empirical and computational predictive techniques.

The authors and co-workers conducted a number of studies to analyze the recorded downhole seismic response

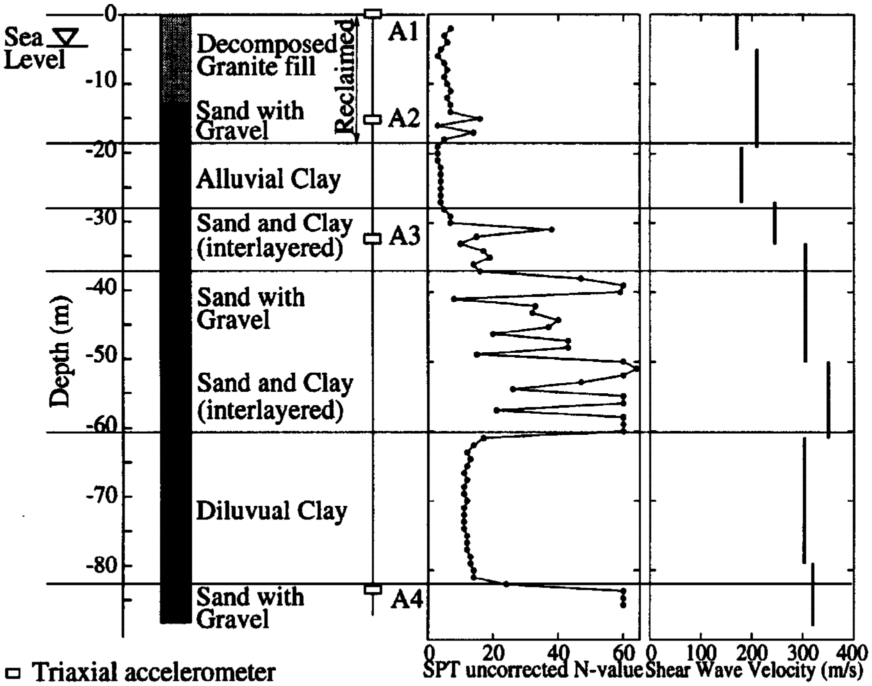

Figure 1: Soil profile and instrumentation at the Port Island site (after Iwasaki 1995).

at Lotung (Taiwan; Tang 1987), Wildlife Refuge (California, USA; Youd and Wieczorek 1984), and Port Island (Kobe, Japan; Iwasaki 1995) sites. Simple identification procedures were employed to: (1) evaluate shear wave propagation characteristics, (2) identify site resonant frequencies and modal configurations (Lotung), and (3) estimate the associated seismic shear stress-strain histories. These stress-strain histories were used to: (1) study variation of soil shear stiffness and material damping characteristics with shear strain amplitude, (2) assess the effects of soil stiffness and strength degradation due to liquefaction, and (3) analyze the involved mechanisms of large strain soil deformations. A detailed description of the conducted studies is reported in Zeghal and Elgamal (1993, 1994), Elgamal *et al.* (1995, 1996), and Zeghal *et al.* (1995). This paper summarizes a number of major findings pertaining to in situ liquefaction, especially at Port Island and Wildlife Refuge sites during the 1995 Hyogoken-Nanbu and 1987 Superstition Hills earthquakes, respectively.

PORT ISLAND, KOBE JAPAN

Port Island is a reclaimed island located on the west-south side of Kobe, Japan. Soil in the reclaimed layer (Fig. 1) consisted of decomposed weathered granite fill with grain sizes ranging from gravel and cobble-sized particles, to fine sand (O'Rourke 1995, Sitar 1995). A downhole accelerometer array was installed at the North-West corner of Port Island in August 1991 (Iwasaki 1995). The array consisted of triaxial accelerometers located at the surface, 16 m, 32 m, and 83 m depths (Fig. 1). All instruments were linked to a common triggering mechanism, and hence the recorded earthquake data were synchronized. The array location is close to an improved-ground (vibro-rod method) warehouse site (Sitar 1995).

The downhole array site consists of (Fig. 1, Iwasaki 1995): (1) a reclaimed, loose surface layer down to about 19 m depth, (2) an alluvial clay layer between 19 m and 27 m depth, (3) sand and sand with gravel strata interlayered with clay between 27 m and 61 m depth, (4) a diluvial clay layer between 61 m and 82 m depth, and (5) sand with gravel layers interlayered with clay starting at about 82 m depth. The water table is located at 4 m depth approximately. In the upper 20 m layer (Fig. 1), low standard penetration test (SPT) blow counts prevailed (average uncorrected N-values of about 6 blows/ft). Such low values in a granular fill are indicative of high liquefaction susceptibility (Seed *et al.* 1983).

In January 17, 1995, the Port Island site was shaken by the Hyogoken-Nanbu earthquake (moment magnitude $M_w = 6.9$). Subsequent field investigations showed abundant evidence of site liquefaction. Ground settlements

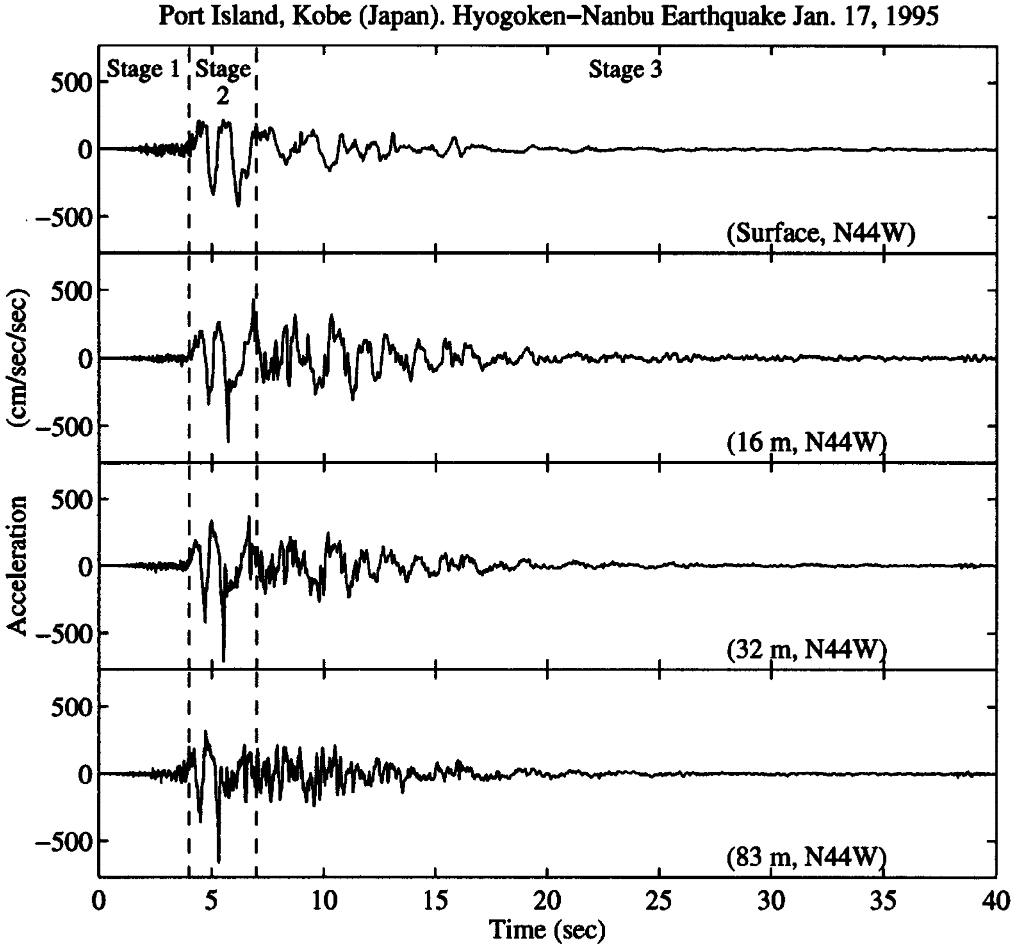

Figure 2: Port Island site N44W accelerations at ground surface and downhole (at 16 m, 32 m and 83 m depths, after Iwasaki 1995).

(as much as 0.7 m), lateral spreadings and ground fissures (of 2–3 m along quay walls) were observed (O'Rourke 1995). Outside the improved area near the array, settlements, fissures, and sand ejecta were widespread (Sitar 1995). Peak horizontal accelerations (Fig. 2) were in excess of 0.5 g throughout the 16–83 m depths. Soil liquefaction at shallower depths appears to have precluded such high acceleration from occurring at the ground surface. Earlier site specific liquefaction studies had suggested adequate resistance to liquefaction for ground acceleration levels below 0.15-0.20 g (Sitar 1995).

The recorded downhole accelerations were characterized by (Fig. 2): (1) an initial phase of low amplitude vibrations at all depths (Stage 1), (2) a strong shaking phase during the 4 s to 7 s (Stage 2) time window (peak accelerations exceeded 0.5 g at all locations, except at the ground surface), and (3) low amplitude vibrations at the surface, and no obvious signs of deamplification or period elongation at 16 m depth and below during the 7 s to 40 s (Stage 3) time window.

SHEAR STRESS-STRAIN HISTORIES

A simple identification procedure, proposed earlier in basic form for shake-table studies (Koga and Matsuo 1990), was developed and used to study the downhole earthquake response at Lotung (Zeghal and Elgamal 1993, Zeghal *et al.* 1995). Using a shear beam model to describe site seismic lateral response, shear stress $\tau(z,t)$ at any level z may be expressed as:

$$\tau(z,t) = \int_0^z \rho \ddot{u}(\zeta,t)d\zeta \tag{1}$$

in which ρ = mass density, and $\ddot{u}(\zeta,t)$ = absolute acceleration at level ζ. Utilizing linear interpolation between downhole accelerations, the discrete counterpart of shear stresses at levels z_i and $(z_{i-1} + z_i)/2$ reduces to:

$$\tau_i(t) = \tau_{i-1}(t) + \rho\frac{\ddot{u}_{i-1} + \ddot{u}_i}{2}\Delta z_{i-1}, \; i = 2, 3, \cdots \tag{2}$$

$$\tau_{i-1/2}(t) = \tau_{i-1}(t) + \rho\frac{3\ddot{u}_{i-1} + \ddot{u}_i}{8}\Delta z_{i-1}, \; i = 2, 3, \cdots \tag{3}$$

in which subscripts i and $i-1/2$ refer to levels z_i (of the i^{th} accelerometer) and $(z_{i-1}+z_i)/2$ (halfway between accelerometers i and and $(i-1)$) respectively, $\tau_i(t) = \tau(z_i, t), \tau_1 = \tau(0, t) = 0$ at the stress-free ground surface, $\ddot{u}_i = \ddot{u}(z_i, t)$, and Δz_i is spacing interval between accelerometers. These stress estimates (Eqs. 2 and 3) are second order accurate. The corresponding second-order accurate shear strains may be expressed as:

$$\gamma_i(t) = \frac{1}{\Delta z_{i-1} + \Delta z_i}\left((u_{i+1} - u_i)\frac{\Delta z_{i-1}}{\Delta z_i} + (u_i - u_{i-1})\frac{\Delta z_i}{\Delta z_{i-1}}\right), \; i = 2, 3, \cdots \tag{4}$$

$$\gamma_{i-1/2}(t) = \frac{u_i - u_{i-1}}{\Delta z_{i-1}}, \; i = 2, 3, \cdots \tag{5}$$

in which $u_i = u(z_i, t)$ is absolute displacement (evaluated through double integration of the recorded acceleration history $\ddot{u}(z_i, t)$).

Using the recorded downhole accelerations (Fig. 2) and Eqs. 3–5, shear stress and strain histories were evaluated at 8.0 m, 16.0 m, 24.0 m, 32.0 and 57.5 m depths (Fig. 3). Two remarkably different response patterns were exhibited at the site. Below 32 m depth, the shear stress-strain histories showed an essentially linear soil response, with no appreciable reduction in soil stiffness. On the other hand, at shallow depths, the stress-strain histories (Fig. 3) indicated: (1) a noticeable reduction in stiffness with a slight shear strain hardening at 24.0 m and 32.0 m depths, and (2) an abrupt sharp loss of stiffness and reduction of yield strength near the surface at 8.0 m depth. At this shallow elevation (8.0 m depth), soil response was marked by a clear and sharp reduction in stiffness during the 4–7 s time window. Thereafter, despite the reduction in shear stresses, shear strain amplitudes remained high (Fig. 3). This stress-strain behavior clearly documents the loss of soil stiffness associated with liquefaction of the site upper strata, as excess pore pressures presumably reached the value of initial effective vertical stress.

As no excess-pore water pressure data were recorded at Port Island, a computational simulation was conducted to assess the corresponding mechanisms of excess pore pressure generation. An undrained effective-stress finite element analysis of the site amplification was conducted (Parra 1996). Soil response was modeled using multi-surface plasticity theories. The employed soil model parameters were derived through nonlinear optimization, so as to achieve the best possible match between the identified stress-strain responses of Fig. 3 and the computed counterparts. The N44W earthquake record at 83 m depth was employed as input excitation. A close agreement was found between the computed and recorded accelerations (Fig. 4). The computed excess pore pressure time history at 8 m depth (Fig. 4) showed that an abrupt rise in excess pore pressure occurred mainly during the phase of strongest excitation (4–7 s), causing the soil layer to liquefy, as stipulated earlier.

The identified liquefaction mechanisms at the Port Island site contrast with those observed at the Wildlife Refuge (Imperial County, California) site (Zeghal and Elgamal 1994). The Wildlife site was instrumented in 1982 by the United States Geological Survey (Youd and Wieczorek 1984) with two triaxial accelerometers (one at the surface and the other at 7.5 m depth) and six piezometers; with all instruments linked to a common triggering mechanism. On November 24, 1987, this site liquefied during the $M_w = 6.6$ Superstition Hills earthquake (Holzer *et al.* 1989).

Fig. 5 depicts the NS (North-South) components of the recorded accelerations at ground surface and 7.5 m depth; and the associated excess pore-water pressure measured at 2.9 m depth. The corresponding NS shear stress-strain (using Eqs. 3 and 5) and effective path histories at 2.9 m depth (location of piezometer P5) are shown in Fig. 6 ($\sigma'_v = \sigma_v - p$, where p is excess pore pressure measured by P5, and σ_v is total vertical stress at P5). The shear stress-strain history depicts a mechanisms of progressive loss of site stiffness. The site experienced a clear and gradual stiffness degradation associated with increase in pore water pressure. Cycles of

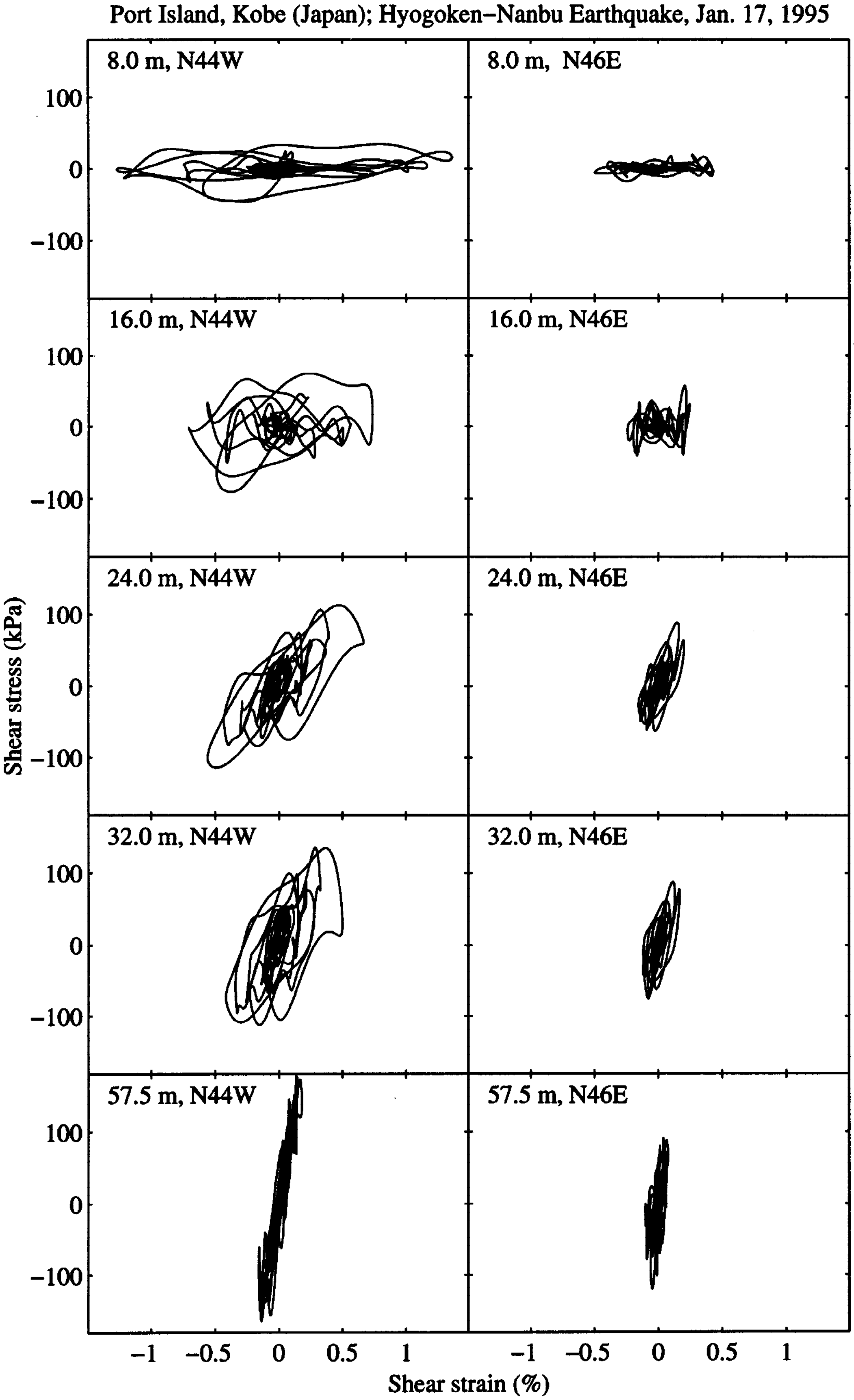

Figure 3: Port Island site shear stress-strain histories at 8.0 m, 16.0 m, 24.0 m, 32.0 m, and 57.5 m depths.

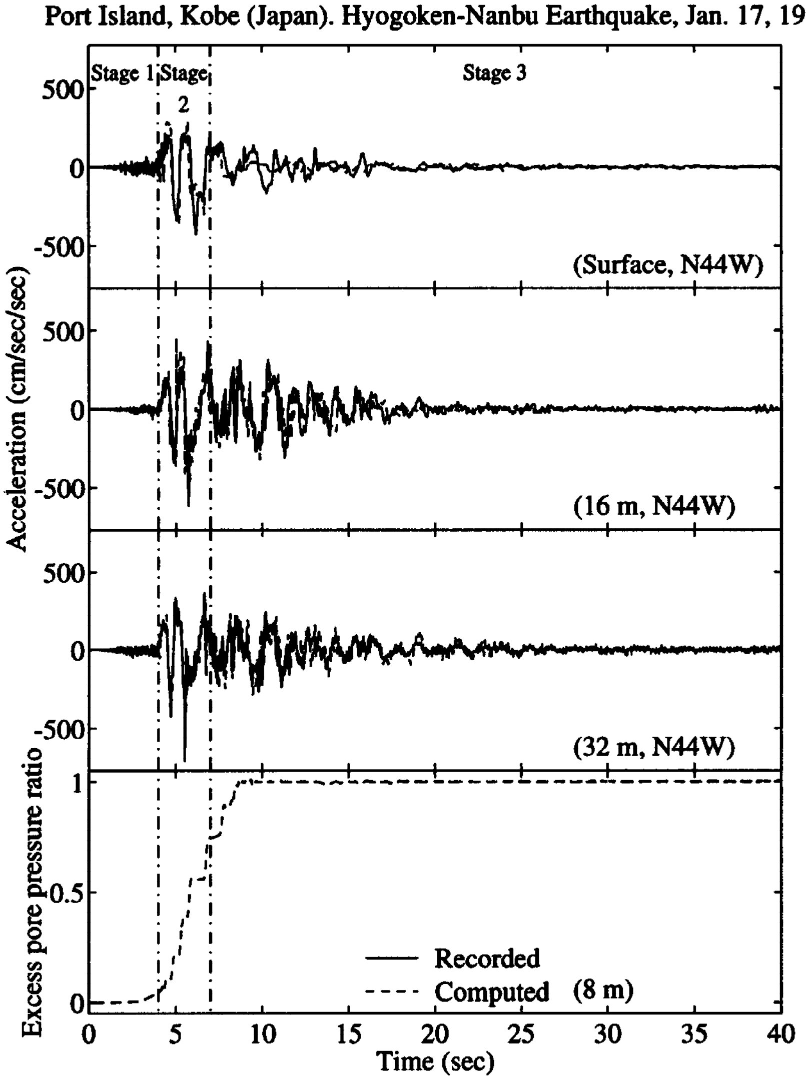

Figure 4: Port Island recorded and computed accelerations at surface and downhole (16 m and 32 m depths), and computed excess pore pressure ratio at 8 m depth.

large shear strain were developed following liquefaction. These cycles were marked by shear stress hardening at large strains (Fig. 6), that occurred simultaneously with instantaneous pore pressure drops (Figs. 5 and 6). At low effective confining pressures (high excess pore pressures), the corresponding effective stress-path (Fig. 6) clearly exhibited a reversal of behavior from contractive to dilative as the line of phase transformation was approached. This case history clearly shows for the first time, an in-situ mechanism of shear stress hardening at large strains during liquefaction. This hardening phenomenon (at large shear strain excursions during liquefaction) is of paramount importance in restricting the extent of lateral deformations.

CONCLUSIONS

The conducted studies showed that downhole acceleration records offer a direct source of information for: (1) evaluating site seismic shear stress-strain histories, and (2) assessing the mechanisms of site liquefaction and associated stiffness degradation. At the Port Island site, the estimated stress-strain histories showed that: (1) site stiffness and strength sharply decreased with excess pore pressure buildup, (2) at high excess pore pressure levels, site response was characterized by large strains and small stresses. At the Wildlife Refuge site, significant shear strength evolved at large shear strains during liquefaction, due to dilation. The employed identification techniques were shown to provide valuable information of direct use for calibration of computational modeling procedures.

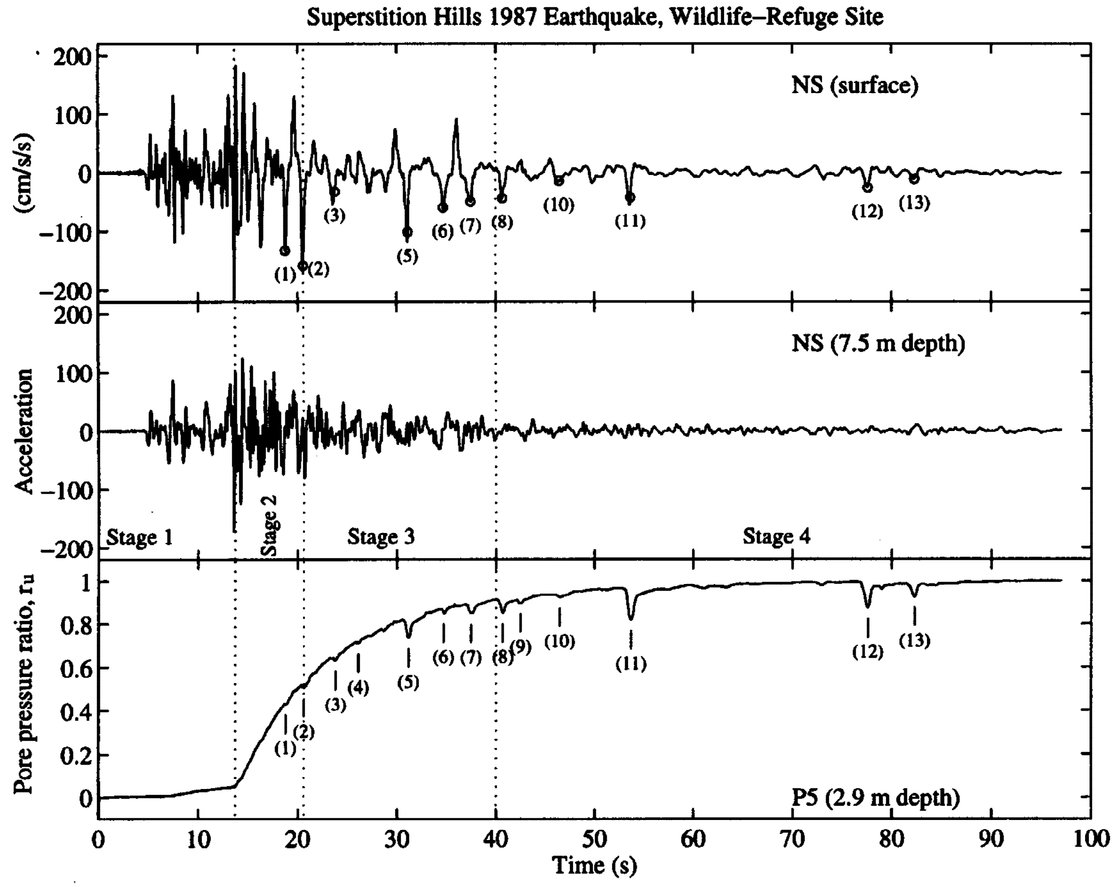

Figure 5: Wildlife Refuge site NS surface and downhole (7.5 m depth) accelerations, and associated pore water pressure (at 2.9 m depth) during the Superstition Hills 1987 earthquake.

ACKNOWLEDGMENTS

This research was supported by the United States Geological Survey (grant No. 1434-94-G-2397) and the National Science Foundation (grant No. MSS-9057388). The research of E. Parra was supported by INTEVEP, SA, Venezuela. The Port Island downhole acceleration data were provided by the Committee of Earthquake Observation and Research in the Kansai Area, Japan, with the help of Dr. Y. Iwasaki.

REFERENCES

Bardet, J. P., Oka, F., Sugito, M., and Yashima, A. (1995). "The Great Hanshin Earthquake Disaster", *Preliminary Investigation Report*, University of Southern California, Los Angeles, California.

Comartin, C. D., Greene, M., and Tubbesing, S. K., eds. (1995). "The Hyogo-Ken Nanbu Earthquake, Great Hanshin Earthquake Disaster, January 17, 1995," *Preliminary Reconnaissance Report*, Earthquake Engineering Research Institute, California.

Elgamal, A.-W., Zeghal, M., Tang, H. T., and Stepp, J. C. (1995). "Lotung Downhole Array. I: Evaluation of Site Dynamic Properties," *Journal of Geotechnical Engineering*, ASCE, Vol. **121**, No. 4, 350-362.

Elgamal, A.-W., Zeghal, M., and Parra, E. (1996). "Liquefaction of Artificial Island in Kobe, Japan," *Journal of Geotechnical Engineering*, ASCE, Vol. **122**, No. 1, 39-49.

Holzer, T. L., Youd T. L., and Hanks T. C. (1989). "Dynamics of Liquefaction During the 1987 Superstition Hills, California, Earthquake," *Science*, Vol. **244**, 56-59.

Iwasaki, Y. (1995). "Geological and Geotechnical Characteristics of Kobe Area and Strong Ground Motion Records by 1995 Kobe Earthquake, Tsuchi-to-Kiso," *Japanese Society of Soil Mechanics and Foundation Engineering*, Vol. **43**, No. 6, 15-20 (in Japanese).

Koga, Y. and Matsuo, O. (1990). "Shaking Table Tests of Embankments Resting on Liquefiable Sandy Ground," *Soils and Foundations*, Vol. **30**, No. 4, 162-174.

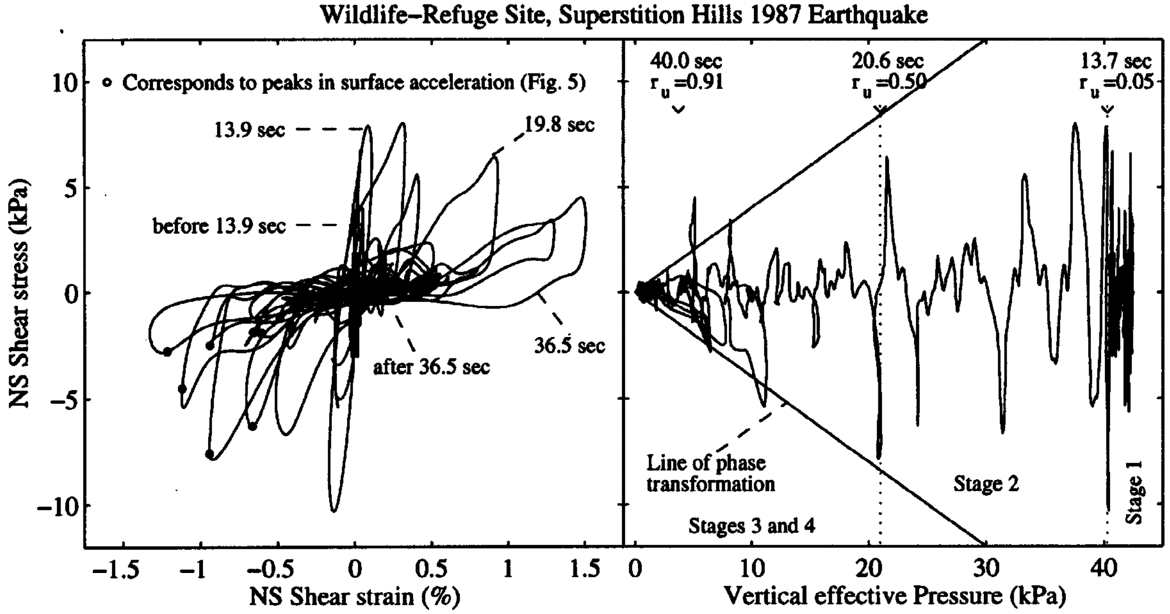

Figure 6: Wildlife Refuge site NS shear stress-strain and effective stress-path histories during the Superstition Hills 1987 earthquake.

National Research Council (1985). *Liquefaction of Soils During Earthquakes*, Committee on Earthquake Engineering, National Academy press, Washington D. C.

O'Rourke, T. D. (1995). "Geotechnical Effects," *Preliminary Report from the Hyogoken-Nanbu Earthquake of January 17, 1995*, National Center for Earthquake Engineering Research Bulletin, SUNY, Buffalo, Vol. **9**, No. 1.

Parra, E. (1996). "Numerical Modeling of Liquefaction and Lateral Ground Deformation including Cyclic Mobility and Dilative Behavior in Soil Systems", *Ph.D. dissertation*, Department of Civil Engineering, Rensselaer Polytechnic Institute, in progress.

Seed, H. B., Idriss, I. M., and Arango, I. (1983). "Evaluation of Liquefaction Potential Using Field Performance Data," *Journal of Geotechnical Engineering*, ASCE, Vol. **109**, No. 3, 458-482.

Seed, H. B., Romo, M. P., Sun, J., Jaime, A., and Lysmer, J. (1987). "Relationship Between Soil Conditions and Earthquake Ground Motions in Mexico City in Earthquake of Sept. 19, 1985," *Report No. EERC-87-15*, Earthquake Engineering Research Center, University of California, Berkeley.

Seed, R. B., Dickenson, S. E., Riemer, M. F., Bray, J. D., Sitar, N., Mitchell, J. K., Idriss, I. M., Kayen, R. E., Kropp, A., Hander, L.F. Jr., and Power, M. S. (1990). "Preliminary Report on the Principal Geotechnical Aspects of the October 17, 1989, Loma Prieta Earthquake,"*Report No. EERC-90-05*, Earthquake Engineering Research Center, University of California, Berkeley.

Sitar, N., Ed. (1995). "Geotechnical Reconnaissance of the Effects of the January 17, 1995, Hyogoken-Nanbu Earthquake Japan," *Report No. UCB/EERC-95/01*, Earthquake Engineering Research Center, Berkeley, California.

Tang, H. T. (1987). "Large-Scale Soil Structure Interaction," *Report No. NP-5513-SR*, Electric Power Research Institute, Palo Alto, California.

Youd, T. L. and Wieczorek, G. F. (1984). "Liquefaction During 1981 and Previous Earthquakes Near Westmorland California," *Open-File Report 84-680*, U.S. Geological Survey.

Zeghal, M. and Elgamal, A.-W., (1993). "Lotung Site: Downhole Seismic Data Analysis," *Report*, Department of Civil Engineering Rensselaer Polytechnic Institute (to appear as Electric Power Research Institute Report TR-106093).

Zeghal, M. and Elgamal, A.-W. (1994). "Analysis of Site Liquefaction Using Earthquake Records," *Journal of Geotechnical Engineering*, ASCE, Vol. **120**, No. 6, 996-1017.

Zeghal, M., Elgamal, A.-W., Tang, H. T., and Stepp J. C. (1995). "Lotung Downhole Array. II: Evaluation of Soil Nonlinear Properties," *Journal of Geotechnical Engineering*, ASCE, Vol **121**, No. 4, 363-378.