A REVIEW OF SITE SEISMIC RESPONSE USING VERTICAL ARRAYS

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SUMMARY

Vertical (downhole) sensor arrays are deployed worldwide at seismically active regions to record soil and overall site responses to earthquake excitations. Such arrays have already recorded a large body of benchmark earthquake case histories; over a wide range of loading conditions that are not readily covered by in-situ or laboratory experimentation procedures. This paper presents a survey of seven unique case-history sites, along with a review of the techniques used in analyses of downhole seismic records. These techniques include correlation and spectral analyses, stress-strain imaging, and system identification procedures. Spectral techniques were used to evaluate shear wave propagation characteristics, variation of shear wave velocity with depth, and site resonant frequencies and modal configurations. Stress-strain imaging is a newly developed technique used to evaluate seismic shear stress-strain histories directly from recorded downhole accelerations. System identification procedures were employed to estimate soil stiffness and damping parameters, and to calibrate computational models of seismic site response. These various studies provided valuable insights and documented: (1) vertical wave propagation and site resonance mechanisms, (2) characteristics of site amplification for soft and stiff soil formations, and (3) cyclic soil behavior during liquefaction and associated loss of stiffness and strength. At present, downhole-array data offer a most effective means for calibration and verification of predictive computational tools of site seismic response.

INTRODUCTION

Seismic motion and ground failure are directly correlated to local site conditions. The effects of surfacial soil strata were evident during recent major earthquakes, such as the 1989 Loma Prieta and the 1995 Kobe events, and manifested in the form of motion amplification and liquefaction-induced ground deformations. These effects often have costly disastrous consequences in terms of structural damage. In-situ testing procedures currently provide convenient means of measuring soil low-strain dynamic properties such as shear wave velocity. At larger strain levels, soil properties are often evaluated through laboratory testing [e.g., NRC 1985]. However, due to limitations in reproducing the in-situ state of stress, seismic loading histories, site stratification conditions, and appropriate boundary conditions, there is a consensus that experimental results may not fully reflect the actual site behavior. Thus, a number of salient mechanisms of site response to seismic excitations are still not fully comprehended, such as those associated with liquefaction induced deformation and stiffness and strength degradation. In this regard, seismic downhole-array records 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.

The dynamic characteristics of ground response are being increasingly documented through a growing set of worldwide sites instrumented with vertical downhole seismic arrays. In the United States, an early down-hole data set was recorded at Union Bay in Seattle, Washington [e.g., Dobry *et al.* 1971]. This data was employed to verify site amplification procedures, and analyze the response of peat and clay deposits in Seattle. In Japan, an array of two surface and two downhole seismometers was installed on the premises of Tokyo Station, and recorded a set of seven earthquakes in the late 1950's [Shima 1962]. Using these earthquake records, site

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resonance and damping characteristics were estimated [Dobry *et al.* 1971, Shima 1962]. These early efforts were followed by more comprehensive array installations, such as at Chiba, Lotung, Hualien, Port Island, and Treasure Island sites. Since the 1980's, data from downhole seismic arrays that include pore-pressure piezometers became increasingly available (e.g., Wildlife Refuge and Lotung sites). Such data sets offer a more complete picture of site response, especially when the potential for soil liquefaction exists. At present, numerous downhole arrays are in operation in seismically active regions worldwide.

This review paper presents a set of unique vertical-array sites, namely Chiba, Lotung, Hualien, Garner Valley, Treasure Island, Wildlife-Refuge, and Port Island, along with a survey of some of the techniques used in analysis and identification of ground seismic deformation, liquefaction and associated stiffness and strength degradation.

CHIBA, JAPAN

The prospect for conducting 3-dimensional (3D) studies using downhole array data is illustrated by the Chiba dense array [Katayama *et al.* 1990]. This array is located at Chiba Experiment Station of the University of Tokyo, Japan. Ground surface at the array location is essentially flat and the site is dry. Geological material consists of a top loam layer 4-5 m in thickness, followed by a 4 m thick clayey layer.A sand layer lies under this clayey stratum. Site instrumentation included a dense network of downhole accelerometers, that constitute a system of 9 vertical arrays extending to a 40 m depth (Fig. 1). Extensive data was recorded by the Chiba array (nearly 160 earthquake events). Most of these events produced low shaking levels with amplitudes below 0.05 g. However, peak ground accelerations of about 0.1g were recorded during one event, and 0.3 g during another. The recorded data was used to conduct numerous valuable studies including back-calculation of the 3D seismic strain field [e.g., Katayama *et al.* 1990, Farjoodi *et al.* 1983], site amplification analyses, and orientation error (also known as azimuthal error) analyses of the buried accelerometers.

Three-dimensional seismic strains. Farjoodi *et al.* [1983] used finite element interpolations to estimated 3D seismic strains at Chiba. For every tetrahedron, defined by a set of 4 non-coplanar accelerometers (Fig. 1), the displacement field may be expressed as follows: $u_i = \sum_{A=1}^{4} N_A d_{Ai}$, ($i = 1, 2, 3$), in which $N_A = N_A(x_i)$ is the finite element shape function associated with tetrahedron node A , d_{Ai} is the i^{th} displacement component at node A , and x_i ($i = 1, 2, 3$) are 3D Cartesian coordinate components. At any recording station, the dynamic component of earthquake displacement, d_{Ai} , may be evaluated through double time integration of the recorded accelerations. Thus, the strain field, ε_{ij} , within the tetrahedron is given by:

$$\varepsilon_{ij} = \sum_{A=1}^{4} \frac{1}{2} \left(\frac{\partial N_A}{\partial x_j} d_{Ai} + \frac{\partial N_A}{\partial x_i} d_{Aj} \right) \tag{1}$$

Farjoodi *et al.* [1983] evaluated the Chiba site seismic strain field using linear finite element shape functions. In general, the calculated strains were found to be in good agreement with those measured in-situ by displacement and strain instruments.

LOTUNG, TAIWAN

The U.S. Electric Power Research Institute in cooperation with the Taiwan Power Company conducted a Large-Scale Seismic Test (LSST) at a site near Lotung [Tang 1987]. Two models (1/4-scale and 1/12-scale) of a nuclear-plant containment structure were constructed on a flat and vast alluvium basin (in the vicinity of seismically active faults). Soil at this site consisted predominantly of interlayered silty-sand and sandy-silt; and ground-water level was at or within 1 m of ground surface. Extensive instrumentation was deployed to record both structural and ground seismic responses. The ground instrumentation included (Fig. 2) three linear surface arrays (arms 1, 2, and 3), and two downhole arrays (DHA and DHB) that extended to a depth of 47 m below ground surface [Tang 1987]. Eighteen earthquakes were recorded during the period 1985-1986 [Tang 1987]. This wealth of data constituted a basis for a number of valuable research efforts. Chang *et al.* [1996] evaluated equivalent-linear dynamic shear moduli from the recorded downhole earthquake accelerations. The identified reduction in shear modulus, as a function of effective shear strain, was shown to be in agreement with laboratory test data, and provided evidence of nonlinear soil behavior during earthquake excitation. A number of other notable studies were also conducted to document nonlinear site amplification at Lotung. Loh and Yeh [1992] proposed a system identification method to estimate the hysteretic soil response parameters. Shen *et al.* [1991] computed the Lotung site seismic response and evaluated excess pore pressures during three different LSST earthquakes. Finally, the authors and co-workers used correlation, spectral and stress-strain imaging techniques, along with nonlinear response modeling to identify the soil dynamic parameters and evaluate the Lotung site seismic performance. In the following, some of these analysis procedures are briefly reviewed.

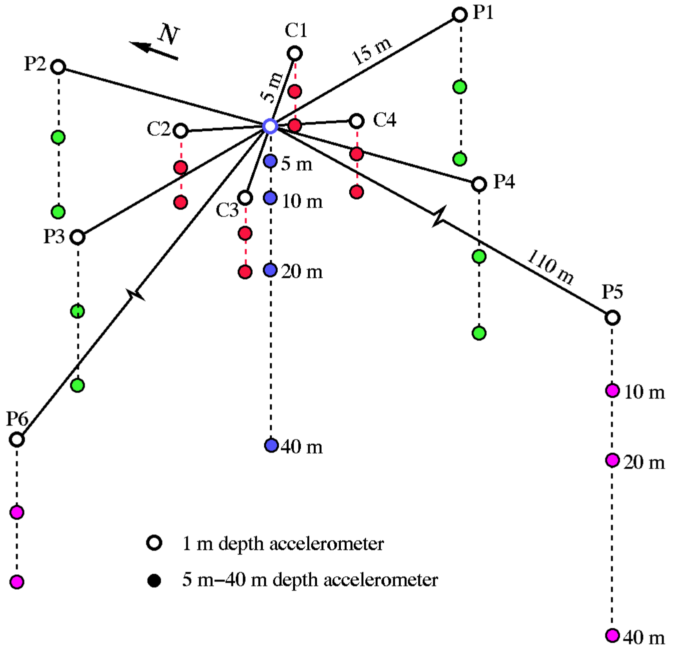

Figure 1: Three-dimensional array at Chiba, Japan [Katayama 1990].

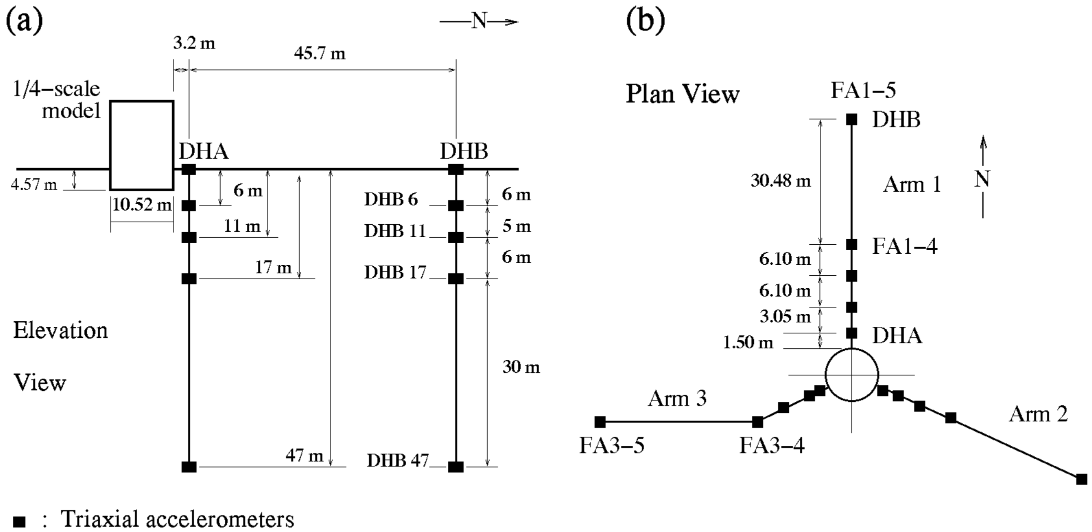

Figure 2: Instrumentation of Lotung experiment site [Tang 1987]: (a) downhole array; (b) surface array.

Correlation and spectral analyses. Cross correlation techniques were employed to evaluate average shear wave velocity between downhole stations, and to investigate shear-wave vertical propagation characteristics [Zeghal and Elgamal 1993, Elgamal *et al.* 1995]. This type of analysis is based on the notion that the cross-correlation function between two downhole acceleration histories recorded at stations i and j, reaches a major peak at a time delay $t = t_d$, where t_d is time for seismic waves to travel from station i to station j. Thus, the apparent velocity v_a of wave propagation between stations i and j may be estimated as: $v_a = d / t_d$, in which d is the known distance between stations i and j. For situations of nearly vertical shear wave propagation, the actual shear wave velocity is practically equal to v_a. At Lotung, this commonly adopted assumption of vertical wave propagation (in numerical studies) was found to be valid from a practical point of view [Zeghal and Elgamal 1993, Elgamal *et al.* 1995].

Cross spectral analyses were used to identify the resonant site characteristics [Zeghal and Elgamal 1993, Elgamal *et al.* 1995]. The amplitude of cross-spectrum energy function $s_{a_i a_j}(f)$ of downhole accelerations $a_i(t)$

and $a_j(t)$, peaks at either a resonant or a dominant input frequency. In general, such peaks represent a resonance if the corresponding phase-angle approaches 0^o or 180^o. The relative displacement of the k^{th} natural mode Φ_k (of frequency f_k), at the i^{th} sensor location may be approximated by:

$$\Phi_k(z_i) = \pm\sqrt{s_{a_i a_i}(f_k)} \tag{2}$$

where $s_{a_i a_i}(f_k)$ is $a_i(t)$ auto-spectral density function, and z_i is depth coordinate of $a_i(t)$. Finally, the phase angle at a resonant frequency may be used to determine the relative direction of motion at each accelerometer location.

Shear stress-strain imaging and soil dynamic properties. Using a shear beam model to describe lateral site response, seismic shear stress at level z_i may be expressed as [Zeghal and Elgamal 1993, Zeghal *et al.* 1995]:

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

in which subscript i refers to levels z_i (of the i^{th} accelerometer), $\ddot{u}_i(t) = \ddot{u}(z_i, t)$ is acceleration at level z_i, and Δz_i is spacing interval between accelerometers. The corresponding shear strains are given by:

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

in which $u_i(t) = u(z_i, t)$ is absolute displacement (evaluated through double integration of the recorded acceleration history $\ddot{u}(z_i, t)$. This technique was employed to evaluate seismic shear stress strain histories at Lotung, for each soil layer located between downhole accelerometers [Zeghal and Elgamal 1993, Zeghal *et al.* 1995]. These histories revealed two salient response features: (1) stiffness reduction due to the increase in shear strain amplitude (Fig. 3), and (2) stiffness reduction due to pore pressure buildup.

These changes in site stiffness may also be assessed from the variation of shear modulus with time during seismic excitation. Within a given time window (t_i, t_f) during an earthquake, the shear stress-strain relationship may be defined by $\tau = G\gamma + \eta\dot{\gamma}$, in which G and η are equivalent-linear shear modulus and viscous damping. These stiffness and damping parameters for the time window (t_i, t_f) may be estimated as follows [Elgamal *et al.* 1996]:

$$G(t_i, t_f) = \frac{\int_{t_i}^{t_f} \tau\gamma dt \int_{t_i}^{t_f} \dot{\gamma}\dot{\gamma} dt - \int_{t_i}^{t_f} \tau\dot{\gamma} dt \int_{t_i}^{t_f} \gamma\dot{\gamma} dt}{\int_{t_i}^{t_f} \gamma\gamma dt \int_{t_i}^{t_f} \dot{\gamma}\dot{\gamma} dt - \left(\int_{t_i}^{t_f} \gamma\dot{\gamma} dt\right)^2}, \quad \text{and} \quad \eta(t_i, t_f) = \frac{\int_{t_i}^{t_f} \tau\dot{\gamma} dt \int_{t_i}^{t_f} \gamma\gamma dt - \int_{t_i}^{t_f} \tau\gamma dt \int_{t_i}^{t_f} \gamma\dot{\gamma} dt}{\int_{t_i}^{t_f} \gamma\gamma dt \int_{t_i}^{t_f} \dot{\gamma}\dot{\gamma} dt - \left(\int_{t_i}^{t_f} \gamma\dot{\gamma} dt\right)^2} \tag{5}$$

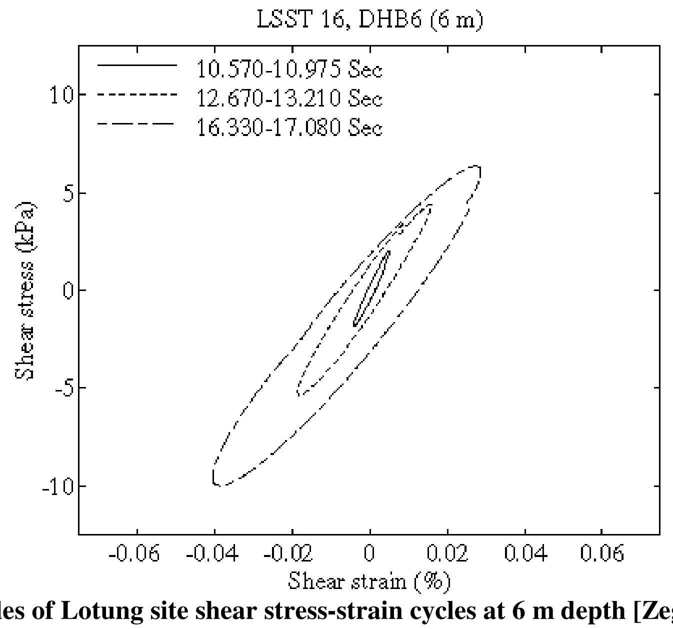

Figure 3: Samples of Lotung site shear stress-strain cycles at 6 m depth [Zeghal *et al.* 1995].

At Lotung, the linear shear modulus was found to remain nearly constant during low strain tremors. However, during the moderate LSST16 earthquake the shear modulus at the end of shaking (where shear strains had practically vanished) was found to be lower than that at the beginning. Such a reduction in stiffness may be attributed to an attained level of excess pore pressure buildup. Assuming that shear modulus G and confining pressure σ' are related by $G = G_o\sqrt{\sigma'/\sigma_o'}$,in which G_o and σ_o' are initial shear modulus and effective confining pressures, the attained excess pore pressure ratio may estimated using $r_u = 1-(G/G_o)^2$.

System identification and computational model calibration. The Lotung downhole seismic records were employed to calibrate linear and nonlinear computational site response models [e.g., Shen 1991, Elgamal *et al.* 1996, Zeghal *et al.* 1996]. In this regard, downhole records were shown to be a most valuable means of advancing the state-of-the-art in computations.

HUALIEN, TAIWAN

Hualien is located south of Lotung on the east coast of Taiwan within a highly active seismic zone. The Hualien LSST was initiated in 1993 by a consortium of industrial and research enterprises from five countries (Japan, USA, Taiwan, France and Korea). In contrast to the Lotung soft soil conditions, the Hualien experiment was located at a relatively stiff site [Tang *et al.* 1991]. Extensive instrumentation was deployed to record seismic structural and ground responses, and to monitor soil pore-water pressure buildup. The ground instrumentation (installed around a one-quarter scale nuclear-plant containment structure) included fifteen surface accelerometer stations; and three downhole accelerometer arrays. Each downhole array consisted of 5 accelerometers and extended to a 52.6 m depth. During the period July 1993 to May 1995, seven earthquakes were recorded at the Hualien site [Yang *et al.* 1995]. The largest peak lateral acceleration of these events is about 0.1g. However, the instrumentation is still active and available to record an anticipated future stronger earthquake excitation.

Response anisotropy. The earthquake records at this site revealed a unique mechanism of azimuthal anisotropic soil response. Correlation analyses and identified seismic stress-strain histories (Eqs. 3 and 4) showed lower shear wave velocity estimates in the EW, compared to the NS direction [Gunturi *et al.* 1998]. A notable study by Ueshima and Okano [1996] arrived at the same conclusion using a frequency domain system identification analysis of the recorded seismic accelerations.

GARNER VALLEY, CALIFORNIA, USA

The Garner Valley experiment [Archuleta *et al.* 1992] is sponsored jointly by the US Nuclear Regulatory Commission and the French Institut de Protection et de Surete Nucleaire. This site is in a seismically active area of southern California located 7 km east of the San Jacinto fault. The array consists of 5 accelerometer stations that extend to a 220 m depth. At this location, the upper 18 m of soil are followed by weathered granite (up to 45 m), with solid granite bedrock thereafter. The outcome of weak seismic motion analyses of 218 recorded events was found to be in agreement with in-situ low-strain shear wave velocity measurements [Archuleta *et al.* 1992].

TREASURE ISLAND, CALIFORNIA, USA

Treasure Island a reclaimed island located in the San Francisco bay. It was constructed in the 1930's of hydraulic fill over natural sand and Bay Mud. The fill (about 12 m thick) is in a relatively loose condition, and is susceptible to liquefaction. Geologic formation at Treasure Island (including the upper loose hydraulic fill) is similar to that of the nearby Marina District in San Francisco [Pease and O'Rourke 1997]. At both locations, widespread liquefaction with devastating consequences was documented during the recent 1989 Loma Prieta Earthquake. The Treasure Island liquefaction and associated loss of soil stiffness and strength was documented by Pease and O'Rourke [1997] using surface accelerations recorded at Treasure Island, and representative bedrock accelerations recorded at the nearby outcrop of Yerba Buena Island. The site was instrumented in 1992 by the California Strong Motion Instrumentation Program, and the National Science Foundation [deAlba *et al.* 1994], in order to: (1) gather seismic data that would elucidate the mechanisms of rock-motion amplification by deep soil deposits in the San Francisco area, and (2) document the mechanisms of site liquefaction in the upper hydraulic fill strata. The Treasure Island array consists of six accelerometer stations extending to a 104 m depth; and 6 piezometers located within the top 12 m reclaimed hydraulic fill [deAlba *et al.* 1994].

Since its installation the array recorded 3 low amplitude shaking events in 1993, 1996 and 1998, and is currently active in anticipation of a future strong earthquake excitation. These low amplitude events provide a source of benchmark information on Treasure Island low strain dynamic response characteristics. The 1993 downhole records were employed to evaluate [Elgamal *et al.* 1996]: (1) shear wave velocity profile, (2) site shear stress-strain response, and (3) low-strain soil dynamic properties. The identified stiffness and damping parameters showed a noticeably higher damping ratio in the upper loose hydraulic-fill layer, possibly reflecting the soft nature of the fill, along with other surface wave propagation characteristics that are not modeled by the employed simple 1D shear wave propagation concept.

WILDLIFE-REFUGE, CALIFORNIA, USA

Evidence of liquefaction at or near the Wildlife-Refuge site was observed following the 1930, 1950, 1957, 1979, and 1981 Imperial Valley earthquakes. In an insightful effort, this site was therefore was instrumented in 1982 by the United States Geological Survey [Holzer *et al.* 1989]. The instrumentation included a surface and a downhole accelerometer (at 7 m depth, below a liquefiable layer), and a number of pore-pressure transducers. On November 24, 1987, the Superstition Hills earthquake occurred (M_W = 6:6), causing a sharp increase in recorded pore-water pressure. The surface records displayed peculiar acceleration spikes associated with simultaneous instants of excess pore-pressure drop [Holzer *et al.* 1989].

Zorapapel and Vucetic [1994] employed the 1987 seismic records to assess the relationship between lengthening of site fundamental period, motion amplification, and excess pore pressure buildup. Glaser [1996] used ARMA modeling and system identification techniques to assess the effects of excess-pore-pressure on the site dynamic properties. Zeghal and Elgamal [1994] used cross-correlation analyses to assess the site stiffness degradation associated with the phase of sharp pore-pressure rise. The dramatic change in site response due to liquefaction was also evident in the stress-strain (evaluated using Eqs. 3 and 4, Fig. 4) history of the Superstition Hills earthquake [Zeghal and Elgamal 1994]. During the strong shaking phase, the site experienced a clear and gradual stiffness degradation associated with the sharp increase in recorded pore water pressure (Fig. 4). At low effective confining pressures (high excess pore pressures), the effective stress-path clearly exhibited a reversal of behavior from contractive to dilative at large strains [NRC 1985, Zeghal and Elgamal 1994]. Thus, this case history clearly showed (for the first time), an in-situ mechanism of shear stress hardening at large strain excursions during liquefaction (Fig. 4). Such a mechanism has been observed in a number of experimental studies and is a consequence of soil dilation at large strain excursions, which results in associated instantaneous pore-pressure drops. This observed phenomenon of hardening at large shear strain excursions (during liquefaction) is of paramount importance in restricting the extent of lateral deformation due to seismic excitation.

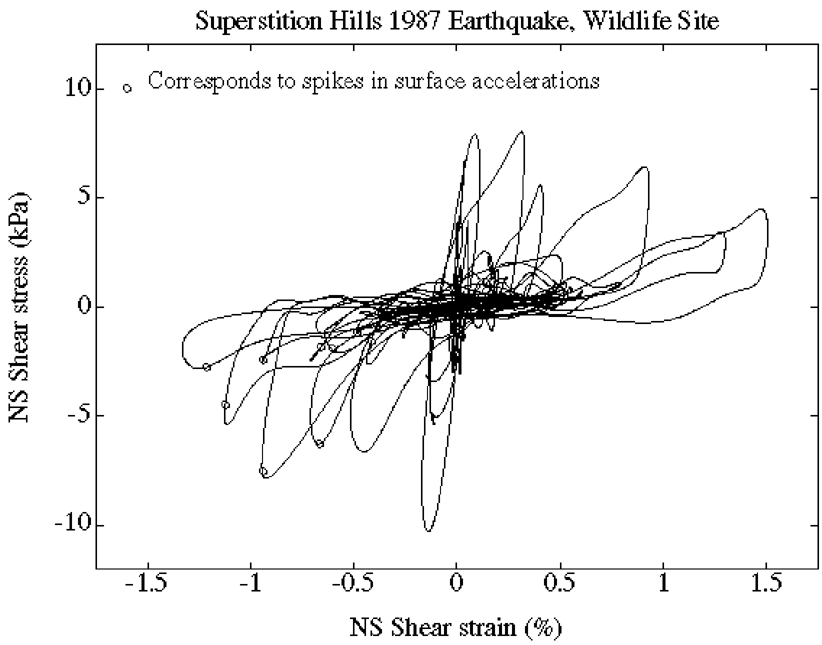

Figure 4: Wildlife Refuge shear stress-strain response at 3.75 m depth [Zeghal and Elgamal 1994].

PORT ISLAND, KOBE, JAPAN

Port Island is a reclaimed island located on the south-west side of Kobe, Japan. Soil in the reclaimed layer consisted of decomposed weathered granite fill with grain sizes ranging from gravel and cobble-sized particles, to fine sand [e.g., O'Rourke 1995]. A 4 station downhole accelerometer array extending to an 83 m depth was installed at Port Island in August 1991 [Iwasaki 1995]. The array site consists of: (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 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 was located at a depth of 4 m approximately.

Using the recorded downhole accelerations, shear stress-strain response (Eqs. 3 and 4) was evaluated [Elgamal *et al.* 1996b, Zeghal *et al.* 1996]. Two remarkably different response patterns were exhibited at the site. Below 32m 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 (near the ground surface) the stress-strain histories indicated an abrupt sharp loss of stiffness and reduction of yield strength, evidently associated with site liquefaction. This liquefaction response mechanism was marked by the virtual absence of hardening at large strains, in contrast to the Wildlife case (Figs. 4). The Port Island records have been the subject of numerous recent studies [e.g., Ishihara 1995]. These records along with the 1987 Superstition Hills record at Wildlife have provided valuable insight into the mechanisms associated with site liquefaction.

CONCLUSIONS

The presented studies showed that downhole vertical-array records offer a valuable source for: (1) evaluating site seismic shear stress-strain histories, (2) assessing the mechanisms of site amplification, stiffness degradation and liquefaction, and (3) calibrating constitutive models and computational modeling procedures. In this regard, system identification techniques were found to be an effective means to evaluate optimal modeling parameters. At present, downhole seismic records are becoming increasingly available worldwide. Such records are finally providing a growing site response databank under a wide range of seismic loading conditions.

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