0266

IDENTIFICATION OF SOIL LIQUEFACTION USING DOWNHOLE ARRAY RECORDS

Jun YANG[1] And Tadanobu SATO[2]

SUMMARY

In this paper, the response of a liquefiable site subjected to the 1995 Hyogo-ken Nanbu earthquake is studied using downhole array records, with particular attention on the identifying the liquefaction-induced nonlinear soil effects. To this end, first, the characteristics of recorded ground motions are analyzed using spectral ratio as well as spectral smoothing technique. Based on the spectral analyses, the nonlinearity occurring in the surface reclaimed layer is identified. Furthermore, a fully coupled, inelastic finite element analysis of the response of the array site is carried out. The stress-strain histories and pore water pressures at different depths are simulated, in particular, their relations to the variation of the characteristics of ground motions are discussed.

INTRODUCTION

A large number of dynamic laboratory tests on soils have provided a valuable insight into the nonlinear soil behavior and liquefaction mechanism [e.g., Seed and Idriss, 1970; Vucetic and Dobry, 1991; Ishihara, 1993]. However, since the laboratory conditions may not be directly applicable to field situations, it is of importance to investigate the nonlinear soil response and liquefaction phenomenon through in-situ earthquake observations. Such a study would also be helpful in verifying and refining the available laboratory observations and analytical simulations on soil behavior and site response. A desirable way to investigate in-situ soil behavior over a wide range of strain is through field observations obtained from downhole arrays in strong earthquakes. One can investigate the nonlinear soil response by examining the Fourier spectral ratio between ground surface and bedrock motions. In addition, using these records, it is also possible to investigate the behavior of soils between the stations at different depths and how much it influences the ground motion. In this paper, the downhole array records obtained at Port Island, Kobe, during the 1995 Hyogo-ken Nanbu earthquake are used to study the liquefaction-induced nonlinear soil effects. The unique features of the Port Island records are that (1) the site consisted of a reclaimed loose surface layer which liquefied during shaking events, and (2) the records included detailed acceleration data at reasonably spaced depth intervals, with the deepest accelerometer at the depth of 83 m. Therefore, it is believed that the nonlinear soil behavior must have been documented by the acceleration records. In this study, the characteristics of the recorded ground motions are analyzed using spectral ratio technique. Based on the spectral analyses, the nonlinearity occurring in the shallow liquefied layer is identified. A fully coupled, inelastic finite element analysis is performed to analyze the ground response at the array site. The stress-strain histories of soils and excess pore water pressures at different depths are calculated, in particular, their relations to the characteristics of the ground motions are addressed.

OBSERVED NONLINEAR SITE AMPLIFICATION

The site is at Port Island which is an artificial island located on the west-south side of Kobe, Japan. The installed downhole array consisted of three-component accelerometers located at the surface, the depths of 16 m, 32 m and 83 m, respectively. The soil profile at the array site is shown in Fig. 1. Site investigations indicated that the

[1] *Disaster Prevention Research Institute, Kyoto University, Uji,, Japan E-mail: yang@catfish.dpri.kyoto-u.ac.jp*
[2] *Disaster Prevention Research Institute, Kyoto University, Uji,, Japan*

SPT values of the surface reclaimed layer (from the surface to the depth of 19 m) were very low. Hence, there existed a high liquefaction susceptibility in that layer. The recorded strong earthquake motions in horizontal components are shown in Fig. 2 for the surface and the depth of 83 m (G.L.-83 m). It should be mentioned that the orientation error in the accelerometer at G.L.-83 m has been corrected according to the displacement orbits for each station in horizontal plane [Sugito et al., 1996]. The distribution of peak horizontal accelerations with the depth is shown in Fig. 3. The two figures clearly indicate that not only the amplitude but also the frequency content of the ground motions was modified when the seismic waves traveling from the bottom to the surface. The nonlinear site amplification manifested by the acceleration records is believed to be caused by the liquefaction in surface reclaimed layer, which was associated with a substantial soil softening. Abundant evidence of site liquefaction such as sand boils, sand ejection and lateral spreading was observed after the earthquake [Shibata et al., 1996; Hamada et al., 1996].

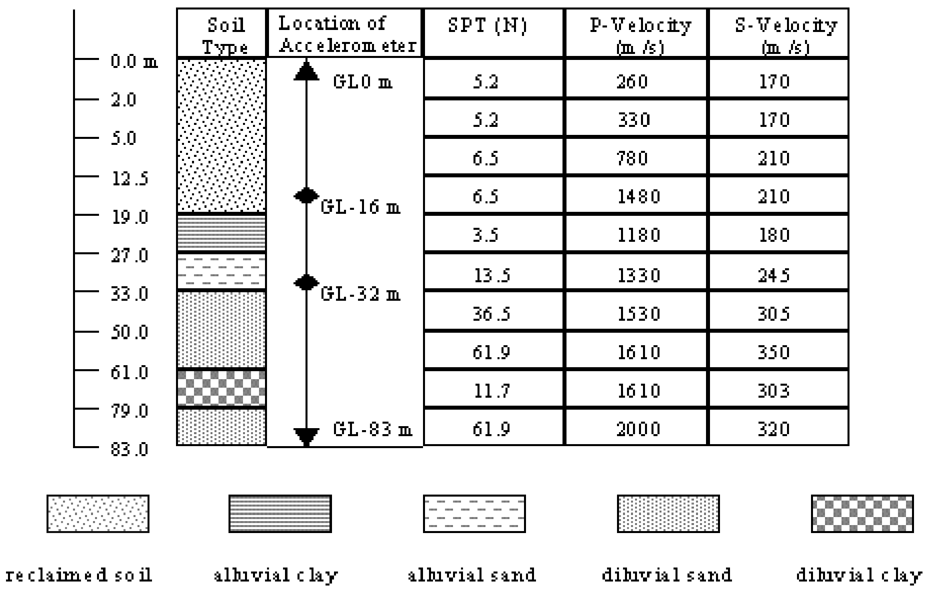

Figure 1: Soil profile at the array site, Port Island, Kobe

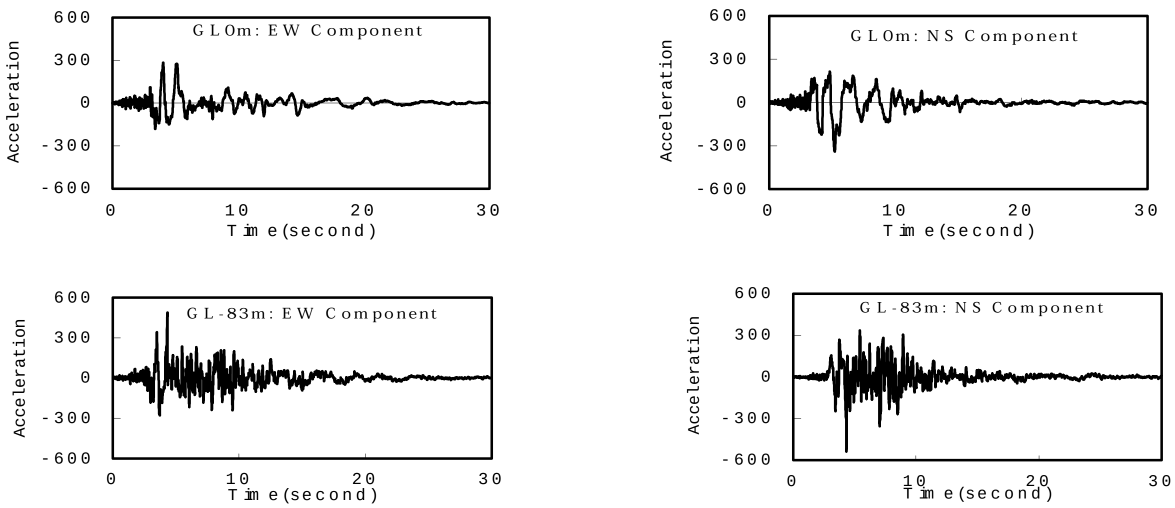

Figure 2: Acceleration records at surface and the depth of 83 m

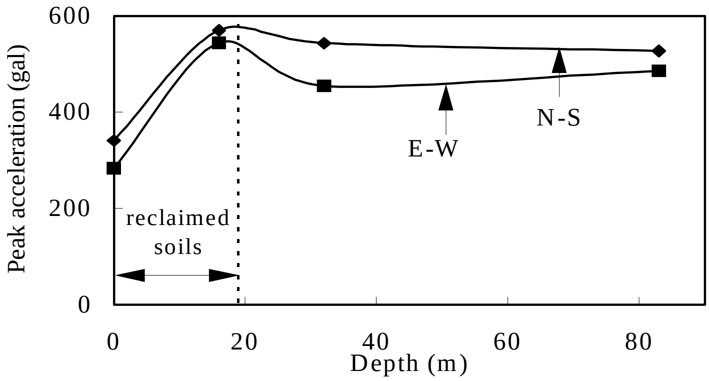

Figure 3: Distribution of peak accelerations with depth

SPECTRAL ANALYSIS OF GROUND MOTION

For a site subjected to strong earthquake shaking, the gradual buildup of pore water pressure in subsurface granular soils can result in the degradation of soil stiffness. If a larger soil softening occurs as a result of very high pore water pressures, or the associated state of full liquefaction, a significant increase of the predominant period and a decrease of the amplitude of surface motions may be manifested. In general, this nonlinear behavior can be investigated by examining the Fourier or response spectral ratio between the surface motion and the motion recorded at other depths. To capture the variation of frequency content during the shaking, in the calculation each acceleration record is separated to three phases according to the observed features of seismograms: Phase 1, from 0 to 3 s; Phase 2: from 3 to 12 s; Phase 3, from 12 to 30 s. Obviously, Phase 2 corresponds to the strongest shaking.

Figure 4 shows the smoothed spectral amplitudes for the surface motions in three phases in N-S and E-W directions, respectively. As expected, the predominant frequencies for both horizontal motions were decreased when the strong motion occurred. In addition, it is seen that the frequency contents in Phase 2 are similar to those in Phase 3, indicating that the softened state of the soils persisted. Figure 5 shows the spectral ratios between the surface motion and the motions at the depths of 16 m, 32 m and 83 m (denoted as SP0/SP16, SP0/SP32 and SP0/SP83, respectively) in phase 1 and 2 for N-S direction. In general, the features of the spectral ratios for E-W component are very similar to those for N-S component [Yang et al., 1999], therefore, the discussion is focused here on N-S component only. It can be seen from Fig. 5 that, in Phase 1, the spectral ratios SP0/SP83 and SP/SP32 are similar, with peak frequencies of around 4.5, 7, and 11 Hz, and 4.2, 6, 10.5 Hz, respectively. The dominant seismic waves were those with high frequencies in this phase. The spectral ratio SP0/SP16, however, exhibited a little different feature: the peak frequencies were around 3.2 and 6.6 Hz. This indicates that, even though the shaking during this stage was not strong enough, seismic motions with relatively longer periods became dominant, when the waves traveled through the surface reclaimed layer. On the other hand, by comparing the spectral ratios in Phase 1 and 2, the influence of nonlinear soil behavior, which was attributed to a strong shaking, was clearly observed: the frequency content was obviously shifted to low frequency end. Especially, it is noticed that, in phase 2 the amplitudes for the waves with frequency higher than 5 Hz were dramatically reduced, with amplification ratios below 1, while in phase 1 these waves were amplified notably. The difference for the two phases indicates that the increase in the predominant period was caused primarily by a strong decrease in the amplitude of low-period waves, rather than by amplification of long-period motions.

INDENTIFICATION OF NONLINEARITY IN LIQUEFIED RECLAIMED LAYER

The previous analyses have indicated that the surface reclaimed layer played a key role in the amplification of earthquake waves. Based on the spectral ratio analyses, the shear modulus of the reclaimed layer (from the surface to the depth of 16 m) before and after the strongest shaking was evaluated using a simple method [Yang et al., 1999]. Table 1 shows the shear wave velocity and shear modulus for N-S and E-W components. These values correspond respectively to the average soil stiffness before and after the strongest earthquake shaking. It is seen that the reduction of shear modulus during the shaking event is remarkable.

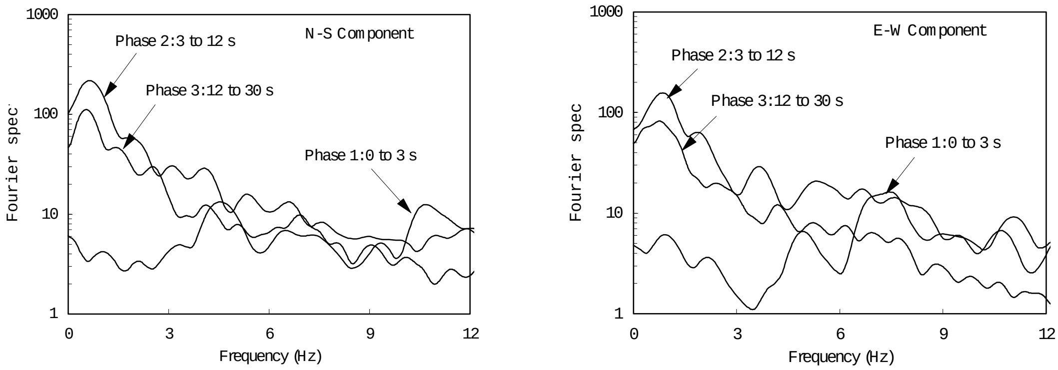

Figure 4: Fourier spectra for surface motions in three phases

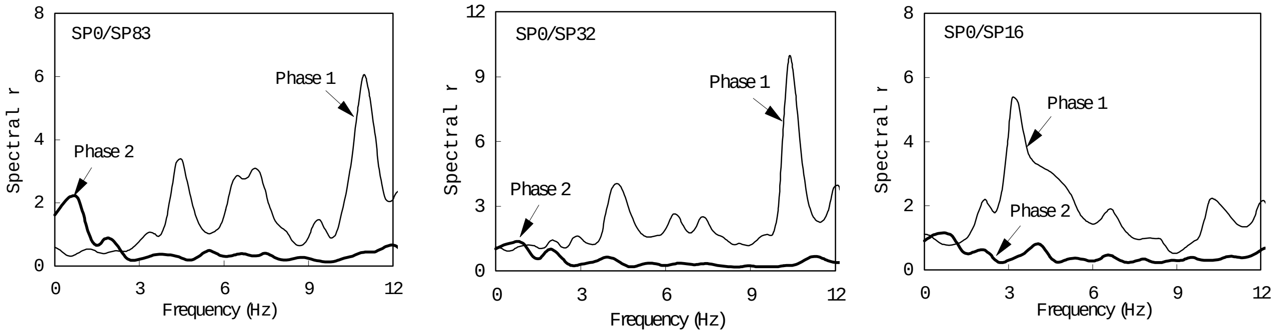

Figure 5: Spectral ratios of ground motions in N-S direction in Phase 1 and 2

Table 1: Identified shear wave velocity and shear modulus for reclaimed layer

Component	V_{s1} phase 1	V_{s2} phase 2	G_1 phase 1	G_2 phase 2	Reduction of G $(G_1-G_2)/G_1$ (%)
N-S	205 m/s	51 m/s	79.8 MPa	4.9 MPa	94%
E-W	154 m/s	57 m/s	45.1 MPa	6.2 MPa	86%
PS logging : Vs=198 m/s G_0=74.5 MPa (average values for the surface layer, G.L. 0 m to G.L. -16 m)					

COUPLED ANALYSIS OF THE RESPONSE OF ARRAY SITE

In this section, a fully coupled nonlinear finite element analysis of the site response to the recorded motions is performed. The purpose here is to simulate the acceleration time histories, pore water pressure responses and stress-strain histories of soils at different depths, and then to discuss their relations to the observed characteristics of ground motions.

The numerical procedure applied is a fully coupled effective-stress procedure for site response under multi-directional earthquake shaking [Li et al., 1992]. The procedure is formulated within the framework of two phase theory by Biot (1941) and Zienkiewicz and Shiomi (1984). The inelastic soil model incorporated in the procedure is a hypo-plasticity bounding surface model [Wang et al., 1990] which was developed within the framework of bounding surface theory [Dafalias, 1986]. This model is capable of realistically simulating the soil behavior under a wide range of loading conditions. Some essential effects are captured, such as the compression and dilation induced effective stress change, the lateral stress change due to shaking and the significant reduction of stiffness upon liquefaction, etc. For level ground earthquake response problems, the model takes a reduced-order form and there are 10 model parameters to be determined for a particular soil. In Fig. 6 the response of soil model to cyclic loading calibrated from the liquefaction resistance data for surface reclaimed soils is presented. The calibrated model parameters are given in Yang et al. (1999). The bottom boundary of soil deposits can be treated as a rigid base considering the input motions are directly taken from downhole records. In the present analyses, the acceleration records at G.L.-83 m serve as input motions.

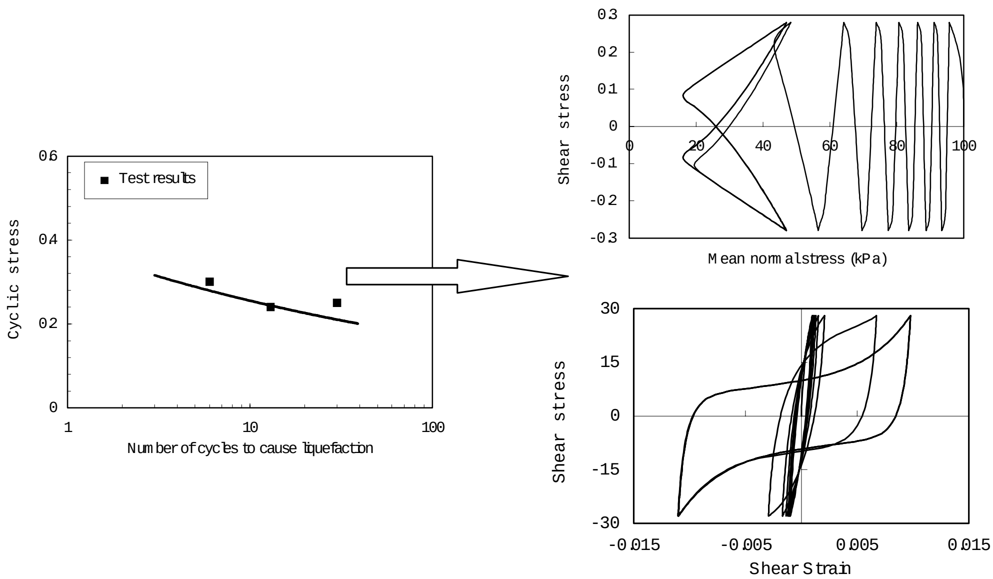

Figure 6: Undrained response of the model calibrating from cyclic strength data

The calculated and recorded acceleration time histories at the surface and the depths of 16 m and 32 m in N-S and E-W directions are shown in Fig. 7. In general, it can be seen that the calculated acceleration histories are similar to the field records. The computed stress-strain histories at depths of 7.7 m, 24 m and 51.3 m during the shaking are shown in Fig. 8 for N-S and E-W directions, respectively. Here, the shear stress is correspondingly normalized to the initial effective vertical stress. Obviously, it is seen that the soils at different depths exhibited quite different behavior during earthquake in either direction. The soil at the shallow depth (7.7 m) showed a dramatic reduction of soil stiffness during the shaking. Especially, it is noted that the shear modulus of soils was almost reduced to zero while the shear strain remained at a large level at the final stage of strong shaking, this indicates that the soils liquefied fully. The soil at deeper layer (51.3 m), on the other hand, responded generally in a very small nonlinear manner, with no appreciable reduction of stiffness and with a low level of strain. The stress-strain history for the soil at the depth of 24 m exhibited a moderate reduction of shear modulus, but the soils did not fully lose strength throughout the earthquake. Figure 9 depicts the excess pore water pressure responses at the depths of 7.7 m and 51.3 m during the shaking. It is seen that an abrupt rise in excess pore water pressure occurred during the phase of strongest excitation (Phase 2, 5 to 8 s). For the soil at the depth of 7.7 m, the excess pore pressure reached the value of initial effective vertical stress around at 8 s, which resulted in a full soil liquefaction.

To clearly show the relation of ground motion and the soil behavior during shaking, in Fig. 10 the recorded surface motion in N-S component, and its Fourier spectra in the three phases, as well as the stress-strain histories of soils at the depth of 7.7 m at different stages are given. It is seen that, at the first stage which corresponds to weak shaking, the soil responded linearly with the strain level less than 0.01%, meanwhile the generated excess pore water pressure at this stage was very small, as shown in Fig. 9. Corresponding to this stage, the spectra of surface motions were dominated by high frequency components. During the stage of 3 to 6 s, which corresponds to strong shaking, the soil exhibited an obvious nonlinearity with the peak strain of the order of 1%. The generated excess pore pressure reached 75% of initial effective vertical stress at 6 s. During the period from 6 to 12 s, the abrupt loss of soil stiffness upon liquefaction was clearly observed. The amplitude of shear strain approximately reached the value of 2%. Correspondingly, the long-period waves were dominant.

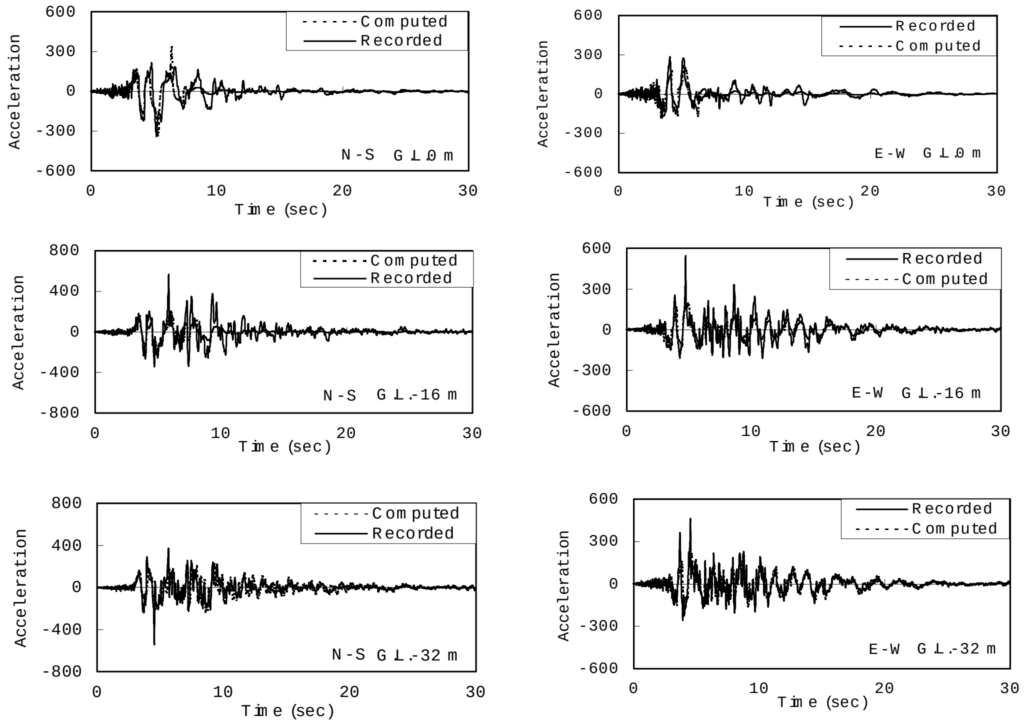

Figure 7: Simulated and recorded acceleration time histories at different depths

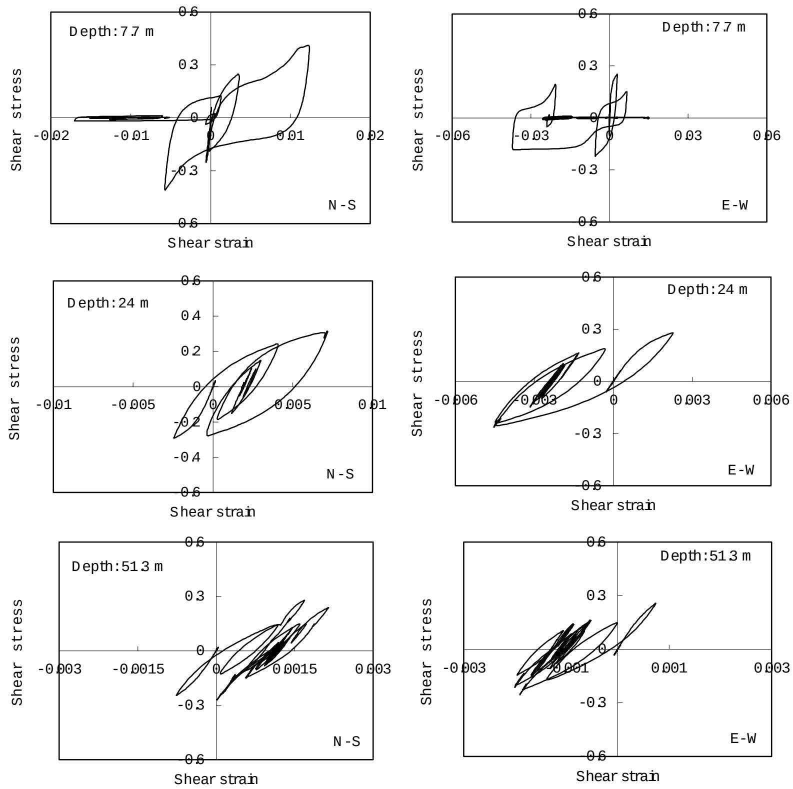

Figure 8: Calculated stress-strain histories of soils at different depths

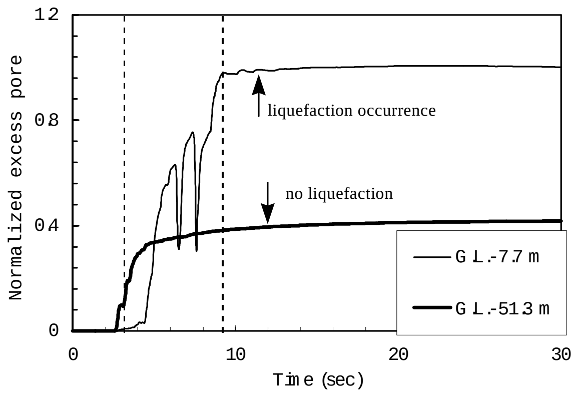

Figure 9: Calculated excess pore water pressures at different depths

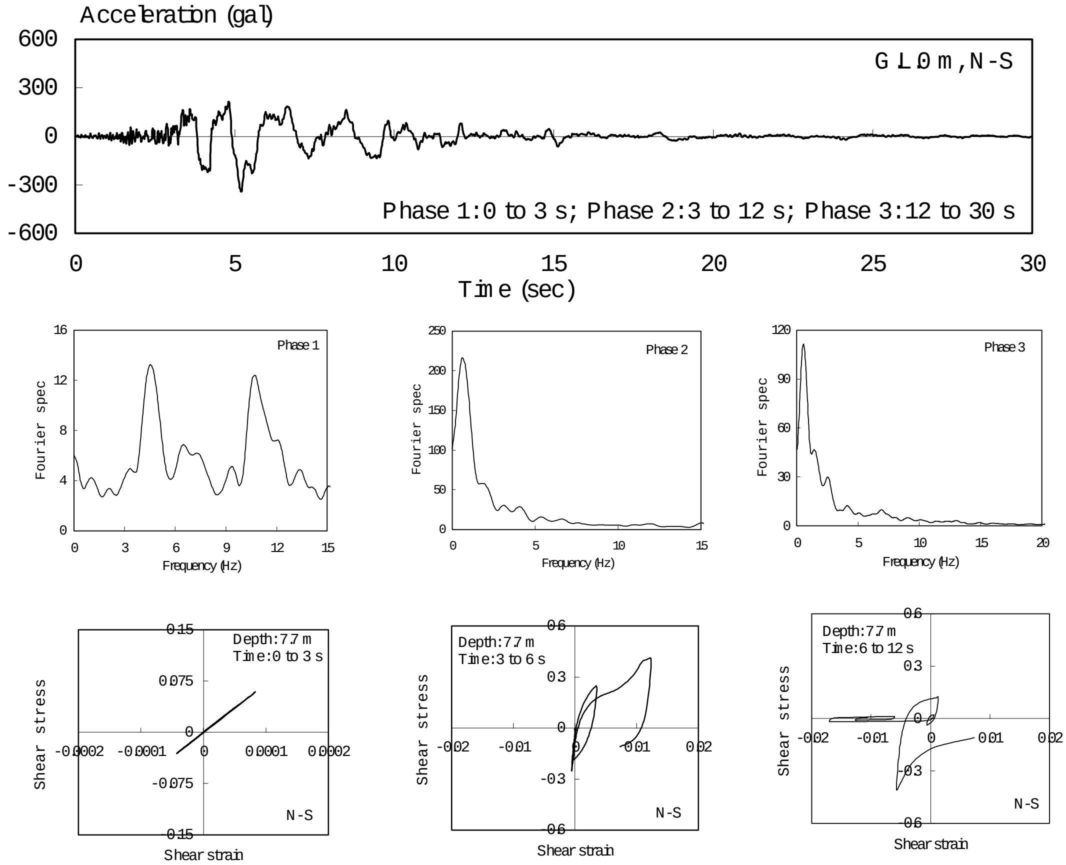

Figure 10: Relation of soil behavior and ground motion during shaking history

CONCLUSIONS

In this paper, the liquefaction-induced nonlinear soil effects on ground motions are studied for the case history of a liquefiable site subjected to the 1995 Hyogo-ken Nanbu earthquake. The present study indicates that: (1) the peak frequencies in spectral ratios were shifted to lower frequencies when the strongest motions occurred; (2) the increase in the predominant period of surface motion was caused primarily by a strong attenuation of low-period waves, rather than by amplification of long-period motion; (3) a large soil softening due to high excess pore water pressure occurred in shallow layer, while the deep soils exhibited a very small nonlinear response with a low level of excess pore pressure; and (4) the simulated stress-strain histories and excess pore water pressure responses are closely related to the variation of the characteristics of ground motions during shaking.

REFERENCES

Biot, M.A. (1941), “General theory of three-dimensional consolidation”, *J. Appl. Physics*, 12: 155-164.

Dafalias, Y.F. (1986), “Bounding surface plasticity, I. Mathematical foundation and the concept of hypoplasticity”, *J. Engrg. Mech.*, ASCE, 112: 966-987.

Hamada, M., Isoyama, R. and Wakamatsu, K. (1996), “Liquefaction-induced ground displacement and its related damage to lifeline facilities”, *Soils Found.*, Special Issue, pp. 81-97.

Ishihara, K. (1993), “Liquefaction and flow failure during earthquakes”, *Geotechnique*, 43: 351-415.

Li, X.S., Wang, Z.L. and Shen, C.K. (1992), “SUMDES, a nonlinear procedure for response analysis of horizontally-layered sites subjected to multi-directional earthquake loading”, *Report*, Dept. of Civil Engrg., Univ. of Calif., Davis, Calif.

Seed, H.B. and Idriss, I.M. (1970), “Soil moduli and damping factors for dynamic response analysis”, *Report EERC 70-10*, Earthquake Engrg. Res. Cent., Univ. of Calif., Berkeley, Calif.

Shibata, T., Oka, F. and Ozawa, Y. (1996), “Characteristics of ground deformation due to liquefaction”, *Soils Found.*, Special Issue, pp. 65-79.

Sugito, M., Sekiguchi, K., Yashima, A., Oka, F., Taguchi, Y. and Kato, Y. (1995), “Correction of orientation error of borehole strong motion array records during the South Hyogo Earthquake of Jan. 17, 1995”, *Proc. of JSCE*, No.531/I-34, 51-63.

Vucetic, M. and Dobry, R. (1991), “Effect of soil plasticity on cyclic response”, *J. of Geotechnical Engineering*, ASCE, 117: 89-107.

Wang, Z.L., Dafalias, Y.F. and Shen, C.K. (1990), “Bounding surface hypoplasticity model for sand”, *J. Engrg. Mech.*, ASCE, 116: 983-1001.

Yang, J., Sato, T. and Li, X.S. (1999), “Seismic amplification at a soft soil site with liquefiable layer”, *J. Earthquake Engrg*. (accepted for publication).

Zienkiewicz, O.C. and Shiomi, T (1984), “Dynamic behavior of saturated porous media: the generalized Biot formulation and its numerical solution”, *Int. J. Nume. Anal. Methods in Geomech.*, 8: 71-96.