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NUMERICAL SIMULATION OF THE KOBE PORT ISLAND LIQUEFACTION

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ABSTRACT

During the 1995 Hyogoken-Nanbu Earthquake unique acceleration records of a heavily liquefied site at the man-made Kobe Port Island have been recovered with a seismic down-hole array. To investigate the ground response associated with the recorded accelerations a series of fully coupled effective stress analyses are conducted. Particular attention is given to the response of the reclaimed Masado layer that exhibited severe liquefaction. Analyses in different directions including the maximum and the minimum shaking intensity directions demonstrated a governing influence of the excess pore pressures on the ground response. A pore pressure response of the Masado layer is identified for which remarkable similarity is obtained between the computed and the recorded accelerations for each direction. This indicates that the computed excess pore pressures are close to the actual excess pore pressures induced by the quake.

KEYWORDS

Hyogoken-Nanbu Earthquake; liquefaction; seismic down-hole array; strong motion records; effective stress analysis; elastoplastic model; acceleration time histories; excess pore pressures.

INTRODUCTION

The January 17, 1995, Hyogoken-Nanbu Earthquake, of magnitude 7.2, severely shook the Kobe area, in the southern Hyogo prefecture, Japan. The violent shaking caused widespread liquefaction in the seaside area of Kobe city leading to large ground deformation and severe damages to many engineering structures. The liquefaction was particularly extensive and severe in the reclaimed lands of the two largest man-made islands, Port Island and Rokko Island.

Ground motions induced by the main shock of the Hyogoken-Nanbu Earthquake have been recorded at several sites that exhibited massive liquefaction of reclaimed soil. Among these records particularly valuable are those obtained with the seismic down-hole array at Port Island since they include acceleration records at four different depths of the soil profile ranging between the ground surface and 83 m depth. A fully coupled effective stress analysis of the Port Island down-hole array site was conducted in order to simulate the acceleration records and to clarify the characteristics of the ground response at this heavily liquefied site.

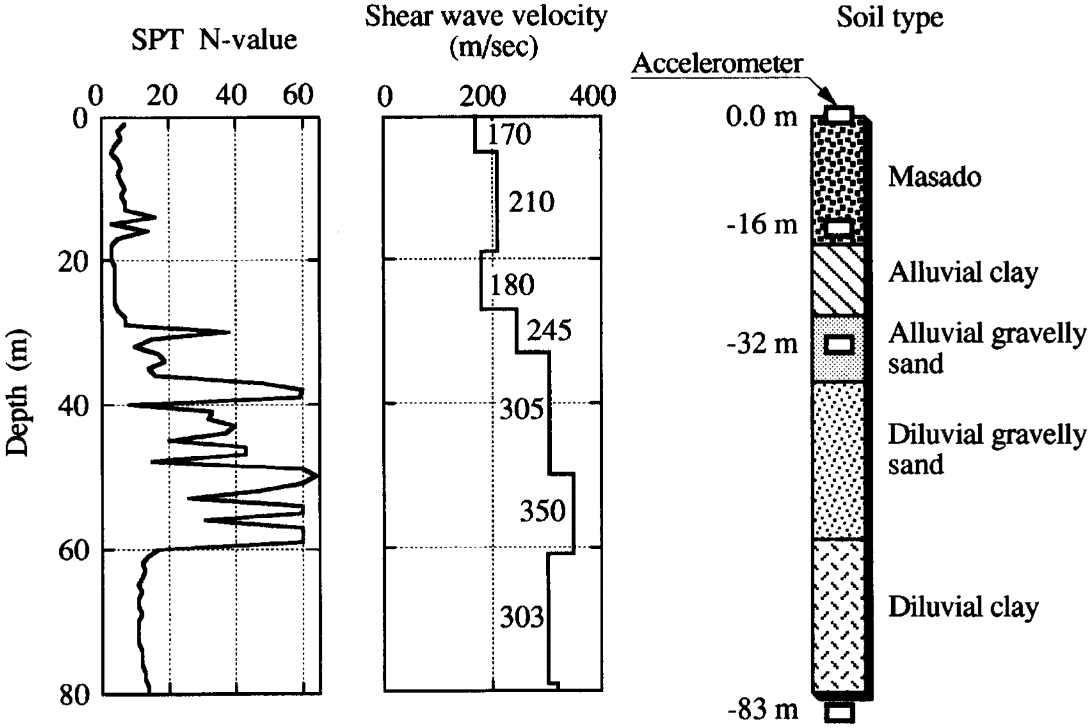

Fig. 1. Soil profile of the seismic array site at Port Island

DOWN-HOLE ARRAY SITE AND STRONG MOTION RECORDS

Port Island is a man-made island, with an area of 436 ha, constructed in the period between 1966 and 1980 by transporting and dumping soils in the sea water by bottom-dump type barges. The soil used for land filling is a decomposed weathered granite known as Masado (Masa-soil). It is a well-graded soil, containing fairly large portion of gravel. At the North-West corner of Port Island a down-hole seismic array was installed in 1991. It consists of four sets of accelerometers located at the ground surface and at depths of 16 m, 32 m and 83 m. Each set has three accelerometers, oriented in N-S, E-W and U-D directions, respectively.

Soil profile characteristics of the down-hole array site including SPT N-values, shear wave velocities, material types and location of the accelerometers along the depth of the profile are shown in Fig. 1. These properties have been obtained by a site investigation conducted prior to the Hyogoken-Nanbu Earthquake (Toki, 1995). As shown in Fig. 1, the soil profile consists of five distinct layers down to a depth of about 80 m. The surface layer is a 18 m thick reclaimed Masado. It overlies the original sea-bed layer of alluvial clay and an alluvial gravelly sand layer underneath, with thicknesses of 10 m and 9 m, respectively. Below these layers lie a diluvial gravelly sand layer and a diluvial clay layer, each with a thickness of 22 m. It is to be noted that both gravelly sand layers are interlayered with silt. The water table is located at 3m depth approximately.

During the Hyogoken-Nanbu Earthquake massive liquefaction occurred in the area of the down-hole array site at Port Island resulting in an average settlement of 30-40 cm and a 15-20 cm thick layer of sand and mud littered on the ground surface due to sand boiling. Figure 2 shows the horizontal acceleration records of the main shock of the quake recovered with the down-hole array accelerometers. It is to be noted that the accelerations at 83 m depth, shown at the bottom of Fig. 2, are corrected by an anti-clockwise rotation of 19 degrees due to an estimated orientation error of the accelerometers at this depth (Ansary *et al.*, 1995). An important feature of these near-source acceleration records is displayed in Fig. 3, where the locus of the ground surface acceleration in the horizontal plane is shown. Apparently, the directionality of the motion is very pronounced,

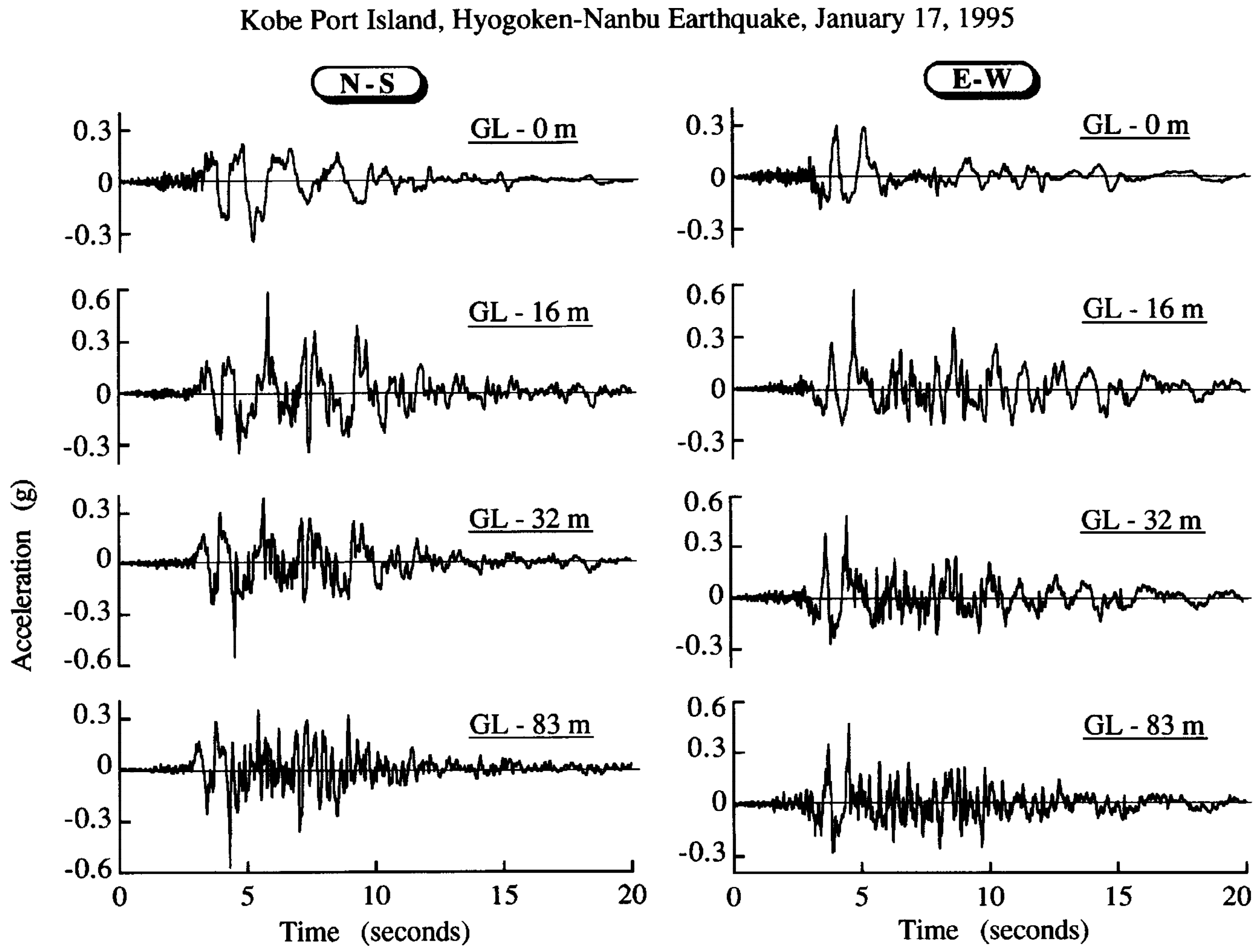

Fig. 2. Recorded horizontal accelerations with the down-hole array at Port Island

with the NW-SE and NE-SW directions being approximately the directions of the maximum and the minimum shaking intensities, respectively. Similar directionality and orientation of the motion are also observed at depths of 16 m, 32 m and 83 m.

EFFECTIVE STRESS ANALYSIS

In order to closely investigate the ground response associated with the recorded accelerations shown in Fig. 2 and Fig. 3, a series of effective stress analyses were conducted by using a couple of soil-column models, denoted as shallow model and deep model. The analyses with the shallow model were used to clarify the response of the reclaimed Masado layer and to analyze the link between the excess pore pressures and the characteristics of the ground response in different horizontal directions. In this paper, a series of independent shallow model analyses in the directions of the two extreme intensities of the motion, NW-SE and NE-SW, are presented. Other characteristics of the response including the deep model analyses are given in Cubrinovski and Ishihara (1996).

A fully coupled effective stress method with the U-u formulation of the Biot equations for the dynamic behaviour of saturated porous media was employed. The analyses were carried out using the finite element code DIANA-J with the Stress-Density Model (Cubrinovski, 1993) as a constitutive model. All the analyses are drained analyses with a plane strain assumption. The numerical model used has a height of 28 m and

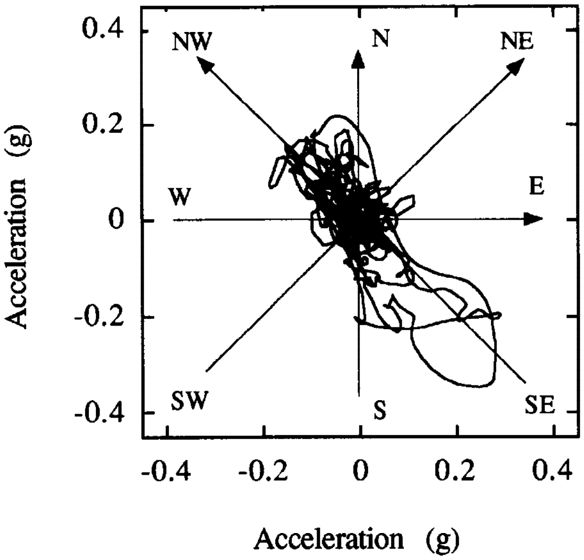

Fig. 3. Locus of the recorded ground surface acceleration on the horizontal plane

includes the surface Masado layer and the original sea-bed layer of alluvial clay. It is a soil-column model composed of 28 four node finite elements, each with a height of 1 m. The recorded horizontal motion at 32 m depth was used as a base input motion.

Material Modeling

In order to facilitate the material modelling only the Masado layer was modeled with the Stress-Density Model, as an elastoplastic material. The alluvial clay was modeled as a linear material with a degraded shear modulus to 30 % of the initial modulus. This stiffness degradation was estimated through a simple analysis of the propagation characteristics of the motions recorded with the down-hole accelerometers (Cubrinovski and Ishihara, 1996).

Dilatancy parameters of the Stress-Density Model, which control the development of the excess pore pressures, were determined by simulating the liquefaction resistance curve shown in Fig. 4. These data are compiled by Ishihara *et al.* (1996) from two series of cyclic triaxial compression tests on undisturbed samples of reclaimed Masado from Port Island, indicated with the empty and the filled symbols in the figure. Due to insufficient laboratory data for Masado, the stress-strain and the state index parameters of the Stress-Density Model were approximated with those of Toyoura sand with a relative density of $D_r = 60$ %.

RESULTS AND DISCUSSION

Independent analyses were conducted in the two directions of extreme shaking intensity, NW-SE and NE-SW, where the corresponding components of the recorded accelerations at 32 m depth were used as one-dimensional base input motions. Figure 5 shows a comparison between the computed and the recorded acceleration time histories at the ground surface and at 16 m depth, for the maximum shaking intensity direction NW-SE. Apparently, there is a very good agreement between the computed and the recorded accelerations at both depths. Similar or even higher level of accuracy was obtained in the corresponding analyses for the N-S and E-W directions (Cubrinovski and Ishihara, 1996). On the other hand, Fig. 6 shows that the computed and recorded ground surface accelerations in the NE-SW direction are very different.

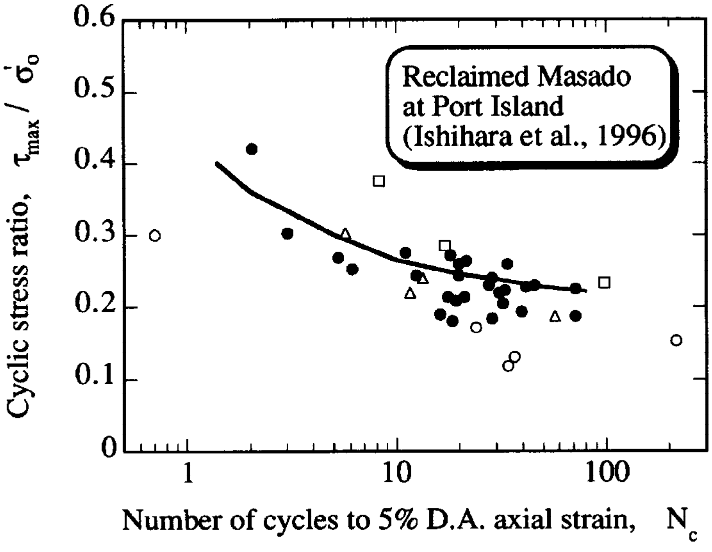

Fig. 4. Liquefaction resistance of undisturbed samples of Masado recovered from Port Island (Ishihara *et al.*, 1996)

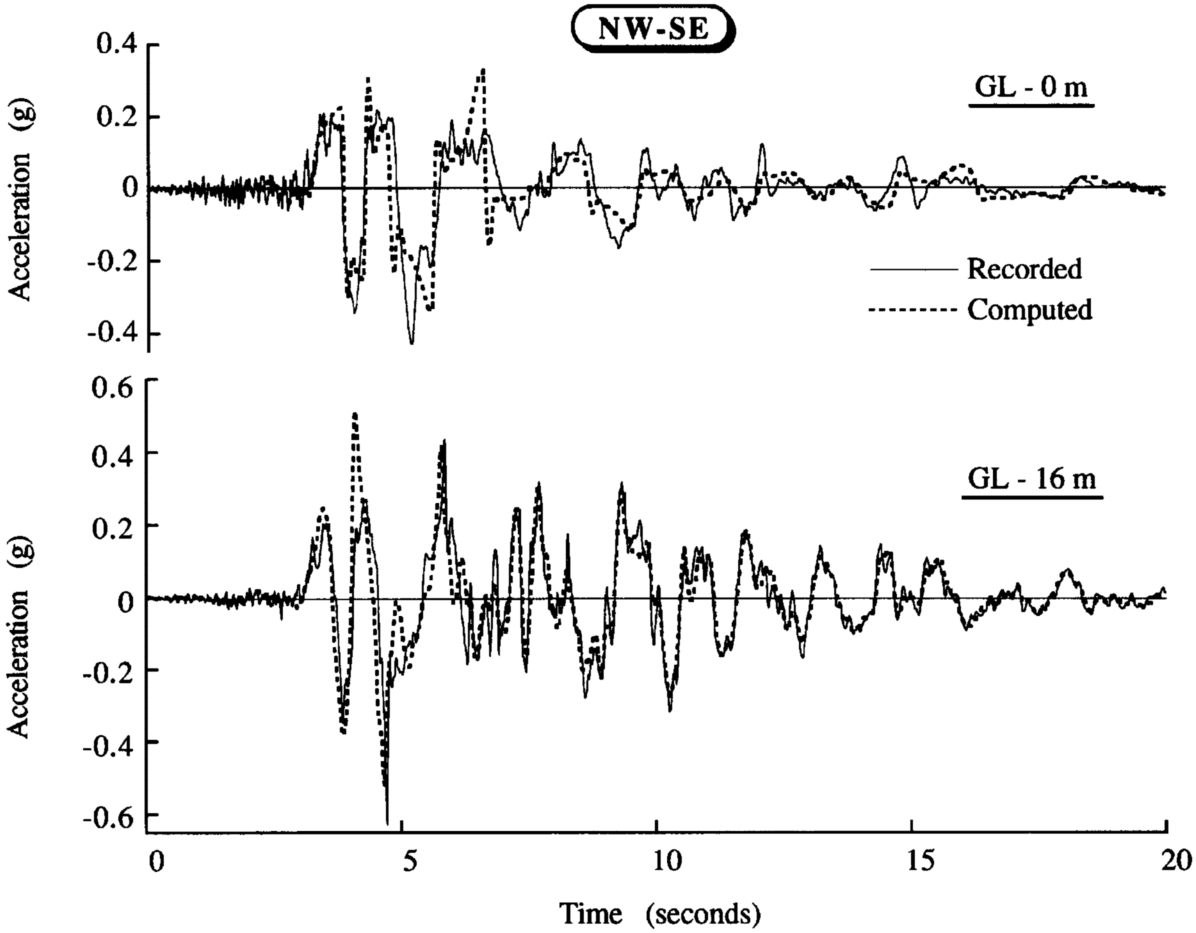

Fig. 5. Computed and recorded NW-SE acceleration time histories at the ground surface and at 16 m depth

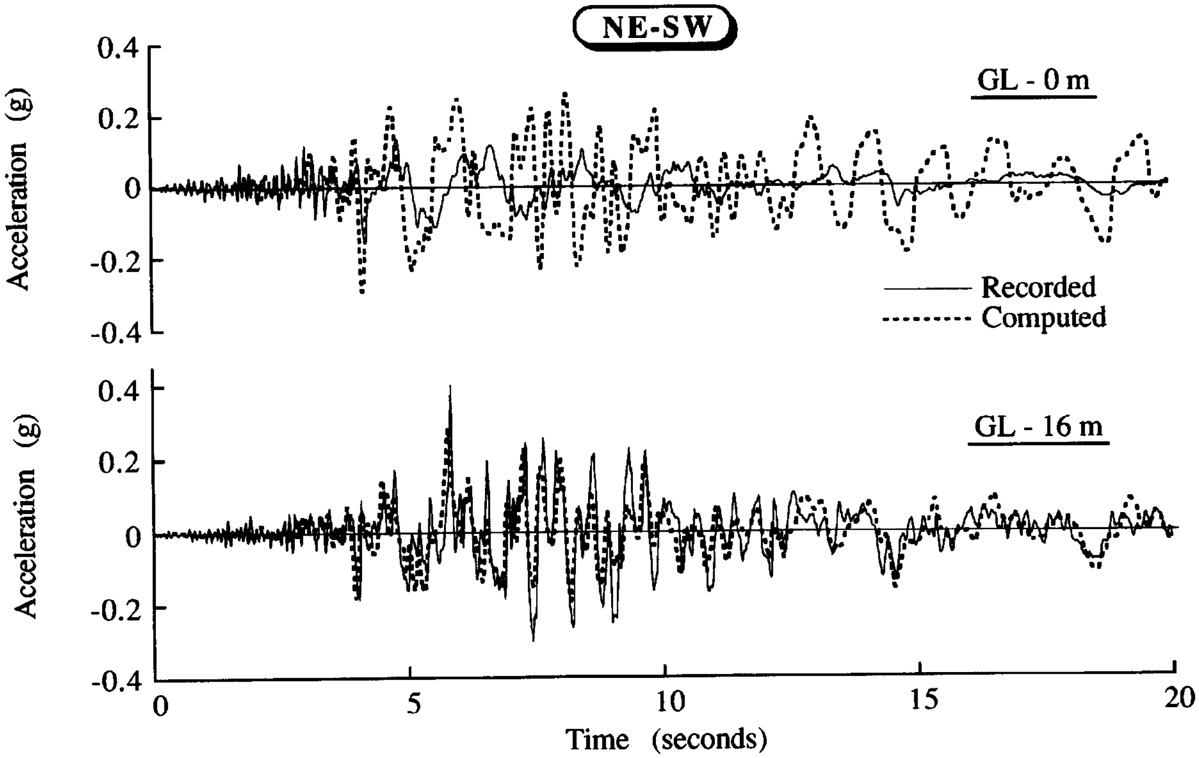

Fig. 6. Computed and recorded NE-SW acceleration time histories at the ground surface and at 16 m depth

It is necessary to recall that due to the strong inherent directionality of the motion, as illustrated in Fig. 3, the shaking intensity in the NE-SW direction was remarkably smaller than that in the other analyzed directions. For this reason, the pore pressure build-up in the NE-SW analysis was comparatively slow and the maximum excess pore pressure eventually reached only about 50 % of the initial effective vertical stress. It can be seen in Fig. 7 that this pore pressure response is substantially different from the nearly unique pore pressure response computed in the N-S and NW-SE analyses.

Similarity among the computed pore pressure responses in the N-S, E-W and NW-SE analyses, and the fact that the computed accelerations in these analyses are very similar with the recorded accelerations, indicate that the computed excess pore pressures in these analyses are close to those actually induced by the main shock of the Hyogoken-Nanbu Earthquake. Hence, the discrepancy between the computed and the recorded NE-SW accelerations might be attributed to the failure of the NE-SW analysis to simulate the actual pore pressure response. To verify such an indication, a quasi NE-SW analysis was conducted in which an initial excess pore pressure was applied and the dilatancy parameters of Masado were determined such to induce pore pressure response similar to that computed in the NW-SE analysis. The pore pressure response computed in the NE-SW analysis with a modified excess pore pressure response as above is also shown in Fig. 7, while Fig. 8 comparatively shows the NE-SW recorded accelerations and those computed in the analysis. It is apparent that, when the pore pressure response is close to the actual one, a very good agreement between the computed and the recorded accelerations is also obtained for the minimum shaking intensity direction NE-SW.

Distribution of the maximum excess pore pressures and the maximum shear strains along the depth of the Masado layer computed in the NW-SE analysis are shown in Fig. 9. These results reveal that the most heavily affected by the liquefaction was the part of the Masado layer from approximately 5 m to 15 m depth. In this layer, the excess pore pressure reached the initial effective vertical stress and a cyclic softening due to liquefaction occurred after only one and a half to two cycles of intensive shaking. This pore pressure response was associated with maximum shear strains of 3-4 %.

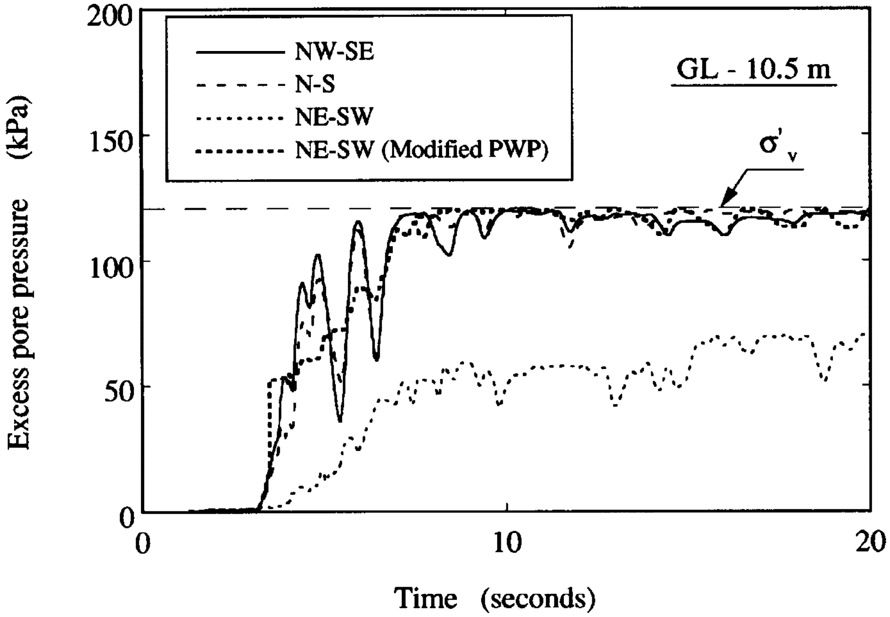

Fig. 7. Computed excess pore pressure time histories at 10.5 m depth

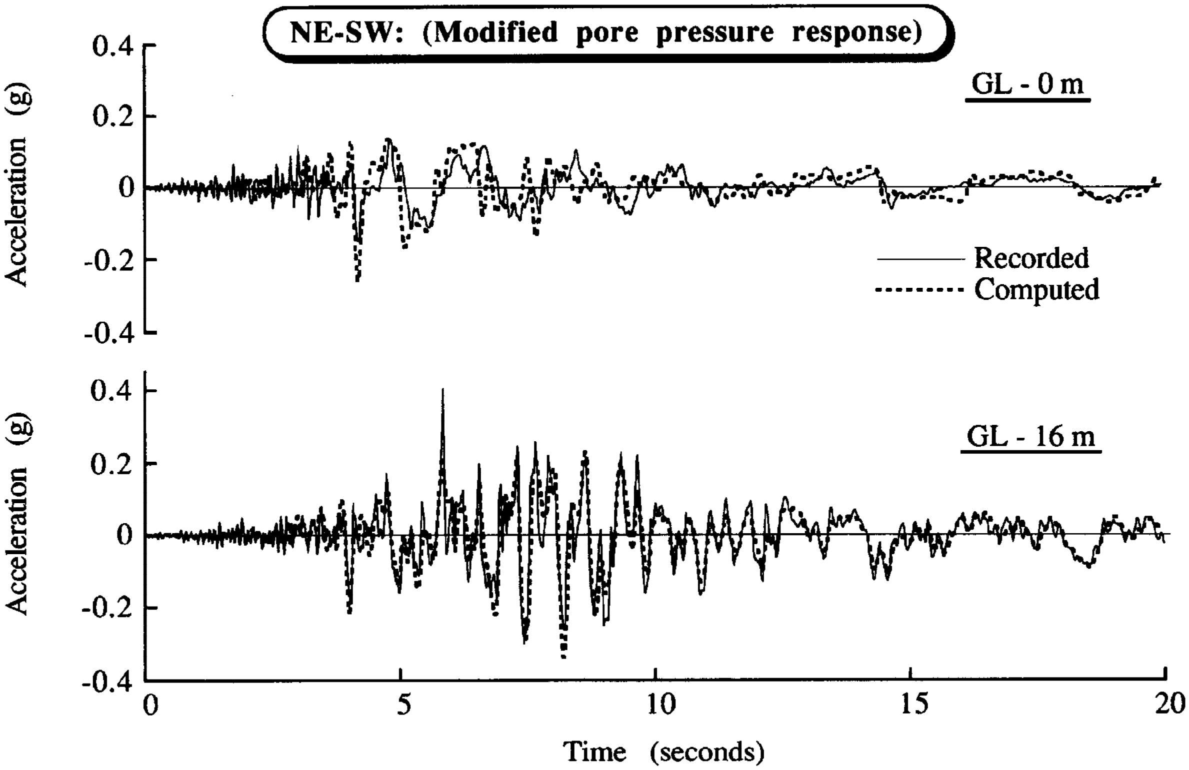

Fig. 8. Computed and recorded NE-SW acceleration time histories at the ground surface and at 16 m depth (Modified excess pore pressure response)

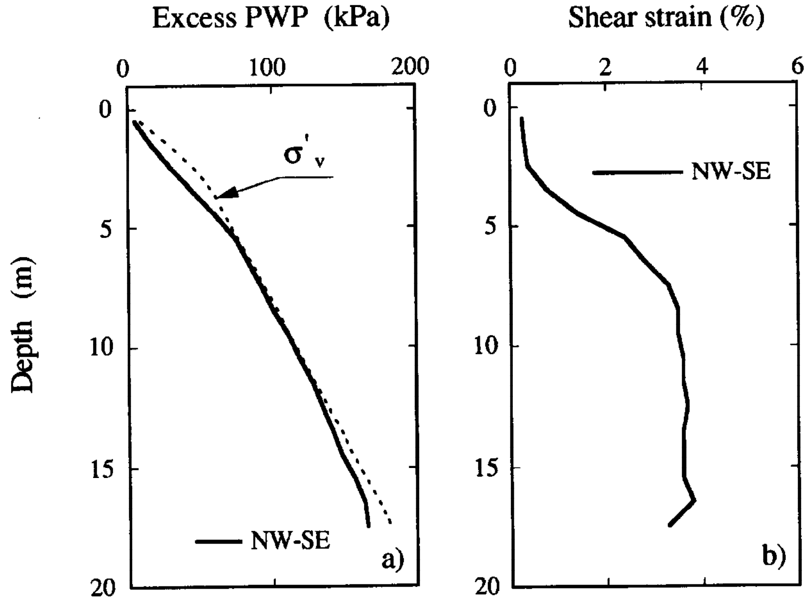

Fig. 9. Distribution of the maximum excess pore pressures and shear strains along the depth of the Masado layer

CONCLUSIONS

The shallow model analyses in the two directions of extreme shaking intensity, NW-SE and NE-SW, clearly demonstrate a governing influence of the excess pore pressures on the ground response, and thus emphasize the need for effective stress analysis of soils that are susceptible to liquefaction. The results of the NE-SW and the quasi NE-SW analyses particularly show that non-linearity alone can not depict the cyclic softening due to liquefaction if the excess pore pressures or the change in the effective stresses are not properly accounted for.

Another important result from the presented analyses is that the excess pore pressure, as a scalar quantity, has to be associated with the characteristics of the pore pressure response for the maximum shaking intensity direction of a given excitation, irrespective of the direction considered. This has an important bearing for an effective stress liquefaction analysis in which one-dimensional horizontal input motion is applied, such as 1-D and 2-D soil column analyses or 2-D plane strain analysis. The remarkable similarity between the computed and the recorded accelerations for different directions, suggests that the excess pore pressures computed in the NW-SE analysis are close to those actually induced by the main shock of the Hyogoken-Nanbu Earthquake.

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