TIME DEPENDENT GROUND MOTION AMPLIFICATION AT RECLAIMED LAND AFTER THE 1995 HYOGO-KEN-NANBU EARTHQUAKE

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SUMMARY

Two sets of borehole array records obtained from the Great Hanshin Earthquake as well as its fore and after shocks, are investigated. One of the station is located in Port Island in Kobe City where the severe liquefaction occurred and the records from the main event includes the typical phenomena of liquefaction. The other station is located in Rokko Island in Kobe City where the liquefaction phenomena was not predominant as it was in Port Island.

The nonlinear ground motion amplification, depending on the level of input ground motion as well as their spectral characteristic, are carefully investigated. Two numerical techniques for seismic response analysis of ground are applied for these stations; one is the frequency-dependent equivalent linearization technique for frequency domain analysis, and the other is the effective stress-based liquefaction analysis. The discussion is focused on the amplification characteristic of these two reclaimed lands depending on their reclamation history. Time-dependent amplification ratio for peak ground motion and spectral contents are demonstrated, which is caused by the recovery of soil rigidity due to the decrease of excess pore water pressure after the main event.

INTRODUCTION

The nonlinear ground motion amplification due to the level of input motion at bedrock is one of the significant topics in the field of earthquake engineering. The extremely valuable borehole records at Port Island in Kobe City were obtained during the 1995 Hyogoken-Nambu Earthquake. At this station, a great number of array records were obtained after June 1994 until December 1996. The other borehole records except the ones from the 1995 Eartqhuake have been obtained at Rokko Island which is also the reclaimed land in Kobe City. Based on these records, the authors discuss the nonlinear ground motion amplification at the soft reclaimed ground, focusing on its time-dependent characteristic due to the decrease of excess pore water pressure after the large event.

BOREHOLE ARRAY OBSERVATION SYSTEMS

Figure 1 shows the locations and layout of array systems of two borehole stations as well as their soil profiles and velocity structures. In Figs.1(b) and (c), the area where the liquefied sand spouted out is represented. It is clear that the liquefaction was much severe at Port Island than at Rokko Island. Each observation system consists of 4 acceleration sensors as shown in Fig.1(d). At PI station, the acceleration sensors are installed at the depth of GL.-0.0m, -16.0m, -32.0m, and –83.0m. At RI station, the sensors are installed at the depth of GL.-0.0m, -35.0m, -98.0m, and –154.5m.

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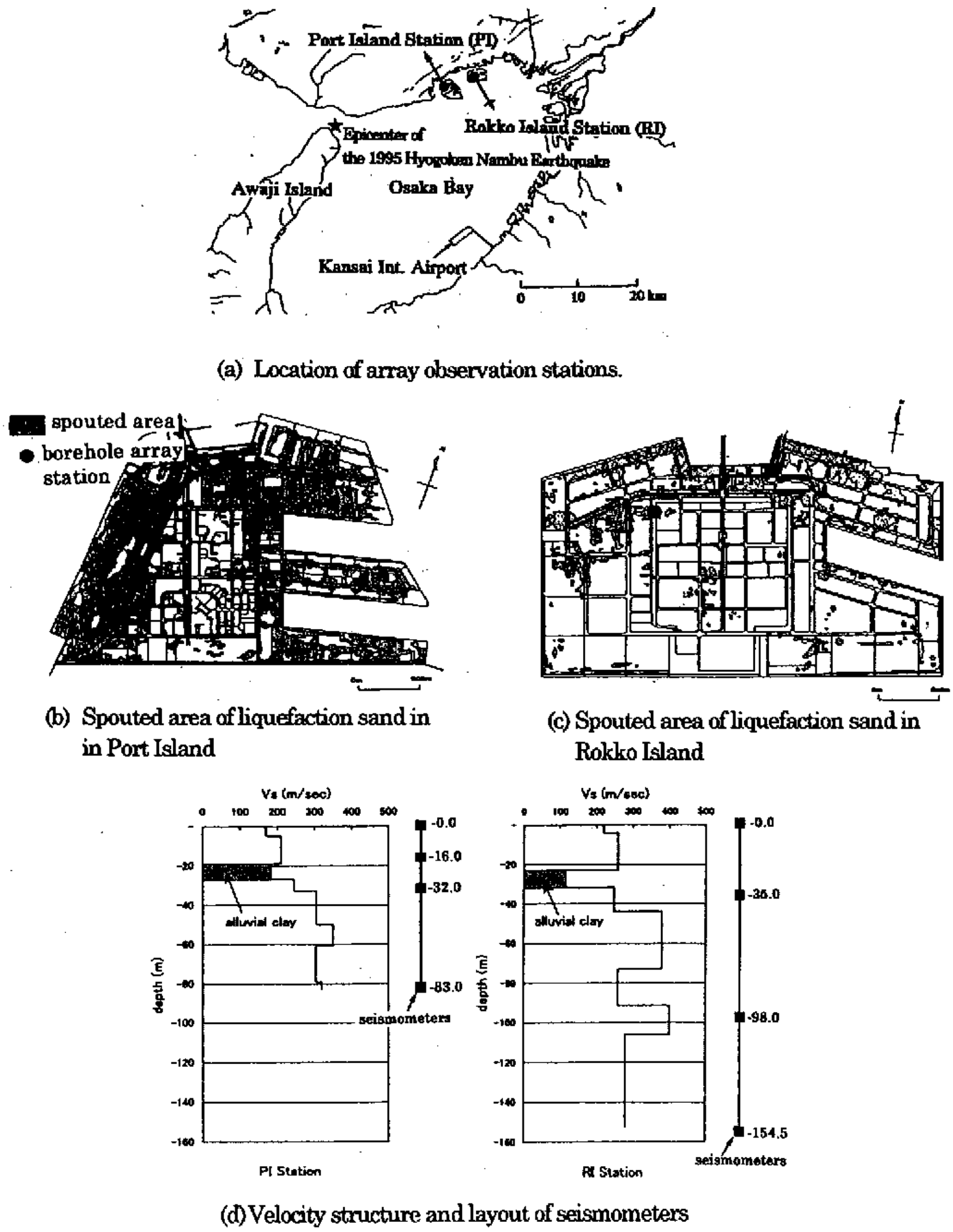
The reclamation work was finished in 1969 at PI station site and in 1979 at RI station site. A decomposed granite soil known as “Masado” was used in the reclamation area of Port Island, and sedimentary rock debris of the Kobe Group, which includes sandstone, mudstone and tuff, was used for Rokko Island. The shear wave velocity in the alluvial layer in the depth of 25 ～ 34 meters at RI station is smaller than that in the depth of 19 ～ 27 meters at PI station, which mainly depends on the term of consolidation. At PI station, the velocity structure has been investigated after the earthquake by using the suspension-type investigator. Figure 1(d) shows the distribution of shear wave velocity at both stations. As shown in Fig.1(d), the shear wave velocity of the alluvial clay at PI station is 180 m/sec, and that at RI station is 115 m/sec.

The records from 39 earthquakes, including the 1995 Hyogoken-Nambu Earthquake, have been compiled. They are classified into 4 groups depending on the recorded date. The group A includes the records obtained before the main event occurred on Jan.17, 1995. In the group B and C, only the records at PI station were obtained. On the other hand, the records were not obtained at PI station during the term for group D.



(a) Location of array observation stations.

(b) Spouted area of liquefaction sand in in Port Island

(c) Spouted area of liquefaction sand in Rokko Island

(d) Velocity structure and layout of seismometers

Fig.1 Location and velocity structure models for borehole array observation stations.

CORRECTION OF ORIENTATION ERRORS OF BOREHOLE RECORDS

The correction of orientation error of borehole records is an indispensable task for use of engineering analyses (Kamata, et. al., 1987). The orientation error of buried seismograph sensors regarding the records used in this study has been investigated (Sugito, et. al., 1996). An error of 22 degrees in the horizontal plane has been detected for the sensor installed at the depth of G.L.-83 m. The peak acceleration of each time history is significantly affected by the correction of the error in the order of 60 % larger or smaller than the original peak value. For example, the peak acceleration in NS and EW components of the corrected time histories were –526.7 and 486.2 cm/sec^2, respectively, while those for uncorrected were –670.5 and –304.6 cm/sec^2, respectively.

All the records obtained at G.L.-83m have been corrected by the rotation of the coordinate in the horizontal plane. Since the records at RI station have not been obtained from the 1995 Earthquake, and the records from other earthquakes are not large enough to detect the orientation error, the original data have been used in the present study.

GROUND MOTION AMPLIFICATION IN CASE OF WEAK INPUT MOTION

Amplification characteristic of peak ground acceleration

The amplification characteristic of peak acceleration at both two stations are compared. The amplification ratio of peak acceleration normalized by the value at G.L.-83m (PI station) and at G.L.-154.5m (RI station) for the records classified in the group A and group E, as well as amplification ratio for the main event at PI station and that for group D at RI station, are represented in Fig. 2 The upper part in Fig.2 shows the result for the group A which is in the term before the 1995 Earthquake. As for the horizontal ground motion, it is observed that the peak acceleration at the PI station is amplified significantly in the surface layers more shallow than 16 meters. In the case of RI station, the peak horizontal acceleration is not amplified in surface layers. In the middle part (c) of Fig.2, the distribution of the peak acceleration during the Hyogoken Nambu Earthquake at PI station is shown. It is

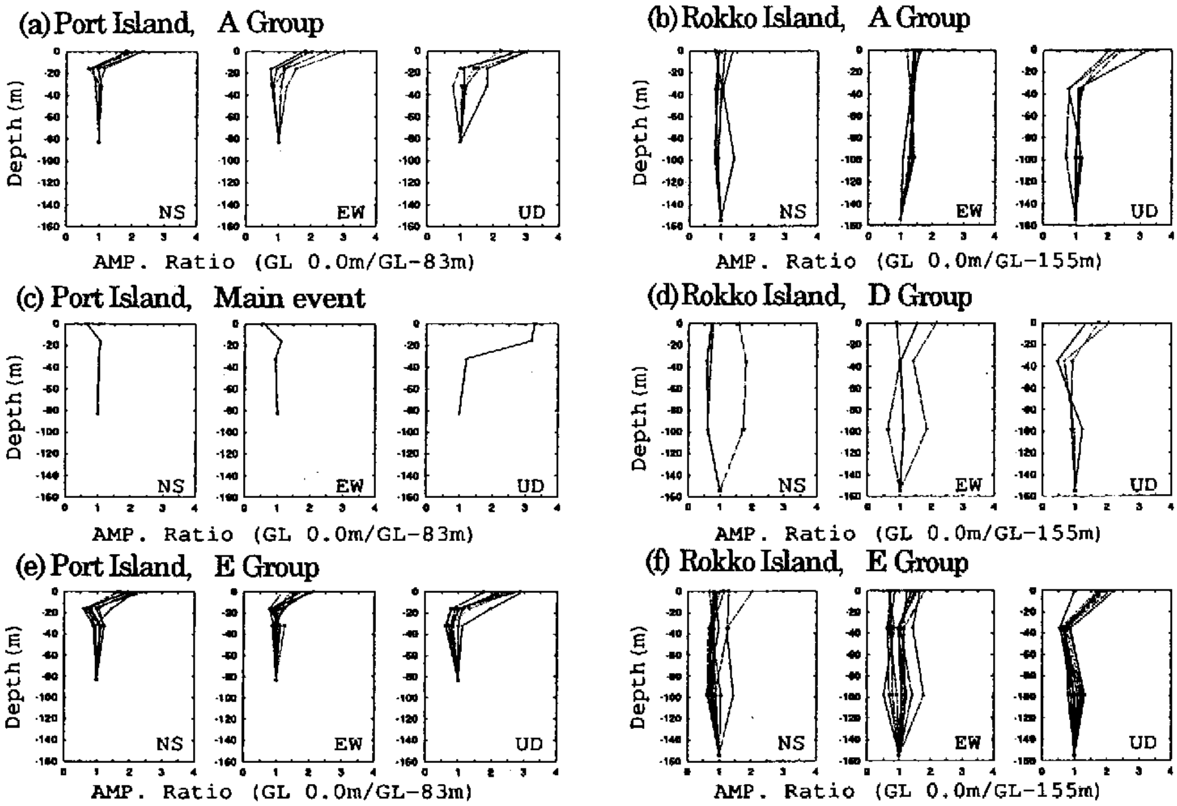


Fig.2 Amplification characteristic of peak acceleration.

clear that the effect of soil liquefaction or reduction of rigidity of soil on amplification of peak ground motion is predominant near the ground surface. In the lower part of Fig.2, 9 days or more after the 1995 Earthquake, the amplification ratio in horizontal components is nearly the same as it was before the 1995 Earthquake both at PI and RI stations. These results in Fig.2 demonstrate that the soil properties, specially the dynamic soil properties recovered in a weak or 10 days after the large event.

Amplification characteristic of spectral contents

The amplification characteristic of acceleration response spectra at both the stations are compared. Figure 3 shows the amplification ratio of acceleration response spectra obtained from typical records in each group of recording term. Figure 3(a) shows the results obtained at PI station. It is clear that the amplification ratio for high frequency range such as *f* >2.0 Hz are very low in the case of the main event (Fig.3(b)) and the case of group B (Fig.3(c)) which is in the term right after the main event. The amplification ratio in the range *f* >2.0 Hz recovered approximately after 10 days after the main event, as shown in group E in Fig.3(d).

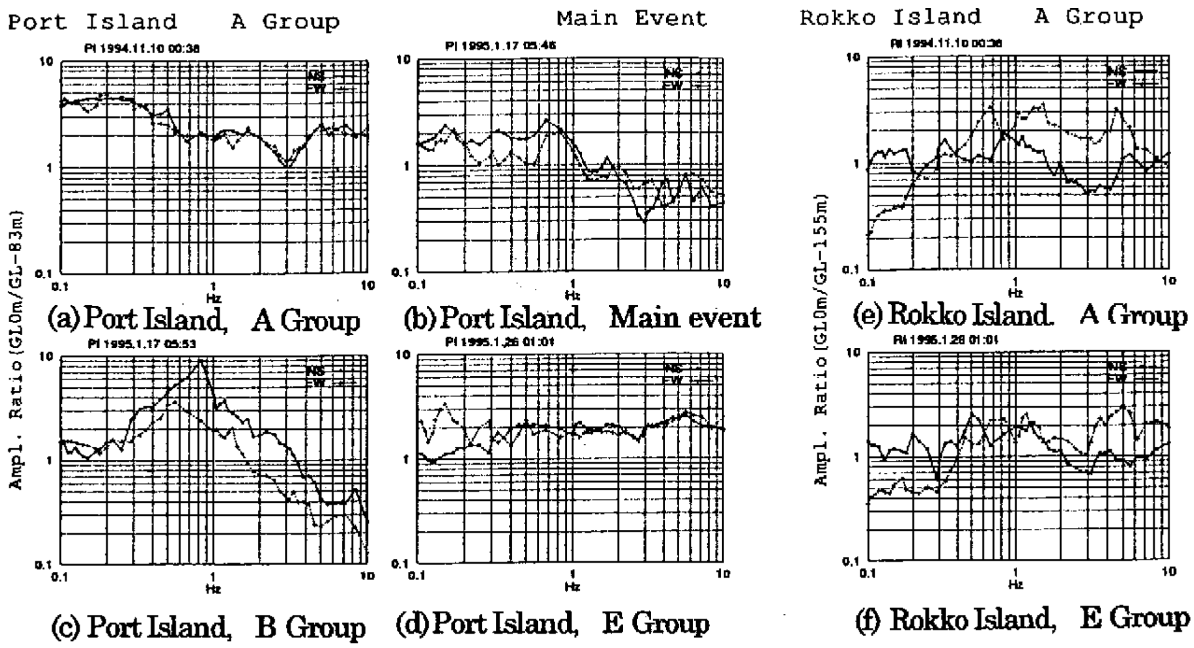


Fig.3 Amplification of acceleration response spectra

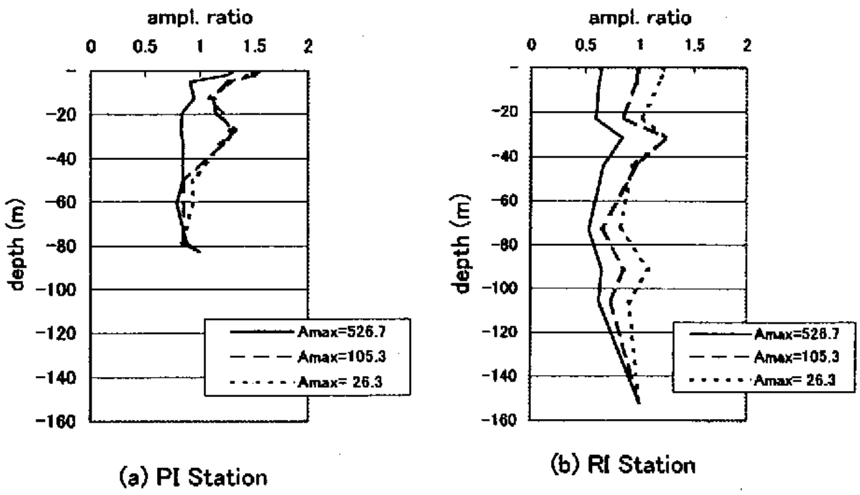


Fig.4 Amplification characteristic of peak acceleration depending on input ground motion levels.

RESPONSE ANALYSIS OF BOREHOLE ARRAY STATIONS

Frequency-dependent equivalent linearization technique (FDEL)

The amplification characteristic of ground motion has been examined for these two stations by using the modified equivalent linearization technique, FDEL, in which a frequency -dependent equivalent strain is incorporated in the numerical analyses (Sugito, 1993). The equivalent linearization technique, in which nonlinear characteristics of shear modulus and damping of soils that depend on the levels of shear strain are modeled as an equivalent linear relation, has been applied frequently for earthquake response analysis of ground, especially in the case of practical fields. The advantage of the technique compared with the nonlinear time domain analysis is that the algorithm is quite simple and the inversion, such as the estimation of input bed rock motion from surface motion, is possible. The computer program, 'SHAKE' (Schnabel et al., 1972), is based on the equivalent linearization technique and has contributed very much to the field of earthquake engineering. It was, however, pointed out that the numerical results do not agree with the observed ground motion in the case of very soft ground and strong ground motion levels.

The technique FDEL(Sugito, 1993) employs as concept of equivalent strain $\gamma_f(\omega)$ that determines the shear modulus and damping in such a way as,

$$\gamma_f(\omega) = C\gamma_{\max}\frac{F_\gamma(\omega)}{F_{\gamma_{\max}}} \tag{1}$$

where C = constant, $\gamma_{\max}$ = maximum shear strain, $F_\gamma(\omega)$= Fourier spectrum of shear strain time history, and $F_{\gamma\max}$ represents the maximum of $F_\gamma(\omega)$. The equivalent strain $\gamma_f(\omega)$ controls the equivalent shear modulus and damping as they are defined to be proportional to the Fourier amplitude of strain time history. The constant C controls the level of equivalent strain uniformly along the frequency axis, and it has been fixed as C =0.65 on the basis of the numerical calculations compared with the strong motion records (Sugito, 1993).

Figure 4 shows the amplification ratio for PI and RI stations with three input motion levels of the peak acceleration as 26.3, 105.3, and 526.7 cm/sec^2. These input motions are scaled from the record obtained at G.L.-83m of PI station in N-S component during the 1995 Earthquake. As shown in Fig.6, the amplification factor at ground surface level at PI station is relatively high in the case of weak input motion, and depends on the input motion level. On the other hand, the amplification factor at ground surface at RI station is not so large even in the case of weak input motion. These results are consistent with the observed ones. It can be concluded that the soft alluvial layer at RI station (G.L.-24 m -34 m) reduces the ground motion amplification even in the weak input motion level, which is so called as the base isolation effect.

Effective stress-based liquefaction analysis

Three-dimensional effective stress-based liquefaction analyses have been carried out in order to understand the basic behavior of the liquefied reclaimed islands. The soil profiles at two observation stations in Port Island and Rokko Island were modeled with three-dimensional finite element mesh. The constitutive model adapted in the numerical analyses is based on the concept of the nonlinear kinematic hardening rule which had originally been used in the field of metal plasticity. Oka et al. (1992) derived a cyclic elasto-plastic constitutive model for sand. Tateishi et al. (1995) incorporated a new stress dilatancy relationship and an accumulative-plastic-strain-dependent shear modulus to modify the original model. The constitutive model is formulated under the three dimensional stress condition and its validity of the constitutive model has been verified by the experimental evidences from a hollow cylindrical torsional shear tests under various stress conditions (Tateishi et al., 1995).

The constitutive model has been incorporated into a coupled finite element-finite difference (FEM-FDM) numerical method for the liquefaction analysis of a fluid-saturated ground. The applicability of the proposed numerical method had been verified by past studies (Yashima et al., 1995; Taguchi et al, 1996; Oka et al., 1996, 1997).

Port Island and Rokko Island are modeled by the rectangular solid element mesh. 39 elements and 160 nodes are used to model the reclaimed ground and natural deposit from the ground surface down to GL –83 m for Port Island. On the other hand, 45 elements and 184 nodes are used to model the ground profile from the ground surface down to GL –93.5 m for Rokko Island. Most numerical parameters for the analysis are determined based on the results of the past field investigations and laboratory tests for the simulation of Port Island. On the other hand, the liquefaction strengths of the reclaimed ground and alluvial (diluvial) sand layer for Rokko Island are assumed to be equal to those of the corresponding layers for Port Island due to the lack of the experimental results. The elastic shear modulus derived from the shear wave velocity of alluvial layers at Rokko Island is, however, smaller than that at Port Island, as aforementioned in chapter 2. Three components of acceleration records with the correction of orientation error are applied at GL –83 m as the base input accelerations for Port Island simulation. The same input accelerations are used at GL –93.5 m for Rokko Island simulation because the main event was not obtained at RI station.

The distributions of the excess pore water pressure ratio along the numerical columns for both PI and RI stations are plotted in Fig.5. It is found that the whole reclaimed layer below sea level for PI station was liquefied by the strong motion during the earthquake. On the other hand, the reclaimed layer at RI station did not liquefied.

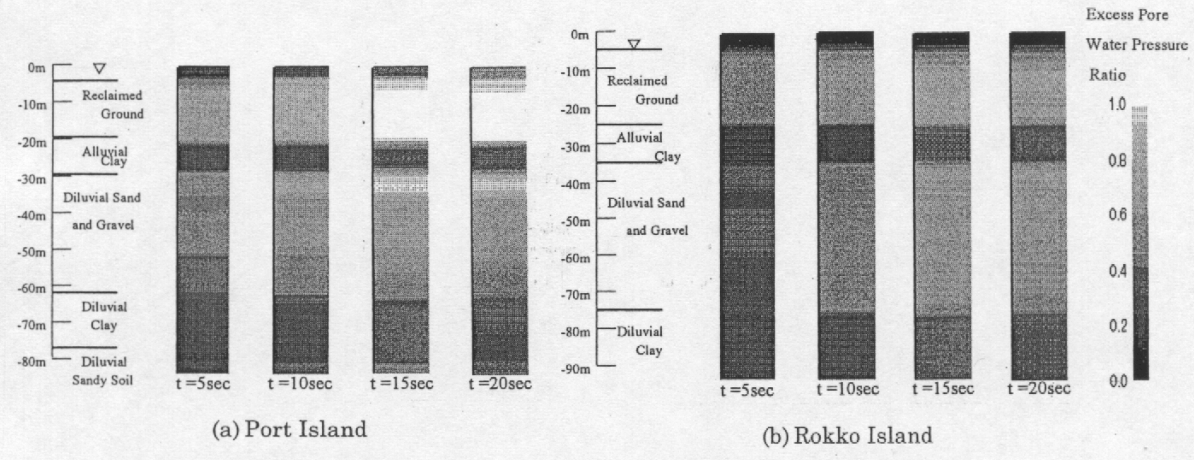


Fig.5 Distribution of excess pore water pressure ratio.

TIME-DEPENDENT AMPLIFICATION RATIO DUE TO DICREASE OF EXCESS PORE WATER PRESSURE

The time-dependent amplification ratio due to the decrease of excess pore water pressure is investigated. It could be caused by the recovery of the rigidity of sandy soils that once liquefied. Figure 6 shows the variation of the acceleration amplification ratio from G.L.-83m level to the ground surface at PI station as well as that from GL.-154.5 m to the ground surface at RI station. It is observed in Fig.6(a) that the amplification ratio decreases in horizontal ground motion just after the main event, and then gradually recovered in about a weak. On the other hand, the amplification factor of up-down component, which mainly consists of P-wave does not change so such as that of horizontal components. In the case of RI station in Fig.6(b), the recovery of the amplification ratio is not evident, since the records were not obtained until 90 hours after the main event. Figure 7 shows the variation of the velocity amplification ratio. In the case of PI station the recovery in the horizontal components is recognized as the case of peak acceleration.

The recovery of the frequency contents are shown in Fig.8. Figure 8(a) shows the variation of the amplification ratio of acceleration response spectrum for f =7.14 Hz and 1.54 Hz at PI station. The decrease and the recovery of the amplification ratio is predominant for the high frequency content (f =7.14 Hz), and they are not clear for the
middle frequency content (f =1.54 Hz). The recovery of the amplification ratio for f =7.14 Hz is quite similar to that of peak acceleration and velocity.
At both the artificial islands the excess pore water pressure were observed. Though the observation sites of the two artificial islands where the excess pore-water pressure were measured, are not close to the array observation stations, the soil profiles are similar to those of array observation stations, respectively. Figure 9 shows the variation of the excess pore water pressure at both the islands after the main event. Though there are not enough data points, it is observed in Fig.9(a) that the excess pore water pressure decreased in some hundreds hours to the level before the main event. This is quite consistent with the recovery of the amplification ratio of the peak acceleration, velocity, and high frequency content.

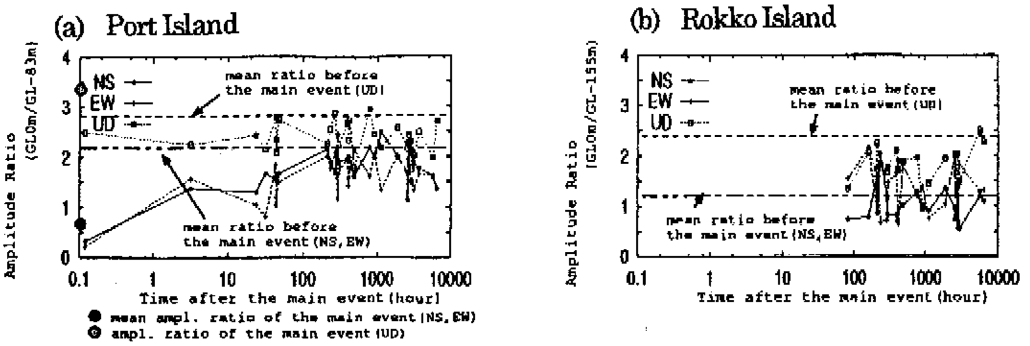


Fig.6 Time dependent amplification characteristic of peak acceleration.

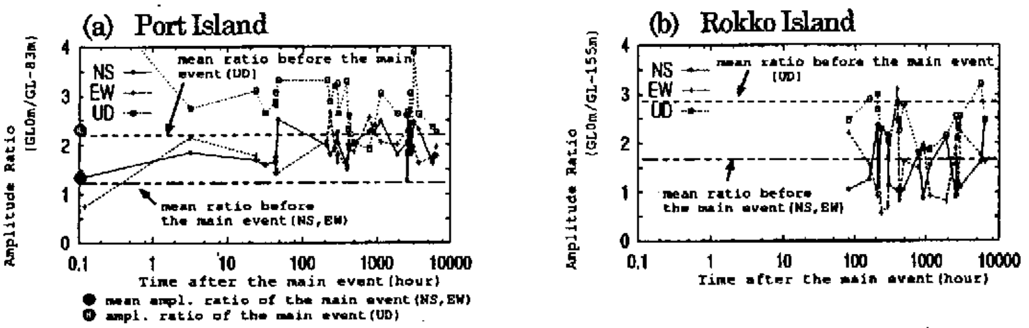


Fig.7 Time dependent amplification characteristic of peak velocity.

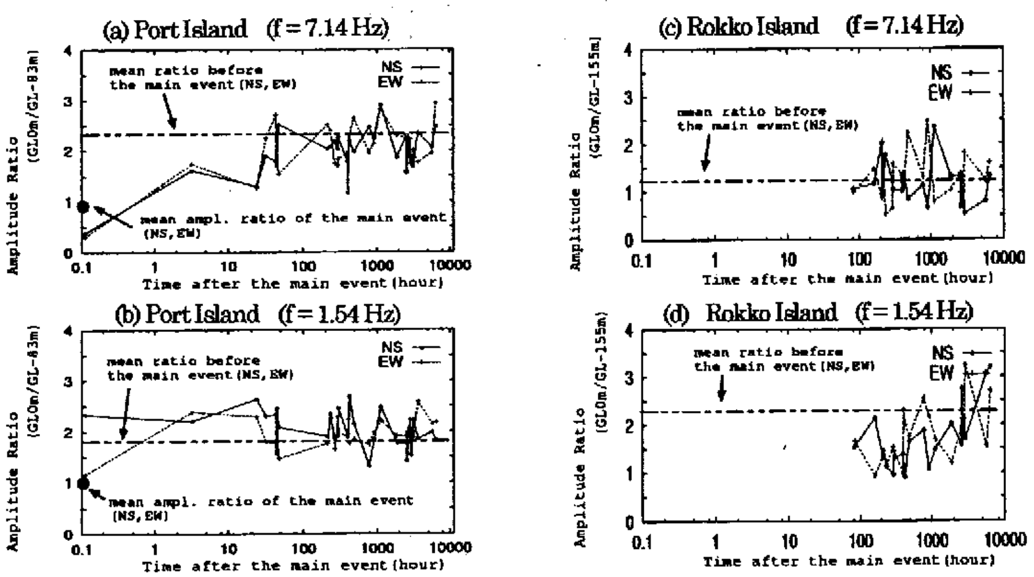
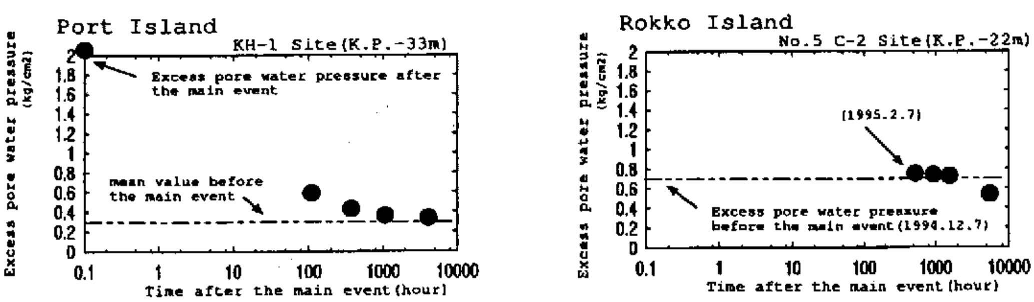


Fig.8 Time dependent amplification characteristic of response spectra.



(a) Port Island (b) Rokko Island

Fig.9 Variation of excess pore water pressure ratio.

CONCLUSIONS

The amplification characteristic of strong ground motion at two reclaimed lands were investigated based on the borehole records obtained from 39 earthquakes including the 1995 Hyogoken Nambu Earthquake. The major conclusions can be summarized as follows.

(1) The amplification characteristic of peak ground motion and spectral contents at Port Island and Rokko Island in Kobe City were discussed. The borehole array records at the two islands are classified regarding their recording term such as before and after the 1995 Hyogoken Nambu Earthquake.
(2) It was found that the amplification characteristic depended on the softness of the alluvial layer under the reclaimed sand. The consolidation term of the alluvial layer at PI station is about 26 years and that of RI station is 16 years. It was pointed out that the ground motion was not amplified at RI station where the shear wave velocity of alluvial layer was less than that at PI station. This is considered as one of the reasons for the difference of the level of liquefaction at these islands during the main event.
(3) Two techniques for response analysis of ground were applied to the two borehole stations. One is the modified equivalent linearization technique in frequency domain, and the other is the effective stress-based liquefaction analysis. In the former analysis, response analysis for several levels of input motion were performed and the results were consistent with the borehole records; namely, the very soft alluvial layer at RI station could reduce the ground motion propagated to upper reclaimed layer, which is so-called base isolation effect. The effective stress-based liquefaction analysis at those two stations with the same input motion shows that the liquefaction is much severe at PI station, which is quite consistent with the observed data.
(4) The time-dependent amplification ratio resulted from the recovery of the soil rigidity after the main event was specially demonstrated. It was found that the amplification ratio of peak acceleration, peak velocity as well as the higher frequency contents decreased considerably just after the main event, and then gradually recovered in about a week. The result was compared with the record of the excess pore water pressure at two islands.

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