A STUDY ON SEISMIC BEHAVIOR OF LIQUEFIED GROUND USING STORNGMOTION ARRAY RECORDS OF THE 1995 HYOGOKEN-NAMBU EARTHQUAKE

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SUMMARY

Strong motion records were obtained during the 1995 Hyogoken-Nambu earthquake at the East Kobe Bridge array station located in reclaimed land approximately 25km away from the epicenter. Around the site, there were many sand boils due to severe liquefaction of reclaimed fill using decomposed granite soil **"**Masado.**"** One-dimensional effective stress analysis and equivalent linear analysis considering liquefaction were conducted to examine the seismic behavior of liquefied ground during an earthquake. In the equivalent linear analysis, the shear moduli of liquefied layers were reduced to between 1/20 and 1/200 of the initial values to take account of liquefaction. The reducing ratio of shear modulus in the liquefied layer was determined according to analysis of the strong motion records obtained at Kobe Port Island array and Wildlife array. The effective stress analysis reproduced the characteristics of the waves at the ground surface, exhibiting the extended predominant period and reduced amplitude after the main phase due to liquefaction. Below the water level, the excess pore water pressure in the reclaimed layer rose to as high as the initial effective overburden pressure, and shear strain level exceeded 2 to 6%. It is considered that the **"**Masado**"** layer was liquefied during the earthquake. In the equivalent linear analysis, where the shear moduli of liquefied layers were reduced to between 1/50 and 1/100, differences were observed at the beginning when the strain was small and the high frequency components were predominant. However, the waveforms agreed well after the time when liquefaction occurred, and the maximum shear strain level in the liquefied layers agreed with that of effective stress analysis. It is considered that the equivalent linear method is useful for examining the seismic behavior of liquefied ground, provided that the shear modulus losses are properly estimated from strong motion records and so on.

INTRODUCTION

The 1995 Hyogoken-Nambu earthquake caused severe liquefaction in wide areas of reclaimed land around Kobe area. Liquefaction and liquefaction-induced large ground displacement in horizontal directions caused serious damage to shore structures and foundations of various structures [e.g. Hamada et al., 1996, Tokimatsu et al., 1996]. When comparing the observed strong motion records, the frequency characteristics at liquefied areas were different from those at inland areas. Surface soft ground shows nonlinearity during strong motions, with varying amplification characteristics depending on the strength of such motions. Liquefiable ground is considered to produce strong effects on the ground motion, as it shows particularly severe nonlinearity by build-up of its excess pore water pressure. In this study, one-dimensional (1-D) effective stress analysis and 1-D equivalent linear analysis were conducted to simulate the amplification of surface soft ground focusing on nonlinear amplification of liquefiable reclaimed waterfront land. The applicability of equivalent linear analysis considering liquefaction is discussed by comparison with the observed records and the results of effective stress analysis, to put this simplified method to practical use.

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SITE CONDITION AND METHOD OF SIMULATION

Site for Analysis

Figure 1 shows the East Kobe Bridge site (EKB) and Kobe Port Island site (KPI) in reclaimed land, where strong motion records were obtained from array observation during the 1995 Hyogoken-Nambu earthquake [Hagiwara et al., 1995, Development Bureau of Kobe City, 1995]. Around the site, there were many sand boils by severe liquefaction of reclaimed fill using decomposed granite soil **"Masado."** EKB is located at the western part of a reclaimed island, at the east end of Kobe about 25km from the epicenter. This island was reclaimed relatively recently between 1964 and 1970 by placing a surface layer of decomposed granite soil about 17m in thickness. The soil profile is shown in Figure 2. The 17m thick surface layer consists of reclaimed decomposed granite soil with a relatively low SPT N-value of 3 to 11, which is considered to have liquefied in the earthquake. Under this layer lies a layer of Holocene silty clay 8m thick on a Pleistocene sand layer. The soil layers can be regarded as almost horizontal from the results of soil investigations near the site. Seismographs were set at the level of G.L.-2.0m, which is regarded as the surface of the ground, and G.L.-34.0m, where the shear wave velocity is almost 300m/s. The analyses were conducted in regard to EKB, also in regard to another array observation site, KPI.

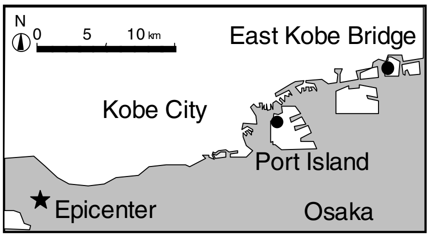


Figure 1: Location of observation sites

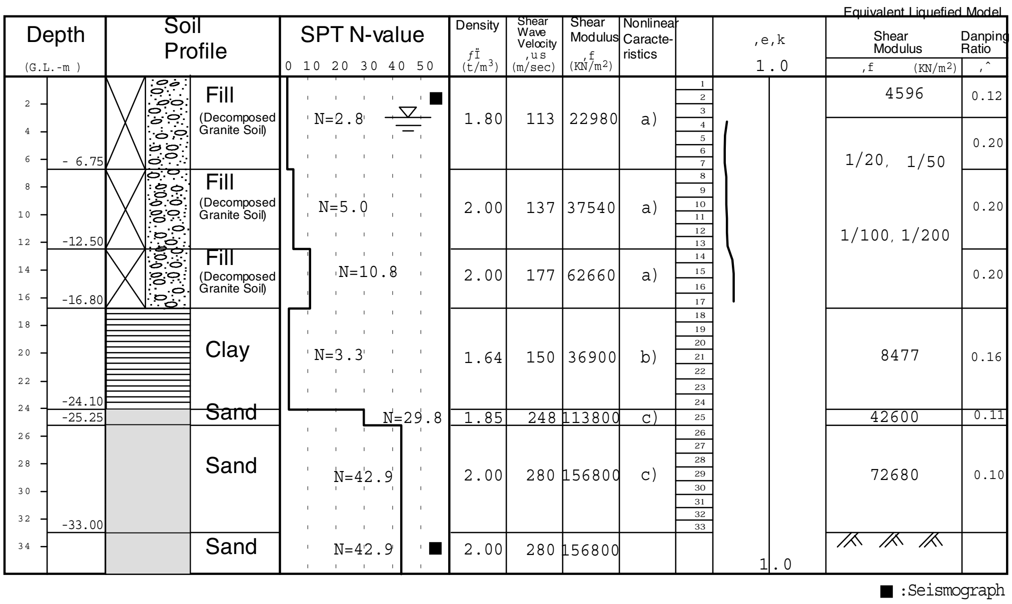


Figure 2: Soil Profile at East Kobe Bridge

Method of Simulation

The 1-D effective stress method and 1-D equivalent linear method are used in this simulation. The effective stress analysis directly evaluates the changes in the effective stress by considering the rise of the excess pore water pressure. The equivalent linear analysis evaluates nonlinearity of the ground equivalently as a linear material. It is generally difficult for this method to examine the behavior of liquefied ground with a very large shear strain, though this method reportedly explains well the amplification of strong motion at a site where the excess pore pressure rose to 75% of the confining pressure [Taniguchi et al., 1997]. In this study, we attempt to accurately and simply evaluate the behavior of liquefied soft ground by estimating the reductions in the shear modulus of a liquefied layer in detail. The results are compared with observed records and the result of the effective stress method to verify the applicability of the method. The codes of analysis are FLIP [Iai et al., 1985] as the effective stress method and SHAKE [Schnabel et al., 1968] as the equivalent linear method. The procedure of "equivalent linear analysis considering liquefaction" is shown in Figure 3. At first, a normal equivalent linear analysis is conducted. Liquefaction judgements of liquefiable layers are then made by comparing the liquefaction strength with the shear stress estimated by the equivalent linear analysis. A shear modulus considering liquefaction is given to a liquefied layer, and a converged value from the analysis is given to other layers. Linear analysis is then carried out to evaluate the amplification of the ground containing a liquefied layer. In this paper, this two-step analysis is referred to as "equivalent linear analysis considering liquefaction" [Miwa et al., 1998b]. In this method, a shear modulus considering liquefaction is estimated by observed strong motion records at liquefied ground, KPI and Wildlife [Holzer et al., 1989].

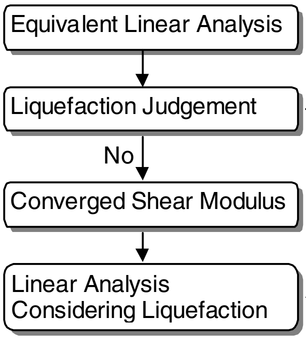


Figure 3: Procedure of equivalent linear analysis considering liquefaction

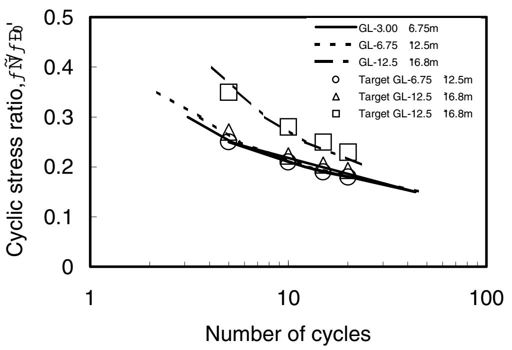


Figure 5: Liquefaction resistance of reclaimed fill (Masado)

Table 1: Liquefaction parameters for reclaimed fill (Masado)

	R_l20	φf	φp	Parameter of dilatancy				
		deg	deg	S_1	W_1	P_1	P_2	C_1
GL-3.00 - -6.75m	0.180	37.9	28	0.005	5.074	0.5	1.056	1.6
GL-6.75 - -12.5m	0.195	38.0	28	0.005	5.266	0.5	1.049	1.6
GL-12.5 - -16.8m	0.230	38.9	28	0.005	7.824	0.5	0.980	1.6

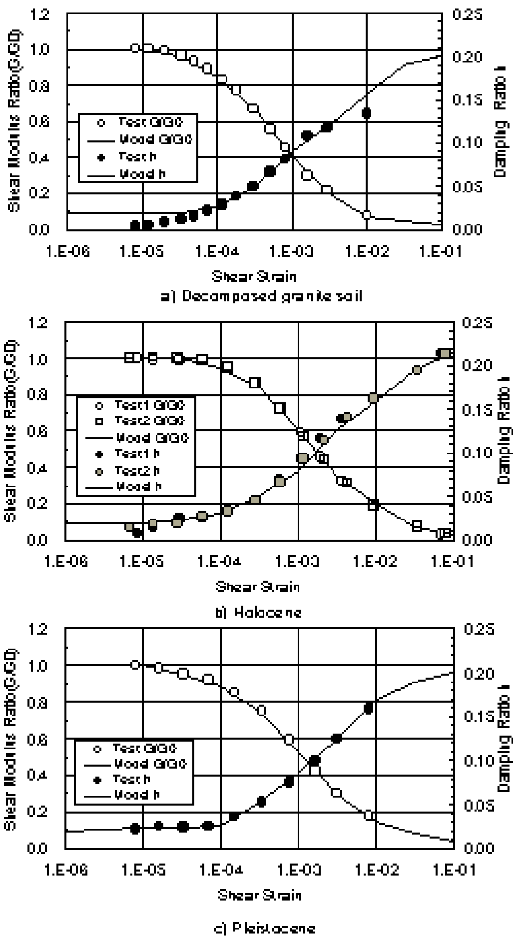
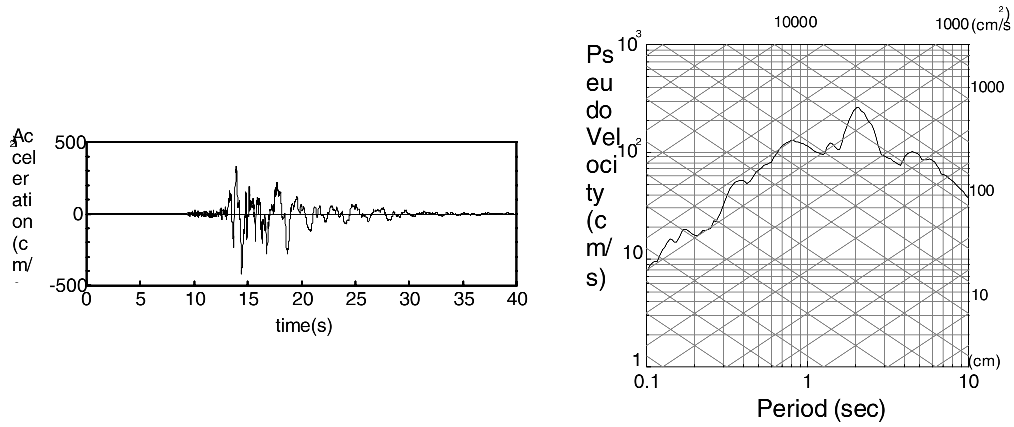


Figure 4: Relation of shear modulus and damping ratio versus shear strain

Surface Ground Model

Figure 2 shows the analytical model of EKB. Nonlinear characteristics evaluated by referring to past tests on samples from the same island [Ikeda et al., 1997, Mizutori et al., 1998] are shown in Figure 4 with the test results. The liquefaction strengths of decomposed granite soil were determined by SPT N-values. SPT N-values were corrected in regard to effective overburden pressure by the method of Liao [Liao et al., 1986], and liquefaction strengths were then estimated according to the method of Tokimatsu and Yoshimi [Tokimatsu et al., 1983]. The liquefaction strength and the element simulation results of the effective stress method are shown in Figure 5. Table 1 shows the liquefaction parameters of reclaimed fill for the effective stress analysis. The parameter setting for the nonlinear characteristics and liquefaction strengths are considered appropriate. Miwa [Miwa et al., 1998a] gathered the results of past research on the estimated values of shear modulus and shear strain in liquefied layers of KPI and Wildlife by back analysis of records and other methods, to examine the ratio of shear modulus in liquefied layers, and found that it is nearly 1/20 to 1/100 of the initial value and 1/50 on average. In the present case, the shear modulus in a liquefied layer is set at 1/50 of the initial value for the equivalent linear analysis considering liquefaction. Also, the cases of 1/20 to 1/200 are set to compare the behavior of response. Analytical ground model of KPI is determined by referring to the report of Kobe City Government [Development Bureau of Kobe City, 1995].



a) Time history b) Response Spectra (h=5%)

Figure 6: Input motion of analysis (Observed record of GL-34m at EKB)

Input Motion for Simulation

Because the waves in the predominant direction control the rising of excess pore water pressure, so the waves of the predominant direction, 26 degrees anti-clockwise from the North direction at G.L.-34m in East Kobe Bridge were used for analysis. Figure 6 shows the time histories and response spectra (h=5%) of input motion. In the case of KPI, waves of NS components at the deepest point of G.L.-83m in a gravel layer were used. In both cases, observed waves are used for input motions (E+F).

SIMULATION AT EKB

An effective stress analysis, equivalent linear analysis, and equivalent linear analysis considering liquefaction were conducted in regard to EKB. The results were compared with one another and the observed records to examine the applicability of these analysis methods. Figure 7 shows the observed and computed acceleration time histories at the ground surface (G.L.-2m). Figure 8 shows the maximum response distribution by the analysis using the observed record at G.L.-34 m as the input motion. Figure 9 shows the pseudo velocity response spectra with 5% damping.

In the observed acceleration time histories, the waveforms show extended predominant periods and reduced amplitudes from the latter half of the main phase, which suggests the liquefaction of the "Masado" layer. Liquefied reclaimed fills and Holocene clay, which show strong nonlinearlity during strong motions, severely affects the amplification of ground motion. The effective stress analysis, which can consider the changes in the effective stress due to the increase in the excess pore water pressure, generally explains the characteristics of the waveforms. Below the water level, the excess pore water pressure in the "Masado" layer rose to as high as the initial effective overburden pressure, which indicated that the liquefaction was successfully simulated. The shear strain exceeded 2 to 6% in the "Masado" layer and severely affected the amplification. On the contrary, in the equivalent linear analysis, as excess pore water pressure was not considered, only the distribution of maximum shear strain was on the same level, while maximum acceleration, relative velocity, and relative displacement were much different from those of effective stress analysis. The phase gained at the surface after the initial two waves of the main phase and the amplitude were so large in the acceleration time histories. Accordingly, this method is not capable of accurately evaluating the effects of liquefaction, though it can roughly explain the seismic response before liquefaction.

An equivalent linear analysis considering liquefaction, where the shear moduli in liquefied layers were set at 1/50 of the initial value, was then conducted. In the acceleration time histories at the ground surface, the extended predominant period and reduced amplitude from the latter half of the main phase were well explained, though the phase was delayed in the first half of the main phase, because a constant shear modulus was given throughout the analysis. Also, the maximum responses agreed well with those of observed record and effective stress analysis. It is considered that the equivalent linear method is useful for examining the seismic behavior of liquefied ground, provided that the shear modulus losses are properly estimated. Comparing the response spectra of these analyses, it is found that the shape of the spectra approaches the observed value, particularly in the predominant period, by considering liquefaction. Figures 10 to 12 show the results of comparing the reducing ratio of shear modulus in liquefied layers from 1/20 to 1/200 of the initial value. In the case of 1/20, it is not capable of evaluating the liquefaction, the same as ordinary equivalent linear analysis. On the contrary, in the case of 1/200, the predominant period was longer than the observed one because of overestimating the reducing of the shear modulus. Maximum responses, waveform, response spectra were best fit to the observed record in the case of 1/50 of the initial value. It suggests that evaluation of the reducing ratio of shear modulus from the observed records was appropriate.

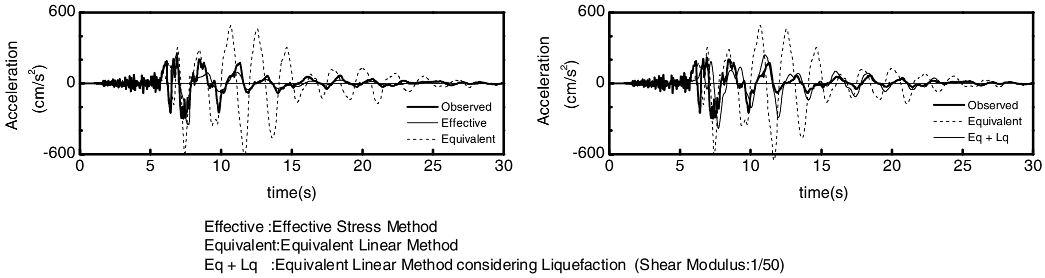


Figure 7: Comparison of acceleration time histories at the surface (East Kobe Bridge)

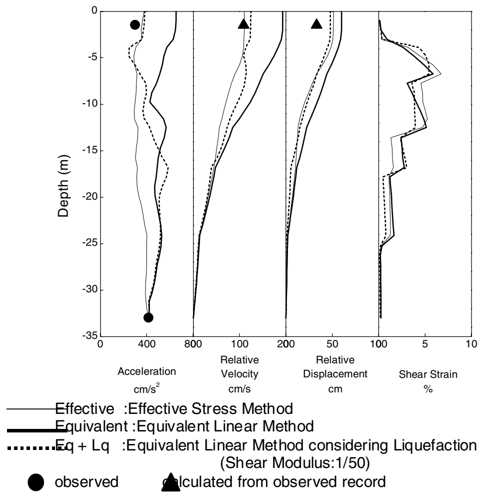


Figure 8: Maximum response distribution at East Kobe Bridge

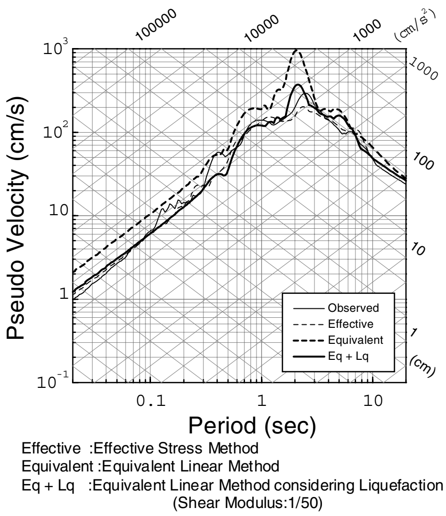


Figure 9: Pseudo velocity response spectra(h=5%)

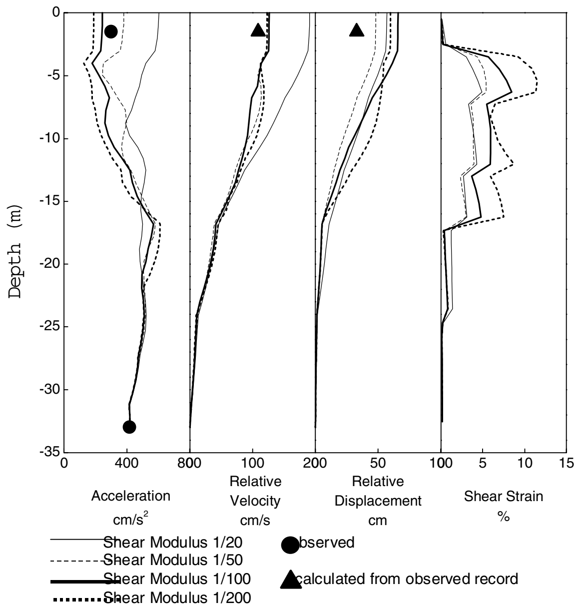


Figure 10: Maximum response distribution at East Kobe Bridge

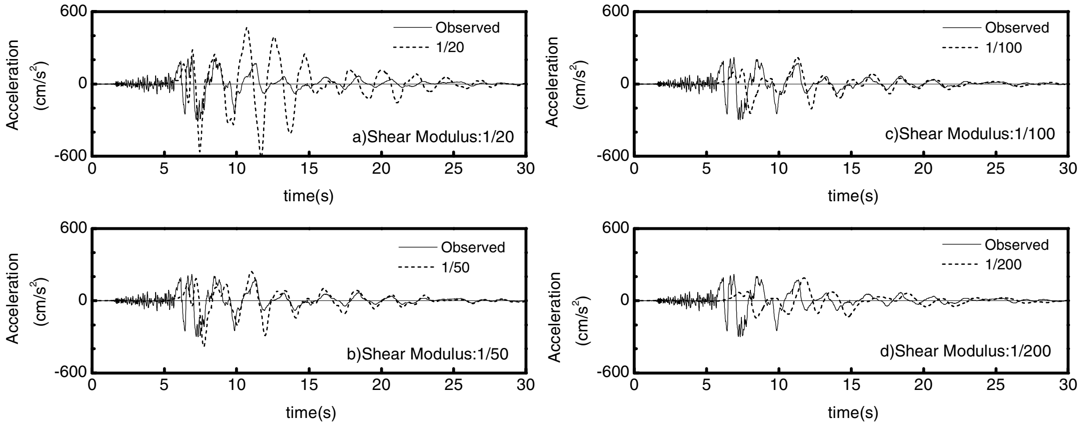


Figure 11: Comparison of acceleration time histories at the surface (EKB)

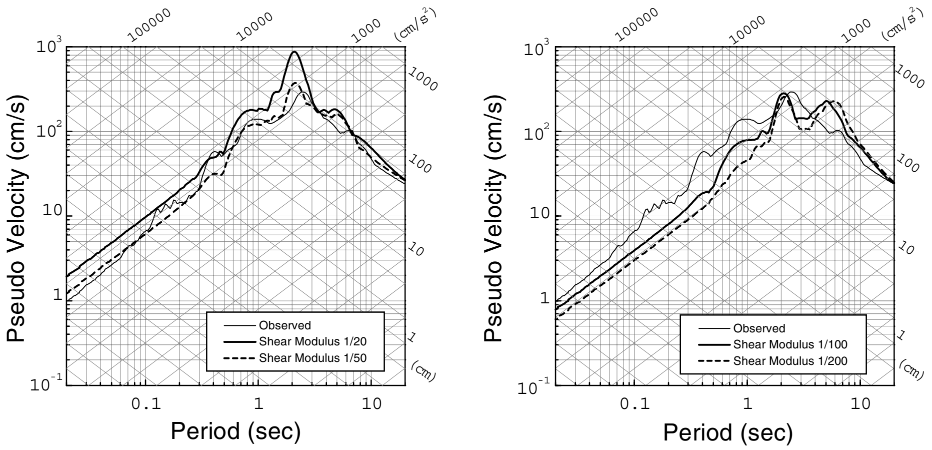


Figure 12: Pseudo velocity response spectra (h=5%) (EKB)

SIMULATION AT KPI

Equivalent linear analysis and equivalent linear analysis considering liquefaction were conducted in regard to KPI [Miwa et al., 1998b]. Figure 13 shows the maximum response distribution by the analysis using the observed record at G.L.-83m as the input motion. Figure 14 shows the observed and computed acceleration time histories at the ground surface and G.L.-16m, which is the boundary between the reclaimed decomposed granite soil layer "Masado" and the Holocene clay layer. Figure 15 shows the pseudo velocity response spectra with 5% damping.

In the equivalent linear analysis, in which the excess pore water pressure was not considered, the phase was delayed at G.L.-16m, but gained at the surface after the initial two waves of the main phase in the acceleration time histories. It is considered that the shear strain in the Holocene clay layer was estimated larger, and the strain in the "Masado" layer was estimated smaller than the actual behavior. On the other hand, in the equivalent linear analysis considering liquefaction, the waveforms at G.L.-16m agreed with the observed record. At the ground surface, the extended predominant period and reduced amplitude after the latter half of the main phase were well explained. Comparing the response spectra of these two analyses, it is found that the predominant period and shape of the spectra approaches the observed value by considering liquefaction. As mentioned above, it makes clear that the equivalent linear analysis considering liquefaction is judged useful for estimating the behavior of liquefied ground including not only a liquefied layer but also another soft layer.

CONCLUSIONS

One-dimensional analyses of the ground at array observation stations in reclaimed land liquefied during the 1995 Hyogoken-Nambu earthquake were conducted. The conclusions obtained from this study are summarized as follows:

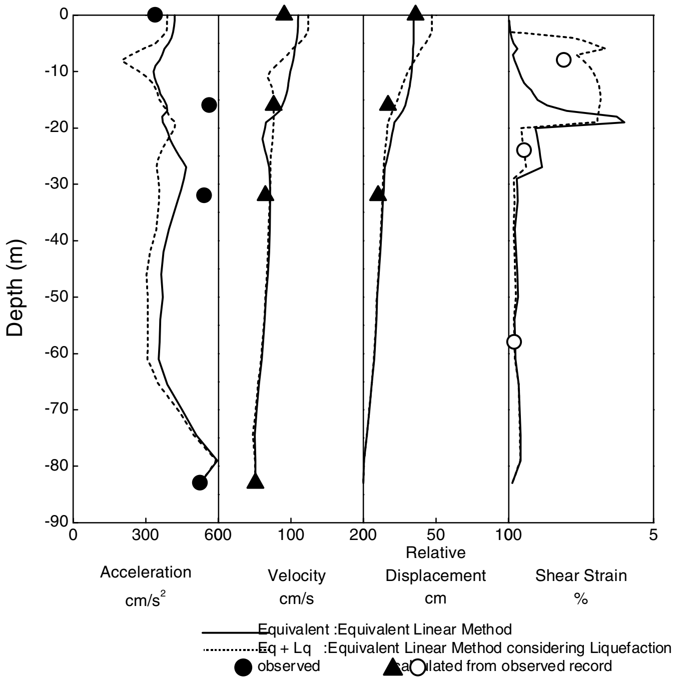


Figure 13: Maximum response distribution at Kobe Port Island

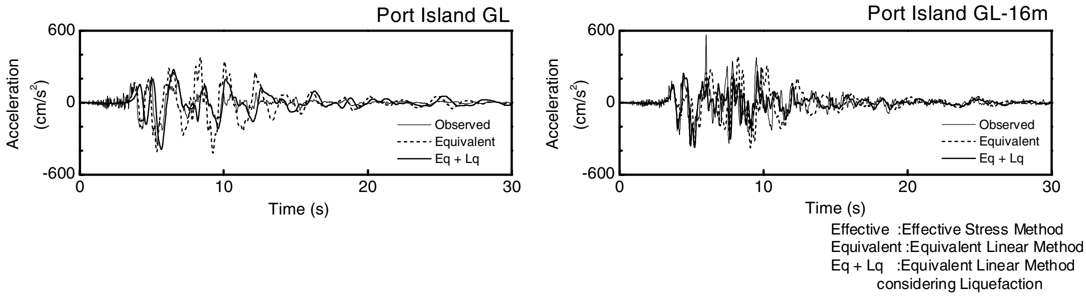


Figure 14: Comparison of acceleration time histories (KPI)

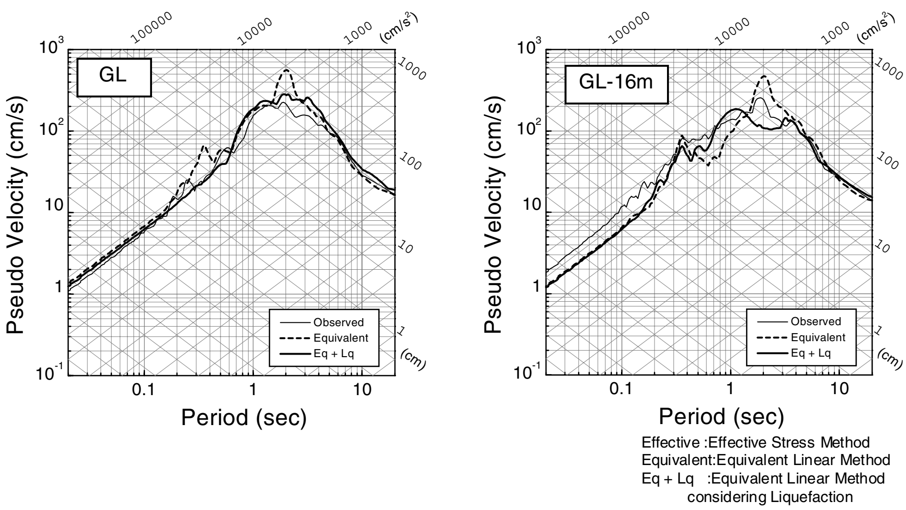


Figure 15: Pseudo velocity response spectra (h=5%) (KPI)

1) The high nonlinearity of soft surface ground during strong motions severely affects the amplification of ground motion. Longer-period components are predominant at seaside areas with thick soft layers including liquefied reclaimed fills and Holocene clay, which show strong nonlinearlity.

2) It is considered that 1-D effective stress analysis is useful for evaluating nonlinear amplification of liquefied fills and soft surface layers of reclaimed land, comparing the analysis results and observed records at EKB.

3) Comparing the analysis results and observed records at EKB and KPI, seismic behavior of both a liquefied layer and clayey soft layer in liquefied ground during an earthquake can be evaluated properly from the standpoint of engineering practice by 1-D equivalent linear analysis considering liquefaction.

4) The shear modulus losses can be properly estimated from strong motion array records. So, equivalent linear analysis considering liquefaction is useful for examining the seismic behavior of liquefied ground, provided that properly evaluated shear modulus losses are used.

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