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STUDY ON DYNAMIC RESPONSE OF RECLAIMED AND SOFT GROUND OF MAN-MADE ISLAND IN KOBE HARBOR DURING 1995 HYOGOKEN NANBU EARTHQUAKE AND LIQUEFACTION CONTROL

Tadahiro FUKUSUMI[1] And Masao KOBA[2]

SUMMARY

Earthquake response of filled man made island of the Kobe harbor during the 1995 Hyougoken Nambu Earthquake is dealt with. Dynamic response characteristics and effects of SPT N-value on liquefaction for such soft grounds are examined. The one-dimensional analysis based on effective stress analysis method considering cyclic mobility is adopted. For modeling of the soil layers, soil parameters such as SPT N-value by standard penetration test and shear wave velocity Vs by PS logging is used. Absorbed energy by hysteresis loop of soils are also calculated as well as ordinary responses such as acceleration, stress and strain responses. The relation between distribution of absorbed energy and liquefaction becomes clear. As conclusion, the portion where liquefaction occurs becomes deeper and the damages such as ejection of water and soil and resultant subsidence can be restrained by increase of SPT N-value.

INTRODUCTION

During the Hyougoken Nambu earthquake in 1995 of magnitude M=7.2, wide spread liquefaction occurred along the seaside area of Kobe city. The liquefaction was particularly extensive and severe in the reclaimed lands of the man-made Islands. The Port Island is reclaimed between 1966 and 1981. While the Rokko Island which is east of the Port Island is reclaimed about more than ten years later between 1972 and 1990. Common to both islands, ejection of water and soil was observed to hardly occur in the site where subsoil improvement is executed. While the ground without improvement suffers different degree of ejection. The ejection of water and solil of the Rokko Island was much less severe compared to the Port Island. The distance between these two island is only about 6km and both grounds are consisted of soil layers of different depth but the soil layers are the same, which are, from the ground surface, alluvial clay, diluvial sand and diluvial clay layers and so on. The difference of susceptibility of liquefaction is interpreted from the geological aspects such as difference of grain size distribution and other properties of the fill (Tanimoto, 1995) and degree of consolidation of alluvial clay layer. In this paper, earthquake response analysis is carried out by using the multi layered ground model and investigated on the difference of behavior of these islands, especially focusing from the constitution of soil layers

2. OUTLINE OF ANALYSIS

The Relation between stress and strain is assumed to be expressed by Ramberg-Osgood Model. Adopting Masing's law, thus following equation are used.

$$\gamma = \frac{\tau}{G_o}\left(1 + \left|\frac{\tau}{\tau_r}\right|^{\beta}\right) \tag{1}$$

[1] Dept of Architecture and Civil Engrg., Faculty of Enrgr., Kobe University Kobe-si, Japan, Email: fukusumi@kobe-u.ac.jp
[2] The Kansai Electric Power Co., Inc., 3-5Nakanoshima, cyuo-ku, osaka, Japan, Email: k461643@kepco.co.jp

where G_0 is initial shear modulus, τ_r is reference stresss and •is a parameter relates to damping of the soil. The excess pore water pressure u is evaluated by the following equation (Seed et al, 1976).

$$\frac{u}{\sigma_0'} = \frac{2}{\pi} Arc\sin\left(R_n^{\ 1/2\alpha}\right) \qquad (2)$$

where •$_0$' is initial effective confining stress, • is a parameter to represent the increase of excess pore water pressure(•=0.7) and R_n is a parameter to express the cumulative damage due to liquefaction which takes from 0 to 1.

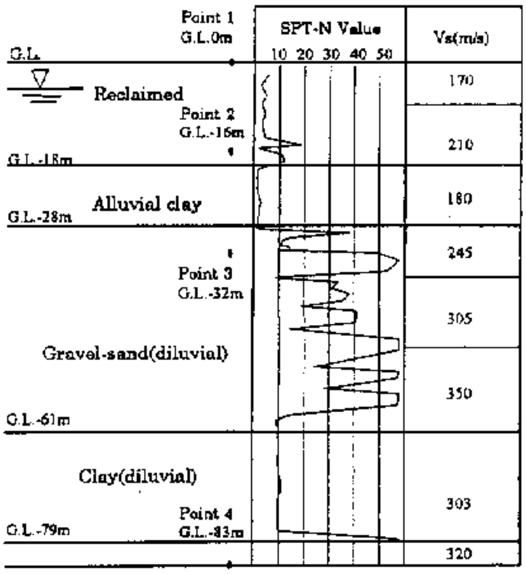

Fig.1 Profile of ground and setting points of seismometers

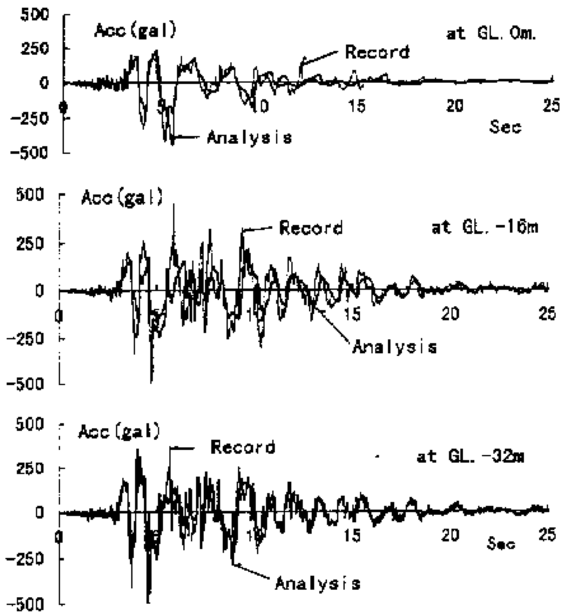

Fig.2(a) Time histories of accelerations

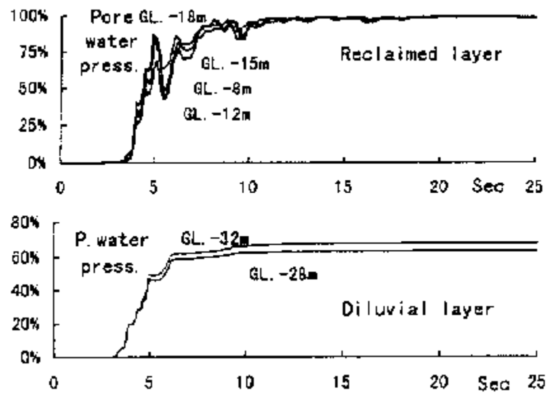

Fig.3 Time histories of pore water pressure for fill and diluvial layer

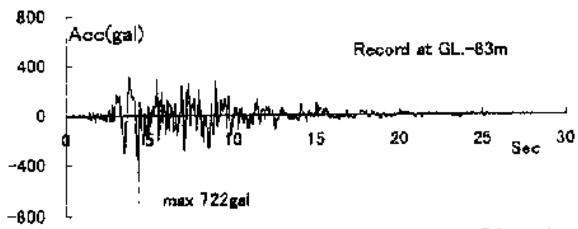

Fig.2(b) Acceleration of Port Island at GL.–83m (in-put wave for the analysis)

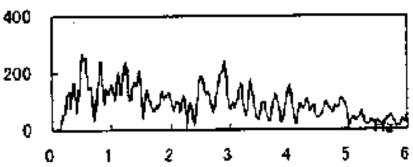

Fig.2(c) Fourier spectrum of acceleration of Port Island at GL.–83m

The acceleration input used in this study are accelerations observed by the vertical array of the downhole strong motion observation site of the Kobe Port Island during the 1995 Hyougo-ken Nambu earthquake. The observation site was not improved and ejected water and soil are observed. As shown in Fig.1, earthquake waves were recorded at four depths (about GL.-83m, -32m, -16m and 0m). The resultant acceleration waves in principal direction obtained by the combination of the NS and EW waves at depth of GL-83m is used as the acceleration input for the analysis. The maximum acceleration is 720 gal and is shown in Figs.2(b) together with its Fourier spectrum of Fig.2(c).

As the results of soil exploration before earthquake which are also achieved by Development Bureau of Kobe City, the N-value (SPT N-value by standard penetration test) and shear wave velocity V_s obtained by PS logging are shown in Fig.1. Near surface, approximately N=5 and at lower portion of the fill, N=10 and the ground seems to be loose. Near the depth of GL.-18m to –28m is an alluvial layer, and the initial shear modulus is about 1/2 of the adjacent diluvial gravel sand layer. The N-value of upper portion along several meters of this gravel sandy layer is about N=15 and this layer is also loose.

Soil parameters used in the simulation analysis on the ground of the Port Island is shown in Table 1. Where the density and shear modulus Go by using the relation of $Go=\bullet V_s^2$ are referred to the report of Kobe city (1995). For the sandy soil, the internal friction angle• of the sandy soil is evaluated as $\bullet=\bullet$20N+15 and shear strength is determined based on the Mohr-Coulomb’s failure criteria. For clay layer, shear strength is taken as 1/2 of the uni-axial test result. The parameter • relates to the maximum damping ratio and it can be estimated based on the test result. Relative density and liquefaction resistance R_{20} (shear stress ratio $\bullet/\bullet_o$’ of which causes the soil layer liquefy with 20 times of cyclic loading) were evaluated by using the N-value and the empirical formulation of Tokimatsu and Yoshimi (1983). In the earthquake response analysis, one dimensional lumped mass model is adopted and the dissipation of the excess pore water pressure is not considered.

3. INVESTIGATION OF EARTHQUAKE RESPONSE

For the Port Island, earthquake response analysis of earthquake observation site where no subsoil improvement is done is carried out as simulation analysis. And its imaginary ground models are also calculated to investigate effects of increase of the N-value. In case of the Rokko Island whose, each soil layer is thicker different from the Port Island. Similar analysis is done and the difference of susceptibility of liquefaction of these two islands is discussed.

Table 1 Parameters of soil for analysis

Depth (m)	Stratum	density (gf/cm^3)	SPT-N value	Internal Friction angle(°)	Initial rigidity G_o(kgf/cm^2)	Referential Strain γ_r(%)	Liq.fac. Resistance R_{20}	Max.damp. factor h_{max}	Relative Density D_r(%)
2.0	Reclaimed	2.0	6.6	26.5	367	0.0121	–	0.22	68.8
5.0		2.0	4.7	24.7	609	0.0171	–	0.22	58.8
8.0		2.0	4.6	24.6	757	0.0210	0.22	0.22	54.3
12.0		2.0	5.7	25.7	900	0.0277	0.22	0.22	54.3
15.0		2.0	10.0	29.1	1020	0.0403	0.24	0.22	58.9
18.0		2.0	7.0	26.8	1120	0.0378	0.21	0.22	52.7
23.0	Alluvial clay	1.64	3.1	–	542	0.1070	–	0.30	–
28.0		1.65	3.8	–	546	0.1410	–	0.30	–
32.0	Gravel-sand Diluvial	1.75	16.7	33.3	1070	0.0852	0.24	0.26	59.4
37.0		1.83	16.0	32.9	1500	0.0676	0.23	0.24	57.3
41.0		1.83	52.1	47.3	1590	0.1090	0.41	0.21	80.5
45.0		1.83	35.5	41.6	1660	0.1000	0.29	0.21	68.3
50.0		1.83	39.8	43.2	1740	0.1090	0.29	0.21	68.8
55.0		1.86	56.2	48.5	1820	0.1290	0.34	0.21	75.4
61.0		1.86	66.4	51.4	1910	0.1420	0.36	0.21	77.4
65.0	Diluvial Clay	1.70	12.6	–	1590	0.0774	–	0.20	–
70.0		1.70	11.1	–	1590	0.0774	–	0.20	–
75.0		1.70	11.0	–	1590	0.1180	–	0.20	–
79.0		1.70	12.5	–	1590	0.1180	–	0.20	–
83.0	Gravel-sand	2.0	48.6	46.2	2090	0.1570	–	0.20	63.6

EARTHQUAKE RESPONSE CHARACTERISTICS OF THE PORT ISLAND

The ground surface is 4m above the sea level and ground water level is 4m below the ground surface. By using the soil parameter for twenty lumped mass model (table 1), the simulation analysis of earthquake observation site subjected to the input earthquake motion at the bottom of the diluvial clay layers (GL.-83m) is carried out. In Fig.2, acceleration time histories obtained by analysis and observation are shown in comparison. Fig.3 shows the excess pore water pressure responses of reclaimed layer and diluvial layer. About five seconds after beginning, remarkable increase of excess pore water pressure is calculated. Figs.4 and 5 show the hysteresis curves and effective stress paths of reclaimed layer and diluvial layer as representatives. The hysteresis curve shows inverse "S" shape due to the occurrence of cyclic mobility. Stress path hits the phase transformation line and recovery of effective stress can be seen. Fig.6 shows the results of maximum earthquake response distribution along depth.

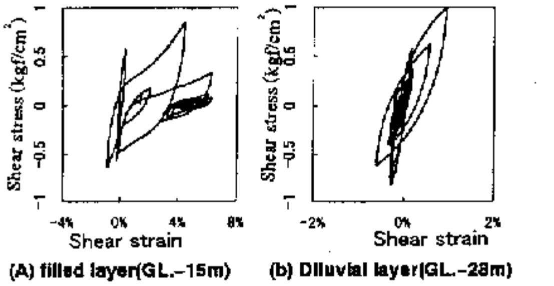

Fig.4 Hysteresis loops of fill and diluvial soil layer

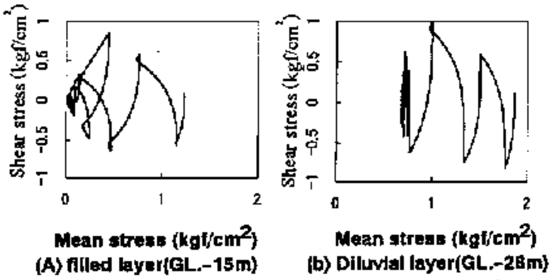

Fig.5 Stress paths of fill and reclaimed soil layer

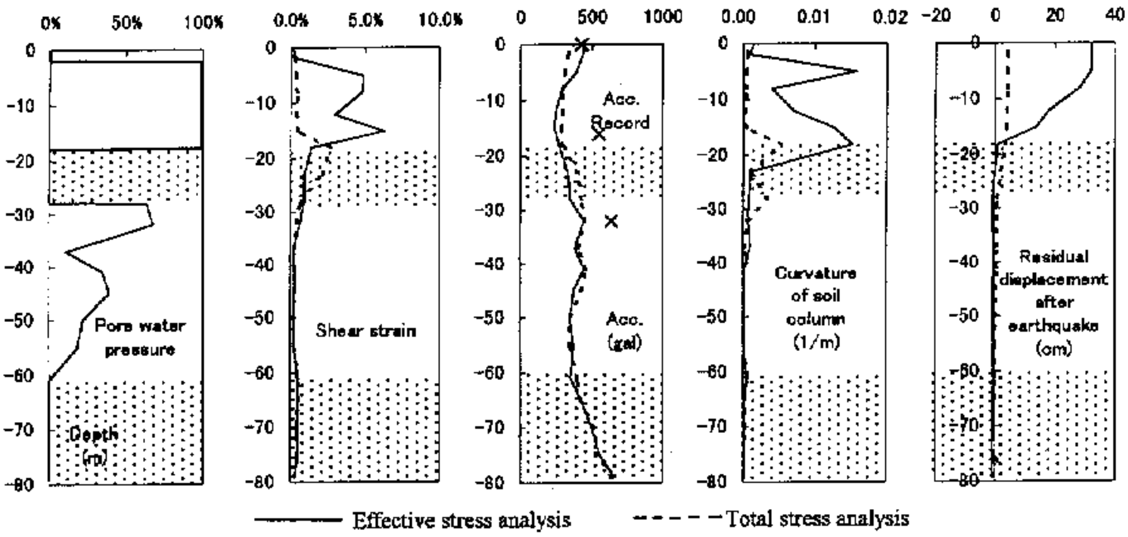

Fig.6 Vertical distributions of maximum responses of pore water, shear strain, acceleration, curvature and residual displacement

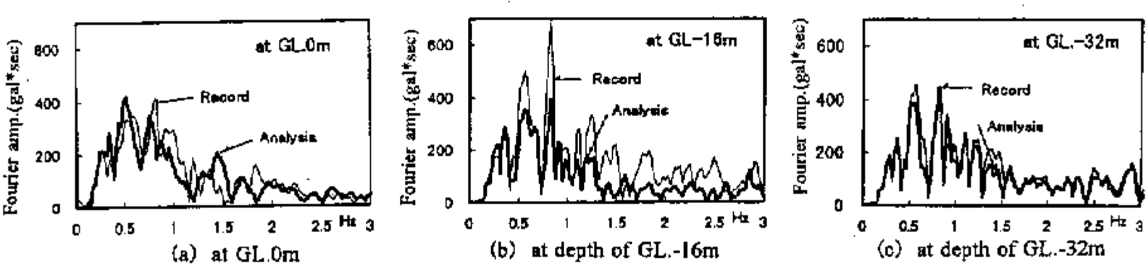

Fig.7 Fourier spectra obtained by analysis and record at three depths

The maximum responses by the total stress analysis without consideration of the pore water pressure development is also shown for reference. In the result of effective stress analysis, excess pore water pressure ratio of the fill under ground water level is almost 100% and liquefaction occurred. Excess pore water pressure of the upper portion of diluvial layer (just under the alluvial clay layer) is over 60 % and is considerably high. In the fill, the maximum shear strain is about 6%, in this case damping ratio of soil becomes more than 20%. In the region of the alluvial clay layer, acceleration is observed to decrease. The curvature (second derivative of displacement in vertical direction z) will be useful to estimate the response of pile foundation. Near the ground water level and near the boundaries of the fill and the alluvial clay layer, the curvature is approximately 0.01(1/m). As one of an experimental result of pre-stressed concrete pile of 60cm in diameter, curvature at yield point is 0.007(1/m) and curvature at the ultimate strength is 0.035(1/m), from which, in case of pile foundation, pile is estimated to have suffered the plastic deformation. The residual displacement after earthquake is about 35cm. These results by simulation analysis seem to be valid. In Fig.7, Fourier spectrum of time histories of acceleration responses obtained by the analysis and the observed record is shown. At underground level of GL.-32m and ground surface, result by analysis shows significant match to the result by observed record. While at GL.-16m, the analytical result is a little smaller than the observed record.

EARTHQUAKE RESPONSE OF IMAGINARY FILLED LAYER MODELS BASED ON THE GROUND OF THE PORT ISLAND

Based on the before descrived actual ground at an earthquake observation site, imaginary filled layer models with different N-value are also calculated here. The original ground model and three imaginary filled layer models are shown in Fig.8 where the N-value at the ground surface is designated as No. The distribution form is assumed to increase linearly along depth z as N=No+0.25z and three cases of No=5, 10 and 15 (density of soil is taken as •=1.8, 1.85 and 1.9, respectively) are considered corresponding to the soft to tight ground. Three levels are examined as input, i.e. maximum acceleration of acc.= 720, 540 and 360 gal.

Fig.9 shows acceleration time histories for input acceleration of 720gal. Difference appears near the peaks due to the change of the N-value. Fig.10 shows six kinds of maximum earthquake responses, which are excess pore water pressure ratio u/•$_o$’, shear stress ratio •/•$_V$’, shear strain • , acceleration, curvature and absorbed energy or hysteresis energy of soil layer. The response distributions of upper layers, especially in fill and alluvial clay layer are changed clearly due to the change of the N-value while in deeper layer, strain is very small and response distribution is little changed since the lower layers are relatively tight. In saturated man made islands, liquefaction occurs more easily near the ground surface than the deeper portion. In case of No=5 and 10, the fill liquefies even input level is small as maximum acc.=360gal. When the input acceleration level is large (acc.=720gal), liquefaction occurs when No=15, while in case of smaller input (acc.=360 and 540gal), liquefaction does not occur. The diluvial sandy layer adjacent to the alluvial clay layer is also susceptibility to liquefy, and the liquefaction occurs in case of maximum acc.=540 and 720gal. Among these six responses, acceleration and stress responses show smooth distribution. For these two responses, the change of the N-value effects only near the ground surface and the shear stress ratio is approximately 0.5. In the liquefied regions of the fill and lower part of alluvial clay layer, deformation (i.e. shear strain and curvature) is large. Absorbed energy response is great near the alluvial clay layer and is rather small in the fill. By increasing the N-value of the fill, excess pore water pressure and absorbed energy decreased in this layer. When the liquefaction is restrained by increase of the N-value, absorbed energy near alluvial clay layer increases. It can be mentioned that restraint of liquefaction does not mean the increase of the absorbed energy of the fill itself and it is induced by shift of absorbed energy to other lower layers. Decrease of energy absorption is correspondent to the decrease of deformation and excess pore water pressure response.

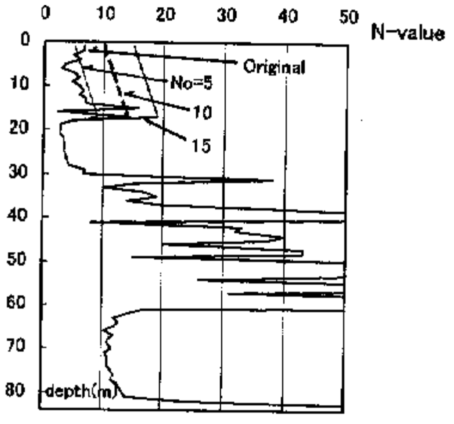

Fig.8 Ground models (Port Island)

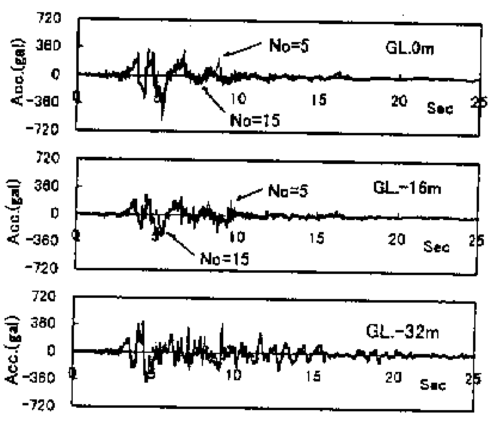

Fig.9 Acceleration time histories

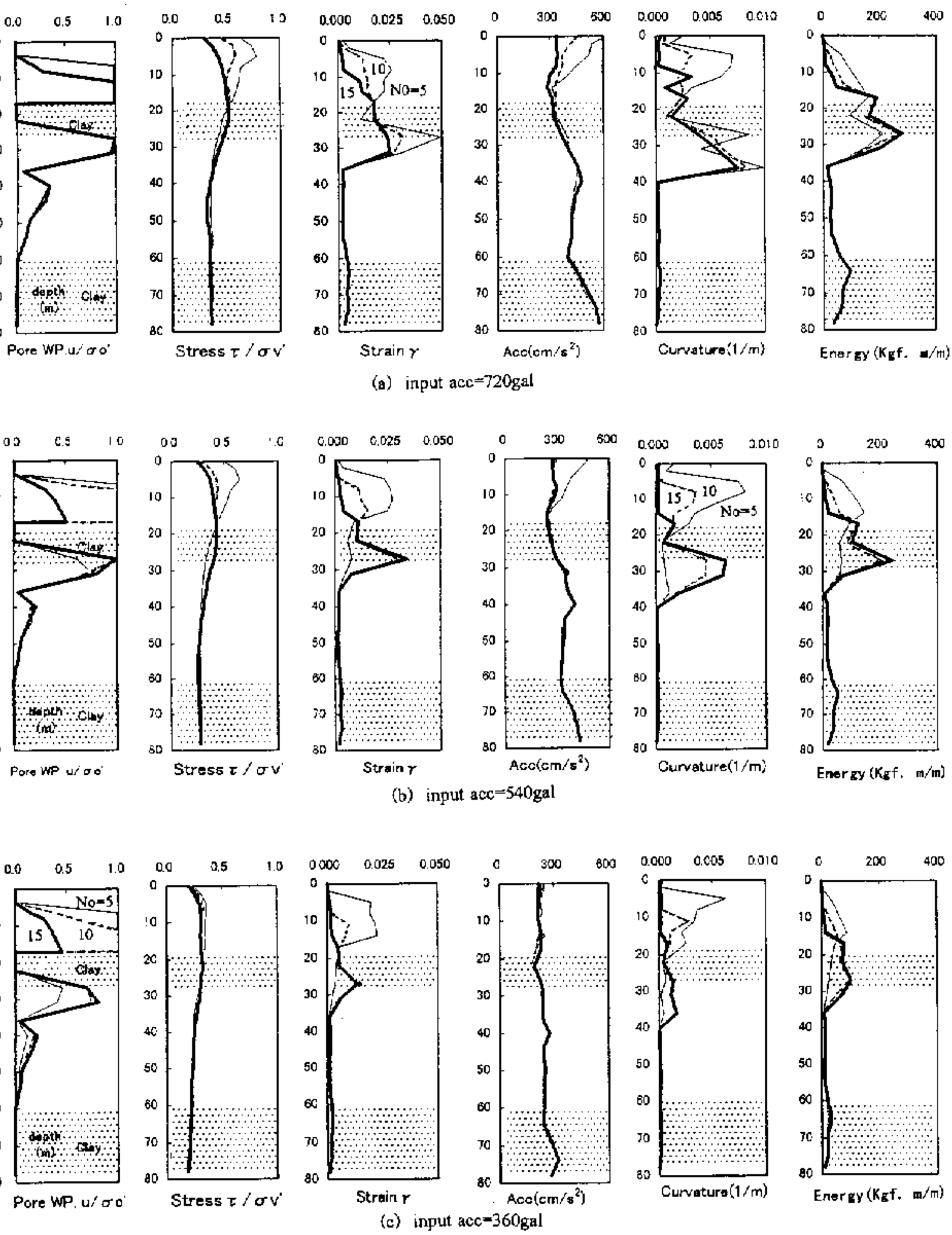

Fig.10 Maximum responses of imaginary filled layer models for different input levels

3.3 EARTHQUAKE RESPONSE OF THE ROKKO ISLAND AND ITS IMAGINARY FILLED LAYER MODELS

In case of the Rokko Island, ejection of water and soil due to liquefaction was little in comparison with Port. For the analysis, one of a site with soil exploration data of 100m depth was selected. As shown in Fig.11 of ground profile, each soil layers is thicker about by 20% and the N-value is higher (N•15), especially near surface, compared to those of the Port Island. The ground surface is about 8m high above the sea level which is higher

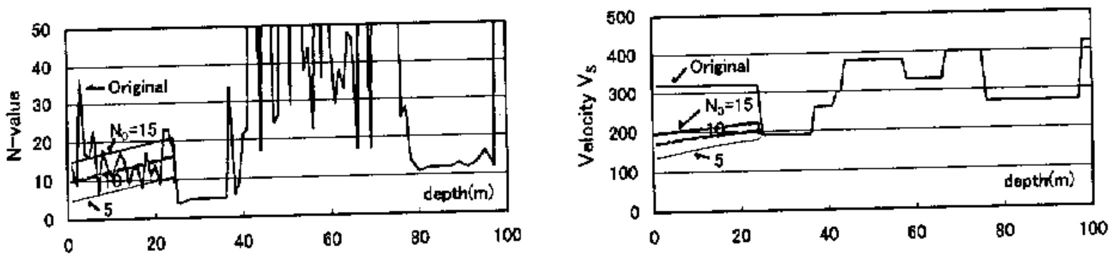

Fig.11 SPT N-value and V_S velocity by PS logging (Rokko Island)

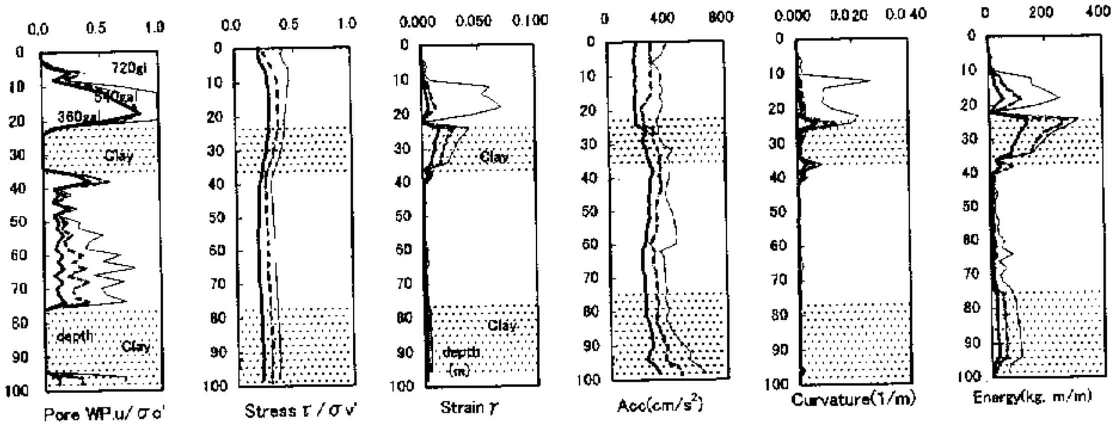

Fig.12 Maximum responses for different input level (Original model of Rokko Island)

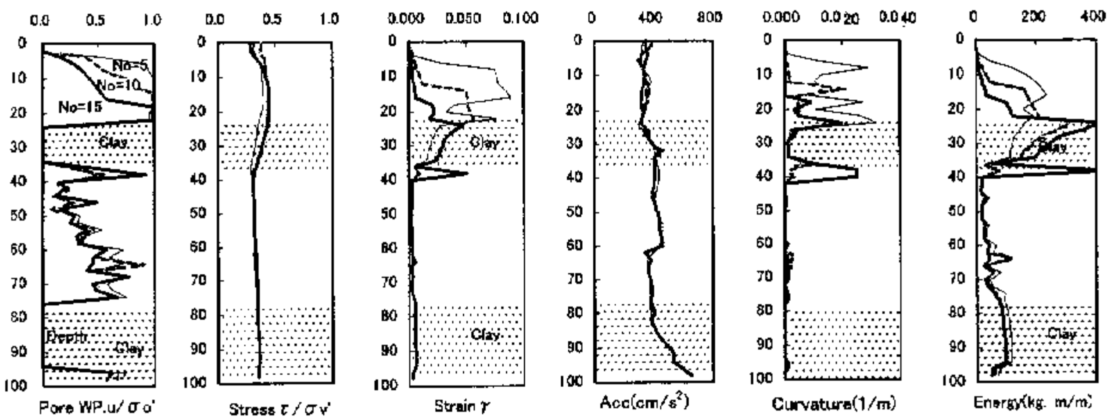

Fig.13 Maximum responses for different N-value (Imaginary model of Rokko Island)

about 4m compared to the Port Island and ground water level is estimated to be 4m below the ground surface. For the analysis, lumped mass model with fifty masses is adopted. It is not lucky that the earthquake wave of the underground was not observed, hence the ground motion of the Port Island is used as input motion at the bottom of the diluvial clay layers (GL.-100m). The fine content is not considered in the stress ratio. Fig.12 shows the maximum response distributions at three input earthquake levels (acc.=720, 540 and 360gal) . Shear stress and acceleration responses are considerably proportional to the input level while the other responses of pore water pressure, deformation and energy absorption responses are not proportional to the input level and remarkably non-linear, especially near the ground surface. Different from the case of the Port Island, responses of pore water pressure are large in deeper layers below GL.-40m. Since the N-value near ground surface is relatively large, the liquefaction occurred at deeper portion of the fill. Hence the ejection of soil and water to the ground surface may be restrained different from the Port Island. Fig.13 shows responses of imaginary ground models where the N-value and velocity Vs ($Vs=80.6*N^{0.33}$) are changed as shown in Fig.11. By increasing the N-value of the fill, excess pore water pressure and absorbed energy are also decreased in this layer and this tendency is similar in case of the imaginary filled layer models of the Port Island in section 3.2.

4. CONCLUSIONS

Earthquake response of the filled man made island of the Kobe harbor during the 1995 Hyougoken Nambu earthquake is dealt with. Dynamic response characteristics is made clear and effects of the SPT N-value on liquefaction are examined. From all the analytical results, followings are found; Results obtained by the analysis showed significant match to the observed records and the applicability of this analysis is confirmed. Large part of earthquake energy is absorbed by the alluvial clay layer which exists

under the fill while a little energy is absorbed at the fill. By increasing the N-value of the fill, excess pore water pressure and absorbed energy and deformation response decreased in this layer. It can be mentioned that restraint of liquefaction of the fill does not mean the increase of the absorbed energy of the fill itself and it is induced by shift of absorbed energy to other lower layers. It should be noted that the protection of liquefaction of the fill becomes practical under the condition that there are soft layers below the fill, which is able to absorb energy of the fill. Decrease of energy absorption is correspondent to the decrease of deformation and excess pore water pressure. Since the response characteristics of the ground depend on the distribution of the absorbed energy, excess pore water pressure, i.e. liquefaction can be controlled by the appropriate adjustment of absorbed energy distribution. The liquefaction seems to have occurred in both the Rokko Island and the Port Island. But in case of the Rokko Island, the N-value near ground surface is larger and liquefaction must occurred at deeper portion of the fill different from the Port Island. Thus, the ejection of water and soil on the ground surface must not be observed in the Rokko Island.

The followings are concluded finally. Dynamic characteristics of man-made islands in Kobe harbor and the relation between distribution of absorbed energy and liquefaction become clear. The damage of ejection of soil and water by liquefaction is considered to be controlled by increase of the SPT N-value.

5. ACKNOWLEDGEMENT

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