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EFFECT OF MULTI-DIRECTIONAL LOADING AND INITIAL STRESS ON LIQUEFACTION BEHAVIOR

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ABSTRACT

Real earthquake loading consists of multidirectional components but most of analyses are done in one or two dimensional model. Aims of this paper survey the importance to use the multidirectional loading (MDL) in the engineering practice. The simulation studies are conducted for the liquefaction phenomena occurred in Hyogoken Nanbu Earthquake 1995. The two phase dynamic equation was applied. It was found that the unidirectional loading (UDL) along the principal axis of earthquake obit gave good agreement with results of the horizontal MDL for the maximum response acceleration except for the process of the pore pressure build up and the other details of response. It was also found that effect of the vertical loading was not significant and that effect of the initial shear stress (ISS) was significant.

KEYWORDS

Liquefaction analysis; multidirectional loading; initial shear stress; three dimensional analysis; constitutive equation; Hyogoken Nanbu earthquake; earthquake response analysis; cyclic behavior of sand

INTRODUCTION

MDL and ISS takes important role in the geotechnical numerical analysis if material nonlinearity is involved. And obviously earthquake is multidirectional movement and ISS exist in soil ground such as a dam, dike and soil ground where structures are on, etc. Most of studies on liquefaction analysis in the past have considered only one horizontal component of earthquake and very few studies have been conducted on the behavior of ground subjected to multidirectional earthquake loading and very few attention was paid for ISS condition. Both are important for prediction but they have different aspects so they are reported in individual sections. At first we discuss about MDL then about ISS.

Effect of MDL was studied experimentally by several researchers. Pyke et al concluded that the settlements caused by multidirectional horizontal motions on a shaking table are about equal to the sum of the settlements caused by the components acting separately (Pyke et al 1975). Ishihara and Yamazaki found that the cyclic stress ratio dropped to approximately 65% to 25% of the cyclic stress ratio causing 3% strain under uni-directional loading depending upon the pattern of the two component of loading (Ishihara and Yamazaki 1980). The volumetric strain due to consolidation following the liquefaction were also different for MDL (Nagase and Ishihara 1988).

From the view point of numerical analysis, there must be influence of MDL on the liquefaction induced by earthquake since the dilatancy, which causes liquefaction, depends on the accumulated shear strain. And the accumulated shear strain is the sum (not simple addition) of the six component of the strain (three deviatoric strain and three shear strain). Ghaboussi and Dikmen firstly studied the effect of MDL on a ground layer problem with their proposed numerical method (Ghaboussi and Dikmen 1981). They used the fully coupled Biot's equation with u-w formulation (Zienkiewicz and Shiomi 1984) and their own material model which is based on the hyperbolic stress-strain relation for shear (Kondner and Zelasko 1963) and the effective stress path approach for dilatancy (e.g. Ishihara et al 1975). In this model decrease of the effective stress (build-up pore pressure) is a function of both components of the horizontal shear strains. A hypothetical horizontally layered ground subjected to the El Centro Earthquake has been solved as a case study. Two dimensional analysis showed quite different results on the build-up behavior of the pore pressure and some difference on the surface velocity spectra. Even with the amplitude increased to the resultant of the peak accelerations from two directions, the results are different from the results of the two dimensional analysis. On the other hand, Fukutake et al suggested the use of 1.3 times large input motions than the earthquake of stronger direction between NS and EW direction although this research is very primitive (Fukutake et al 1995).

So it is still very important to survey the three dimensional behavior of the level ground for MDL for the other conditions such as soil properties and input motions etc. In this paper the authors investigated the effects of MDL on the real site. The site was the Port Island in Kobe and the input motions were the recorded earthquake during Hyogoken Nanbu earthquake on January 17 of 1995 where the liquefaction phenomena has been observed all over the island and the settlement was about 20 cm. At first the post prediction of the observed data are shown and the parameter survey are reported.

In addition to MDL, ISS also gives significant effects to the results of the liquefaction analysis. ISS due to selfweight is usually assumed through Ko or static analysis but the real value is hardly obtained. There is no means to investigate the initial stress in situ. Only few studies for measurement have been done such as measuring Ko by in situ sampling (Hatanaka and Utida 1995). Consequently there are very few reports in numerical analyses to investigate ISS. Effect of ISS could be modeled implicitly by adjusting shear strength of the material if only shear resistance is important and if it is a static problem. But that is not easy since not only shear strength but also dilatancy are affected by ISS.

A layered soil ground was analyzed with two initial conditions, i.e. "with ISS" and "without ISS" condition. The mean stresses are kept same at the same depth since liquefaction strength is often treated same for the same mean stress in the soil column problem (Yoshimi 1991). These analyses showed significant difference in our approach.

MULTIDIRECTIONAL LOADING

Simulation of Liquefaction Phenomena Observed at the Port Island

During the Hyogoken Nanbu Earthquake, liquefaction took place at most of the seaside of Kobe city. Sand boiling and flushing water due to liquefaction occurred many place including Port Island where the array of seismometers at four depths were set. Fig. 1 shows the orbit of the records at Port Island for Hyogoken-Nanbu earthquake 1995. Two to four very large amplitude are seen in the figures. The maximum acceleration at the surface (GL 0.0m) was 314gal for NS and 288gal for EW direction. The figure of the bottom left shows the orbit at GL-83.8m during zero to five seconds. Several large amplitudes are clearly seen. The direction, when the maximum amplitude occurred, was about 20 degrees from north to west. In this paper this direction is considered as the principal axis of the earthquake components of NS and the principal direction are similar (Fig. 2). The figure at the bottom right (Fig. 1) shows the orbit of NS-UD. At GL -83.8m, UD component was not significant.

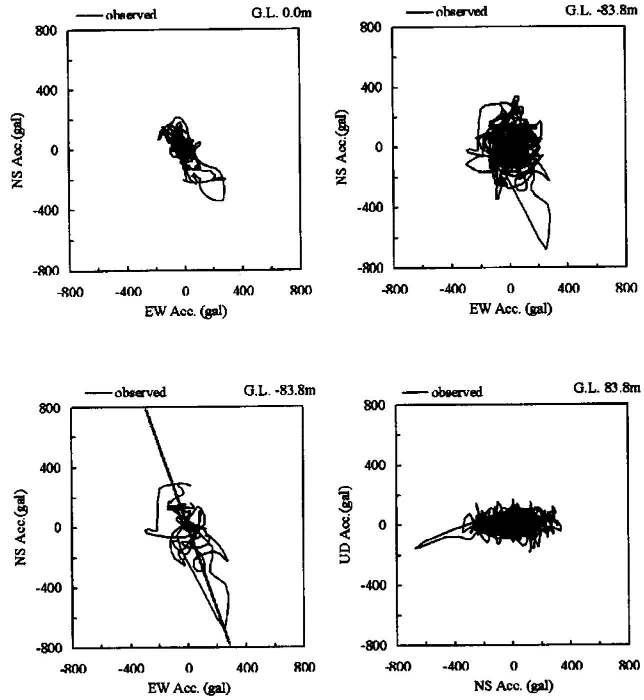

Fig. 1 Orbit of an observed earthquake record

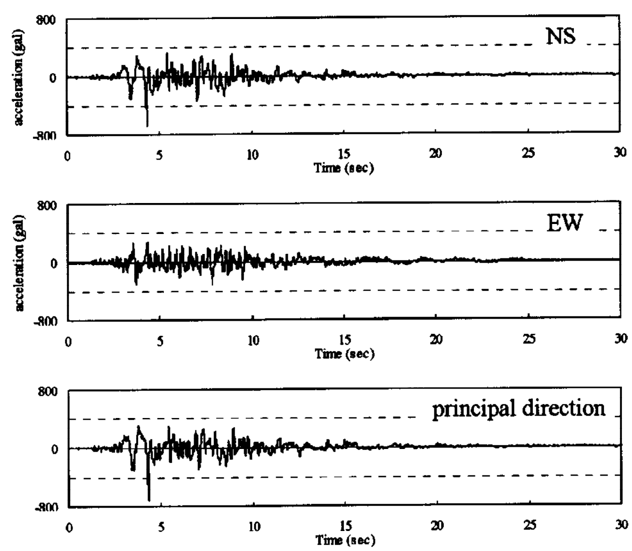

Fig. 2 Acceleration of NS, EW and principal direction

Analytical Model

Effect of MDL was studied by simulating the above records. Table 1 shows the material properties of ground layer in Port Island. Numerical modeling is shown in Fig. 3. The record at GL -83.8m was considered as the input motion. Four cases are studied. Case 1 simulates the observed record by the three directions of earthquake motion. Case 2 was studied to find the influence of vertical input motion on the liquefaction phenomena. Case 3 to 5 are for the comparative studies to the three dimensional analysis.

Table 2 Cases studied

Case	Analysis type	Input motion
1	3 D analysis	NS, EW and UD
2	3 D analysis	NS and EW only
3	2 D analysis	NS and UD only
4	2 D analysis	EW and UD only
5	2 D analysis	principal axis and UD only

Material properties are shown in Table 3. The other properties are calculated through the data shown in the table and/or considering the soil properties at similar site. For example, friction angle and liquefaction strength were calculated through N value.

Table 3 Soil layer and material properties

Layer No.	Depth (m)	Soil type	V_P (m/s)	V_S (m/s)	Average N-value	Density (kN/m^3)
1	0.0～-5.0	Man-made fill	330	170	5.2	17.64
2	-5.0～-12.6		780	210	6.5	17.64
3	-12.6～-16.8		1480	210	6.5	17.64
4	-16.8～-19.0		1180	210	6.5	17.64
5	-19.0～-27.0	Silty clay	1180	180	3.5	16.17
6	-27.0～-32.8	Layers of gravelly sand and silt	1330	245	13.5	17.15
7	-32.8～-50.0		1530	305	36.5	18.13
8	-50.0～-61.0		1610	350	61.9	18.13
9	-61.0～-79.0	Silty clay	1610	303	11.7	16.66
10	-79.0～	Diluvium sand	2000	320	68	23.52

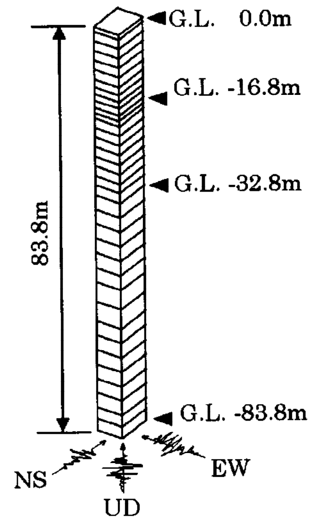

Fig. 3 Analytical model

Results of Simulation

Fig. 4 shows the time history of the response accelerations for NS direction with the observed accelerations. They agreed well but the response at the surface after 5 second showed little difference. The observed acceleration showed very long period of wave while the calculated acceleration had component of the higher frequency. Fig. 5 shows that time history of the pore pressure in Case 1 and Case 2. The layer at GL -12.6m～ -14.0m fully liquefied. The deeper place of GL -15.4m was nearly liquefied. The tendency of liquefaction at the deeper layer was found. To find the effect of the vertical input motion, Case 2 was analyzed. The result in Fig. 5 shows that vertical wave propagation only affected to compressible wave of water so that the result of Case 1 is very similar to the Case 2 if the high frequency is filtered out.

Then the results of unidirectional loading in Fig. 6 and 7, and that of MDL in Fig. 5 were compared. The response of EW direction showed difference while the response of NS direction showed better agreement. The response of NS direction was close to that of the principal axis. The build-up of pore pressure could have been dominant at NS direction. To find how much the direction of input motion affects, response for the principal axis was calculated (Fig. 9). In this case, the results are similar to the one for NS direction.

Effects of Multidirectional Loading

Maximum accelerations for uni- and multi-directional loading are plotted in Fig. 9. Results of NS direction for NS+EW and NS only showed similar behavior. Response of the principal axis is similar to one of the NS+EW (same direction). Maximum vertical acceleration was hardly influenced by the horizontal excitation. This tendency is same as the results by Ghaboussi/Dikmengave.

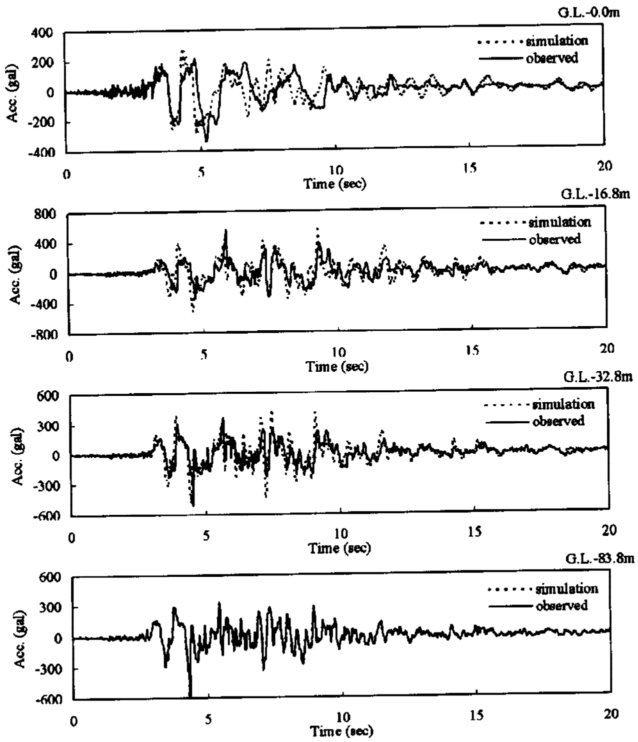

Fig. 4 Response acceleration of NS direction

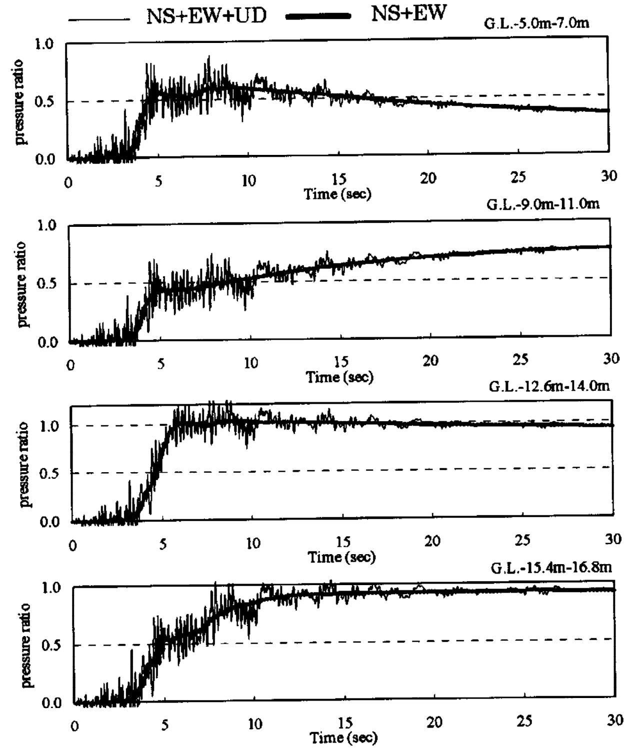

Fig. 5 Excess pore pressure ratio (NS+EW+UD,NS+EW)

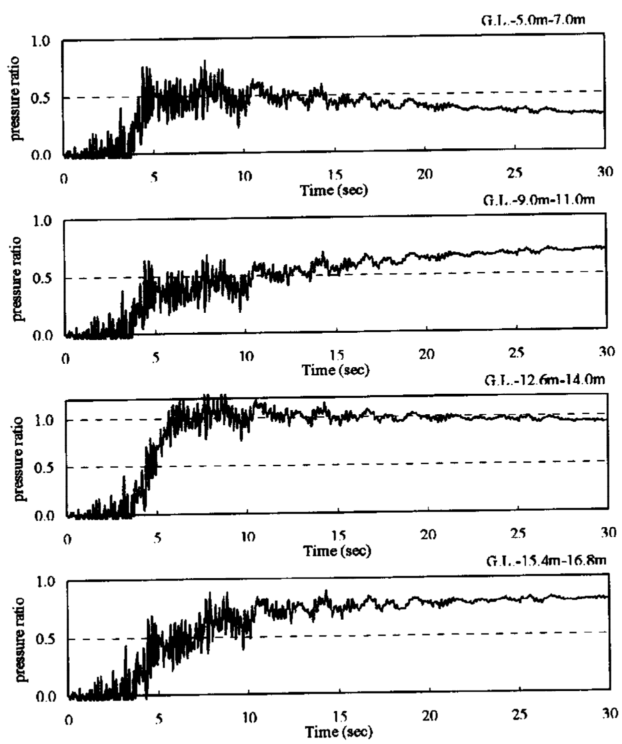

Fig. 6 Excess pore pressure ratio (NS+UD)

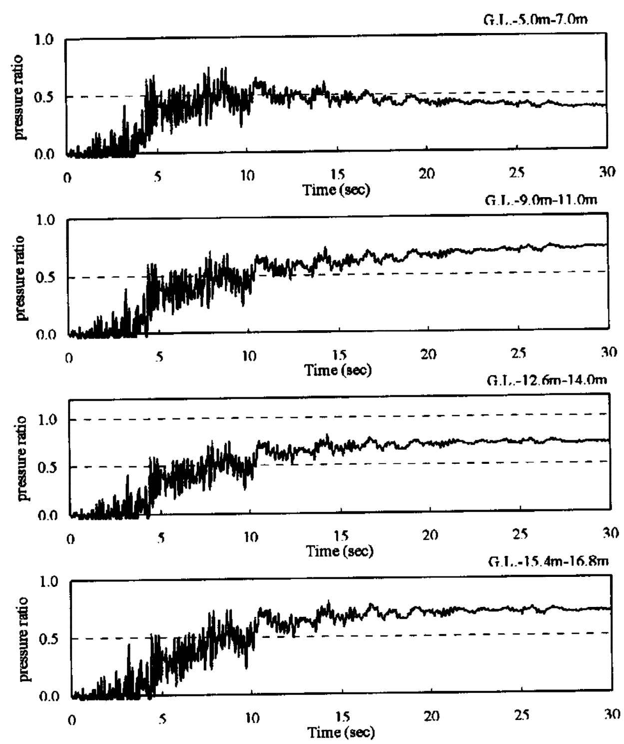

Fig. 7 Excess pore pressure ratio (EW+UD)

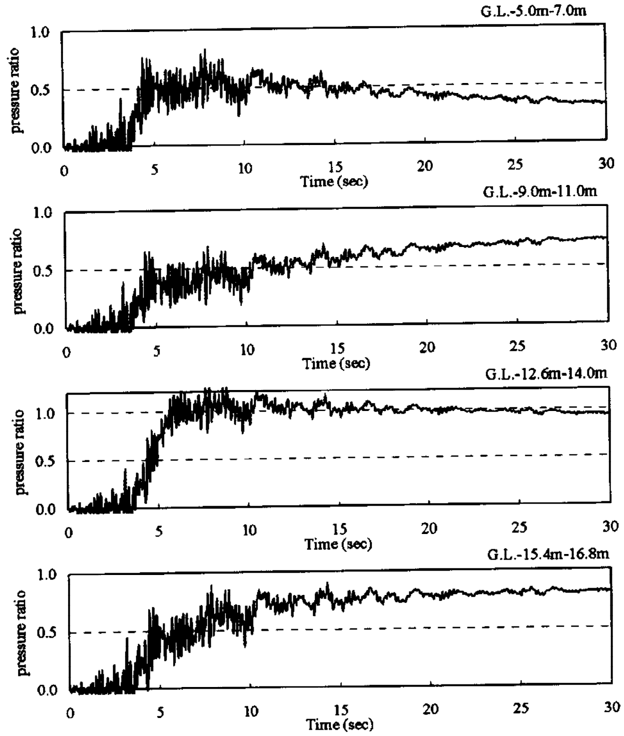

Fig. 8 Excess pore pressure ratio (principal direction+UD)

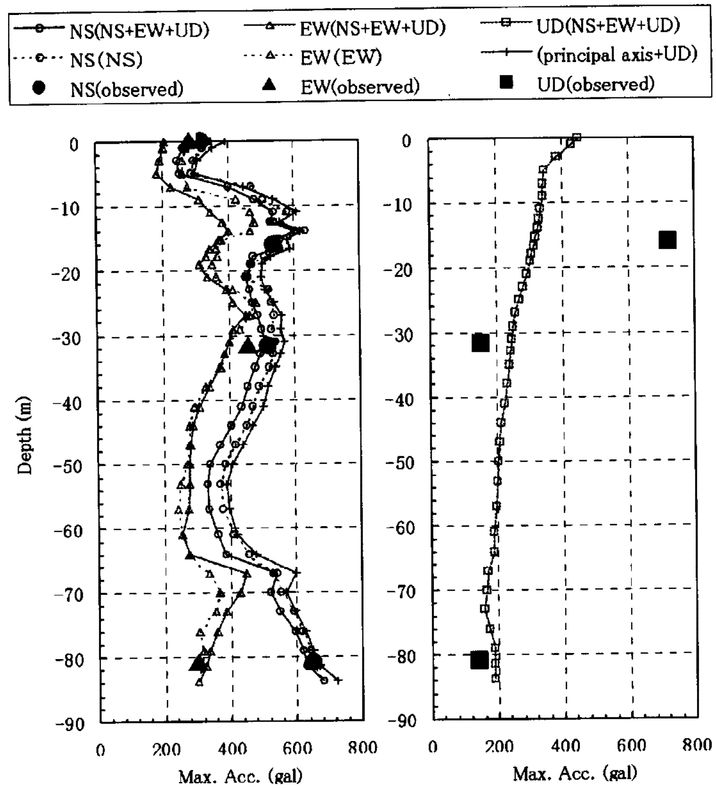

Fig. 9 Max. acceleration of horizontal response

Fig. 10 Max. acceleration of vertical response

INFLUENCE OF INITIAL SHEAR STRESS ON GROUND LYAER PROBLEM

ISS is modeled differently by the existing analysis codes (Shiomi 1994). Here the behavior on a numerical model is reported.

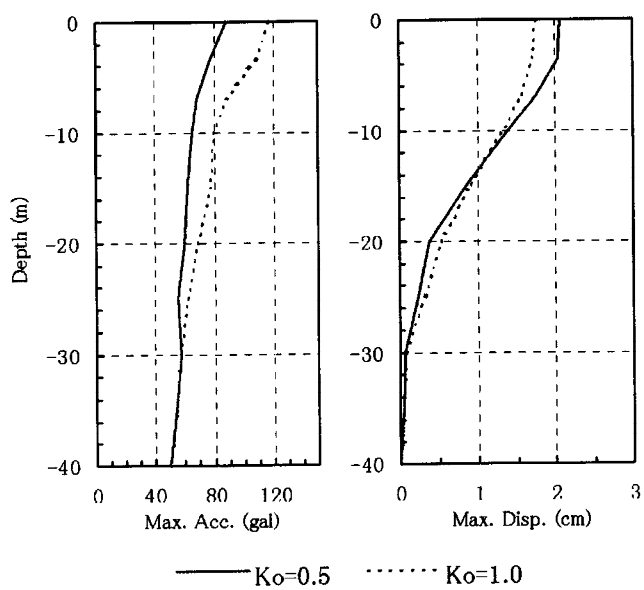

Fig. 11 Profile of maximum response acceleration

Ground Layer Problem : One dimensional layer problem was solved by the Densification model (Zienkiewicz et al 1978) to see the influence of ISS to the liquefaction analysis (Shiomi 1994). The Densification model takes into account the shear strength and the dilatancy through stress ratio and accumulated strain ratio. They are influenced by ISS. The most of constitutive models based on the flow rule has similar mechanism for ISS. The layer from -3.5m to -20m was assumed to liquefy. The shear velocity of the layer was 167m/sec. The layer from -30m to -40m was rather stiff and its shear velocity was 560m/sec. The input motion was the recorded data at Akita city during the Niigata Earthquake 1964. Two cases are surveyed. One is with ISS and the other is without ISS. The mean effective stress was kept same at the same depth. The lateral earth pressure ratio of the case with ISS was 0.5 assuming Poisson' ration was 0.33. Ko of the model without ISS is 1.0.

Response Acceleration : The influence of ISS was significant. Fig. 11 shows the maximum response acceleration and displacement. The response near the surface of "with ISS", i.e. Ko=0.5 was larger for acceleration and smaller for displacement than those of "without ISS". This means that the stiffness of the soil material for the case "with ISS" was reduced more than the case "without ISS". The existence of ISS placed the stress near the failure line so the material with ISS became weaker and that was the main reason of the less acceleration and more displacement for the case with ISS. The difference is about 30% for acceleration and 20% for displacement.

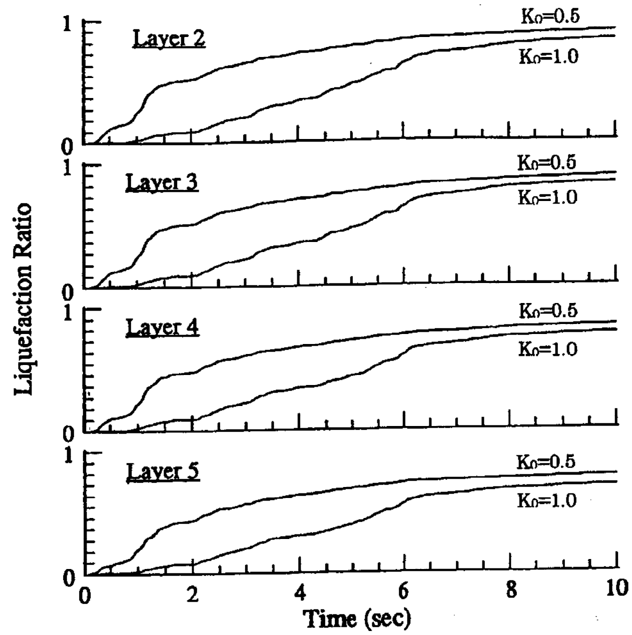

Fig. 12 Time history of pore pressure ratio

Excess Pore Pressure : Fig. 12 shows the time history of the liquefaction ratio. The pore pressure of "with ISS" was built up quickly and higher. Both cases reached the full liquefaction but the excess pore pressure without ISS was about 10% less in the case of "without ISS". This tendency was almost same as the recent laboratory element tests(Hyodo 1988) except the final pore pressure. The liquefaction ratio was 75% for the "with ISS" and 40% for the "without ISS" at 3.5 second. Fig. 12 may give a cue why the liquefaction strength curve give the same value for liquefaction strength for the same mean stress. The liquefaction strength curve is determined by the value when the sample reaches final liquefaction which is at 5% shear strain or 95% pore pressure of the initial vertical stress. The pore pressure ratio is almost same after 8 seconds.

Theoretical Consideration : ISS might be classified into two types. Type I is the case that the external force is applied to the perpendicular direction to ISS. In this case, the incremental shear stress is mostly used to rotate the principal stress and the increment of equivalent stress is small. For example, the soil underlaid a structure has almost no shear stress for horizontal direction but deviatoric shear stress (vertical stress minus horizontal stress) is large. The maximum shear stress acts for the direction of 45 degree. External force due to earthquake produces large horizontal shear stress. Type II is the case that external force is applied to the direction close to the direction of ISS. In this case the incremental equivalent shear stress is equal to the external incremental shear stress. For example, a slope such as dam has ISS in a horizontal direction. These two type of ISS might work differently. There are no evidence but theoretically it should affect differently. A soil-column type dynamic effective analysis is obviously classified into the Type I.

CONCLUDING REMARKS

Effect of MDL (multidirectional loading) and of ISS (initial shear stress) on liquefaction phenomena during earthquake were studied. The experimental test for MDL is not easy so that the effect of MDL is usually ignored. Here the effect of MDL was analytically examined. Addition of earthquake loading perpendicular to a horizontal unidirectional analysis makes the loading larger so the ground layer liquefy more. This is obvious. In this report UDL applied to NS, EW and the principal axis (20 degree form NS to EW). MDL gave slightly greater build-up of the pore pressure at the lower layer of the liquefied layer in the UDL case of NS and the principal axis. EW loading did not give much influence to the liquefaction and worked as a little additional loading. So the difference between MDL and UDL of NS or the principal axis were not so significant. The pattern of the maximum acceleration profiles were identical for MDL and UDL. The problem here examined was a simple layer problem. If the boundary condition is complicate, MDL would be very important. Addition to the study for the horizontal loading, it was confirmed that vertical earthquake loading did not give any significant influence on the liquefaction of the layers.

ISS conditions were classified into two types. Type I is the case that the direction of ISS and the applied force are different and Type II is the case in which ISS is in the same direction of the applied stress. Type I ISS (i.e. Ko=0.5 and K0=1.0) was analytically examined. It was found that ISS makes the liquefaction process different. Existence of ISS make more slowly the build-up pore pressure as found by the experiments. In the example problem in this paper, the upper soil layers with ISS were more weakened than without ISS. It should be noticed that most of the ground layer analyses are conducted without ISS. The differences due to the analysis codes and the behavior of Type II ISS were reported in the reference (Shiomi 1994).

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