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Evaluation of drainage effect in sand liquefaction

Evaluation de l'effet de drainage dans la liquéfaction des sables

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SYNOPSIS A liquefaction test method has been developed to evaluate liquefaction resistances under partially drained conditions. It is found experimentally that the increase of cyclic shear strength due to drainage can be well represented by the relative density Dr and the coefficient of drainage effect defined by $\bar{\alpha}=k/(fL)$, in which k is the permeability, f is the loading frequency and L is the drainage path length. Selected examples of the evaluation of the drainage effect with k, f and L in practical problems are also presented in this paper.

INTRODUCTION

The conventional type of liquefaction test on saturated sands is performed under conditions where there is no drainage. Thus, it cannot be made to represent field conditions where there is some dissipation of pore pressure during the loading period. The drainage under field conditions during an earthquake or ocean storm may be expressed in terms of the permeability k, the loading frequency f and the drainage path length L (Martin et al.,1980, Umehara et al.,1980). An experimental technique to evaluate the influence of these factors on the cyclic shear strength is investigated in this paper and test results are applied to practical problems.

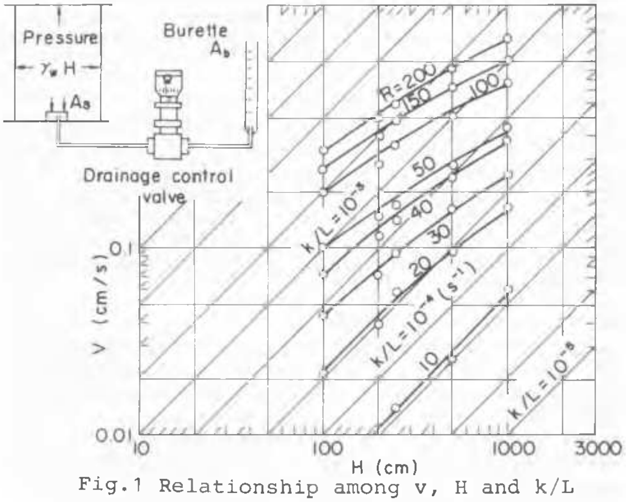

Fig.1 Relationship among v, H and k/L

CYCLIC TESTS UNDER PARTIALLY DRAINED CONDITIONS

Calibration of the drainage control system

The drainage system of the dynamic triaxial test apparatus is a drainage control circuit consisting of a drainage control valve with a micrometer and a buret as shown Fig.1. When the flow in the drainage system follows Darcy's law, the velocity of flow v can be written as Eq.(1);

$$v=ki=k(H/L)=(k/L)H=\alpha_b H \quad (1)$$

where i is the hydraulic gradient and H is the head due to cell pressure. As the value α_b for the drainage system is unknown in Eq.(1), the calibration of the system should be executed prior to the tests. The calibration procedure is; (1)set the valve's micrometer to a certain position R, (2)supply the cell pressure $\gamma_w H$, (3)open the other valve to start the flow, (4)measure the time and movement of kerosine in the double tube buret with motor driven cameras, (5)plot v and H on the log scale paper as shown in Fig.1. The relations between v and H should be linear when the flow follows Darcy's law. The white circles in Fig.1 show the linear relations between v and H for the values of R which give flow velocities low enough to apply Darcy's law. In this case, as the gradients of the lines indicate α_b , drainage control can be easily attained by setting the micrometer R to the appropriate reading corresponding to the required α_b. It is noted that α_b changes according to the area of the buret A_b used for the measurement of v. The value of α_h should be corrected by using the velocity that would be measured by use of a buret with an area A_s equal to that of the pedestal in the cell. Then, the corrected α_s can be represented by Eq.(2) (Umehara et al.,1981);

$$\alpha_s=(A_b/A_s)\alpha_b \quad (2)$$

Evaluation of liquefaction resistances

Fig.2 shows the stress ratio τ_D/σ_c and the number of cycles N_l needed to cause liquefaction of Niigata sand under partially drained and undrained conditions. It is evident that the influence of f and α_b differs considerably depending on the relative density of the specimens. For loose sand (Dr =30%), the partially drained cyclic strengths are not influenced greatly by either the frequency or the drainage condition, being almost equal to the undrained cyclic strengths. On the other hand, for medium dense sand(Dr=50%), the partially drained cyclic strengths are influenced by the frequency and the drainage condition showing higher values than in the undrained case. In addition, it is interesting that the larger the value of α_b, the higher becomes the cyclic strength for the same value of f, and the smaller the value of f, the lower becomes the cyclic strength for the same value of α_b. Fig.3 shows the stress ratio necessary to cause liquefaction at N_l=20 plotted against the relative density. It is clear that the cyclic strength obtained under partially drained conditions is dependent on the values of α_b, f and Dr. The influence of α_b and f tends to increase with the increasing relative density Dr. In order to evaluate the drainage effect, the partially drained cyclic strength is normalized using the undrained cyclic strength, and the strength ratio $SR(N_l)$ is defined as shown in Eq. (3);

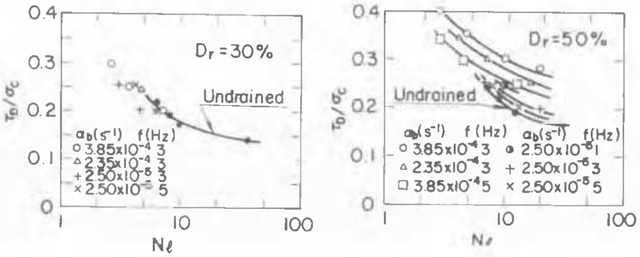

Fig.2 Partially Drained Cyclic Strength

$$SR(N_l) = (\tau_D/\sigma_c)_p / (\tau_D/\sigma_c)_u \qquad (3)$$

where $(\tau_D/\sigma_c)_p$, $(\tau_D/\sigma_c)_u$ are the partially drained and the undrained cyclic strengths respectively. As the strength ratio is a function of α_b, f and Dr, the non-dimensional parameter $\bar{\alpha}$, which is called the coefficient of drainage effect in this paper, is introduced in the following form after careful examination of above mentioned governing parameters;

$$\bar{\alpha} = \alpha_s/f = k/fL \qquad (4)$$

in which $\alpha_s = (A_b/A_s)\alpha_b$ is adopted for α_b because α_b is only a tentative measure of drainage conditions used for convenience in the laboratory test. Fig.4 shows the strength ratio plotted against the relative density. It is found that the strength ratio becomes larger as $\bar{\alpha}$ increases, namely the drainage effect increases. This means that the non-dimensional $\bar{\alpha}$ could be a useful parameter to evaluate the influence of drainage on the cyclic strength of saturated sands.

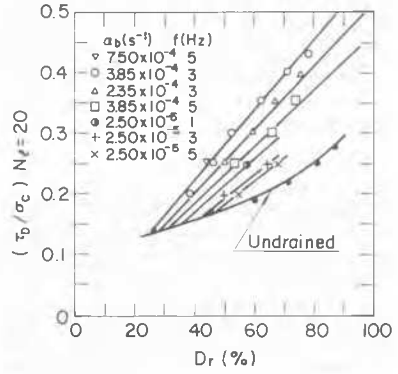

Fig.3 Cyclic Strength and Relative Density

DRAINAGE EFFECT IN A NATURAL DEPOSIT

In the application of the partially drained cyclic strength to a natural deposit, some consideration should be made to the fact that the drainage conditions in the laboratory test are different from those in the deposit. It has been shown analytically that the pore pressure distribution in a deposit is greatly affected by the loading characteristics of earthquakes such as the form, frequency and amplitude of input motion(Blázquez et al.,1980). As the prediction of earthquakes is difficult at the moment, some simplified paterns of pore pressure distribution which might be observed in natural deposits are illustrated in Fig.5. When the drainage effect of the element P in Fig.5 is evaluated from the laboratory test, the following differences in the drainage conditions will be found;(1)the influx of pore water into the element is zero, and (2)the pore pressure buildup is only within the limits of the specimen. Taking account of these differences,the drainage effects in cases (a) and (b) in Fig.5 are overestimated because the pore pressure dissipation from the element P in the deposit would be restricted by the pore pressure generated between the element and the surface of ground. Moreover, the influx of pore water into the element P enlarges the residual pore pressure and decreases the cyclic strength of the element in case (a). On the other hand, the drainage effect is underestimated in case (c). This case, however, will hold for extremely low values of the loading frequency or for non-uniform deposits. It is concluded, from the above discussion, that the partially drained cyclic strength obtained from the laboratory test indicates the maximum potential cyclic strength of the element in the deposit

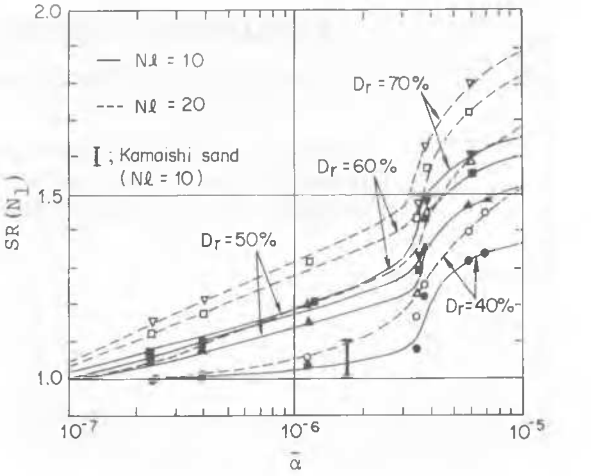

Fig.4 Drainage Effect on Cyclic Shear Strength

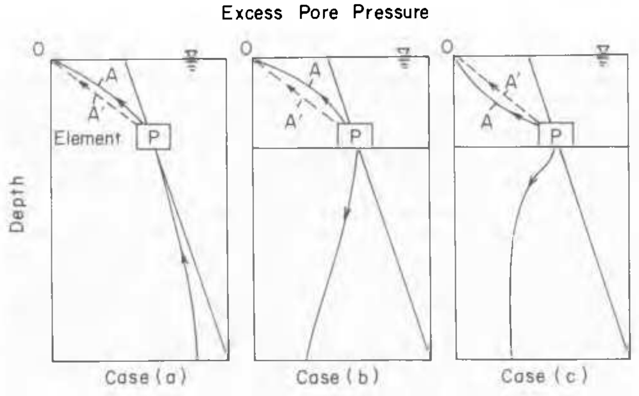

Fig.5 Pore Pressure Distribution in Deposit

excepting the special case shown in Fig.5(c). As an example of the application of laboratory test results, the evaluation of the drainage effect on the cyclic strength of undisturbed sand, which was sampled at a project site in Kamaishi bay, is presented in Fig.4 (Umehara et al.,1984). Since the strength ratio falls on between 0 to 1.1 for the in-situ value of $\bar{\alpha}=1.8\times10^{-6}$ (L=3m, f=3Hz, $k=1.67\times10^{-5}$m/s), and the strength measured in the laboratory indicates the maximum potential strength in the layer, it was decided that the drainage effect could not be expected for natural deposits in Kamaishi bay.

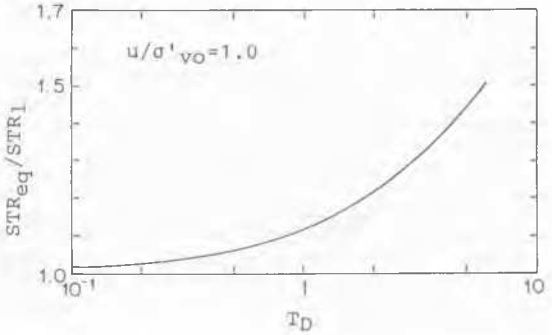

Fig.7 STR_{eq}/STR_1 and T_D (after Tokimatsu et al.)

DRAINAGE EFFECT FOR GRAVEL DRAIN

In order to evaluate the drainage effect of improved ground with gravel drain directly from the triaxial test, the pore pressure distribution in the ground and the idealized distribution in the laboratory test are compared in Fig.6. As the radial influx of pore water is equal to zero at the radius r_e which is the effective length of the gravel drain, the difference in the pore pressure ratio $\delta u/\sigma'_{vo}$ can be attributed to the simplified experimental conditions by assuming that no pore pressure generates between the gravel drain and the objective element in the ground. The pore pressure dissipation in the element, however, seems to be restricted by the pore pressure which developes between the drain and the element. Therefore, the partially drained cyclic strength obtained from the laboratory test indicates the maximum potential strength of the element. This is very important when the results are applied to the ground. For example, as shown in Fig.2, no drainage effect is expected for Niigata sand with a relative density of 30% even when we remember that the results indicate the maximum potential cyclic strength. This implies that the gravel drain may not be effective for ground such as that composed of loose Niigata sand. On the other hand, for denser sand, a potential drainage effect can be expected, as shown in Fig.4. Since the actual drainage effect in improved ground cannot be measured directly by laboratory tests, the following comparison between the analytical solutions and the results of experiments on the strength ratio was executed. Fig.7 shows the strength ratio represented by STR_{eq}/STR_1 and the time factor T_D (Tokimatsu et al.,1980). The time factor is defined by the following equation;

$$T_D=kt_e/m_v\gamma_w\bar{L}^2 \quad (5)$$

where t_e is the effective duration of significant ground motion, m_v is the coefficient of volume compressibility, γ_w is the unit weight of water and L is the corrected radial drainage path length. The relation between T_D and $\bar{\alpha}$ is;

$$\bar{\alpha}=\bar{\beta}T_D \quad (6)$$

$$\bar{\beta}=\gamma_w m_v\bar{L}/N_e \quad (7)$$

where N_e is the equivalent number of cycles and $\bar{\beta}$ is a non-dimensional parameter. As the STR_{eq}/STR_1 is equivalent to the $SR(N_1)$, the ratio R_a defined by Eq.(8) is calculated,

$$R_a=(STR_{eq}/STR_1)/SR(N_1) \quad (8)$$

and the relations among R_a, T_D and $\bar{\beta}$ which are obtained by using Eq.(5), Eq.(6), Fig.4 and Fig. 7 are drawn in fig.8. In fig.8, R_a becomes constant for some value of $\bar{\beta}$ because when $\bar{\alpha}$ is more than 10^{-5}, $SR(N_1)$ in Fig.4 is assumed to be constant. It is clear that the partially drained cyclic strength is smaller than that obtained from the analysis for values of β greater than about 10^{-6} which we meet in the field. It is, however, interesting that the ratio R_a approaches close to 1.0 as T_D increases. The reason is that the pore pressure distribution shown in Fig.6(a) will be close to that in Fig.6(b) when T_D is large, namely when the drainage effect is large. If the T_D is large enough so we would expect a drainage effect in improved ground with gravel drain, R_a may be equal to 1.0, irrespective of the values of T_D and β. One of the advantages of laboratory tests under partially drained conditions is that the drainage effect on the cyclic shear strength can be directly measured in order to check the effectiveness of the gravel drain.

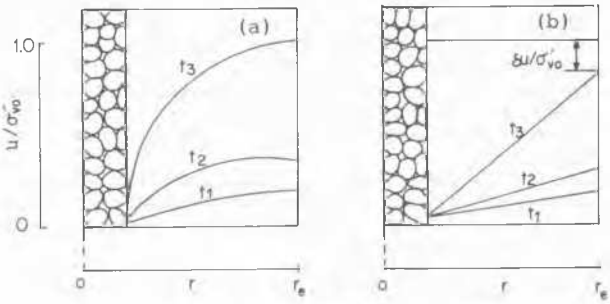

Fig.6 Pore Pressure Ratio in Improved Ground with Gravel Drain

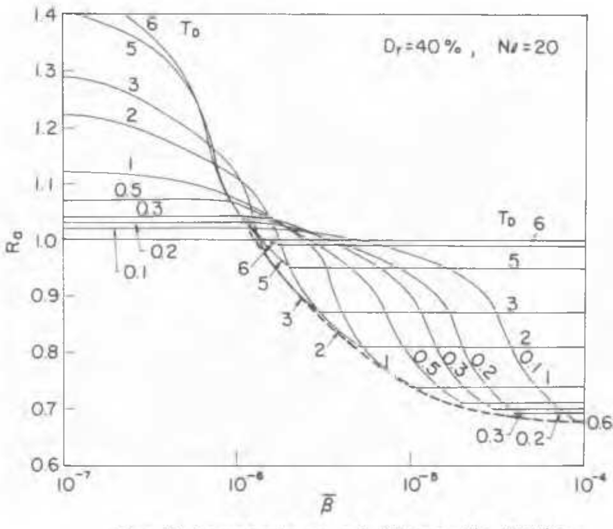

Fig.8 Comparison of Strength Ratio

DRAINAGE EFFECT IN WAVE-INDUCED LIQUEFACTION

The high waves in the ocean, whose periods are on the order of 10 seconds, continue several hours. Thus, the dissipation or redistribution of pore pressure could have a major influence on the residual pore pressure in the subsoil. In addition, when we treat the sand liquefaction under offshore gravity structures, the influence of the drainage should be taken into account as a two or three dimensional problem. In such a case, the techniques used to measure the drainage effect in the laboratory are not directly applicable to the element in the subsoil because the pore pressure distribution is too complicated to be simplified. The analytical approach is performed to evaluate the influence of governing factors such as k, f and L. The pore pressure buildup due to the cyclic wave loading is estimated based on the endochronic technique (Finn et al.,1980) while the dissipation of pore pressure is calculated using Terzaghi's consolidation equation (Rahman et al.,1977). Fig.9 shows the finite element model of the idealized profile under a breakwater off Niigata in which circular failure was caused by a heavy storm in 1976. Fig.10 indicates the endochronic constants obtained from the dynamic triaxial test under undrained conditions for undisturbed Niigata sand sampled at the site. The other constants used for the analysis are described elsewhere (Zen,1984). Fig.11 indicates the influence of the permeability of silty layers on the residual pore pressure ratio. It is found that the permeability of the silty layer greatly affects the residual pore pressure ratio even after the cyclic loading has ended. Especially, for $k_{silt}=3x10^{-7}$m/s, the peak of the pore pressure in element No.90 appears 35 minites after the loading stopped. The influence of the loading period is shown in Fig.12. It is clear that the loading period T, or the loading frequency f=1/T, is one of the major factors affecting the residual pore pressure in the subsoil.

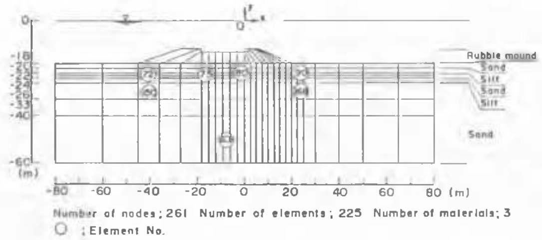

Fig.9 Finite Element Model

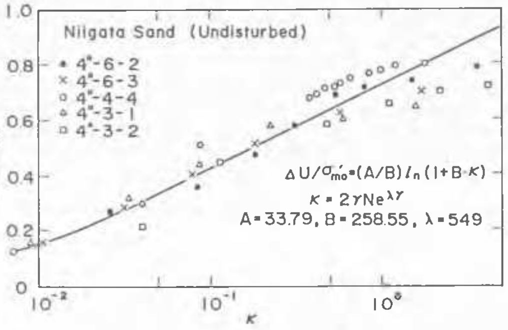

Fig.10 Endochronic Constants

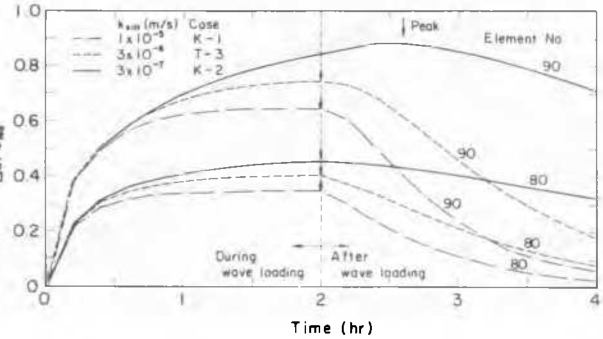

Fig.11 Influence of Permeability

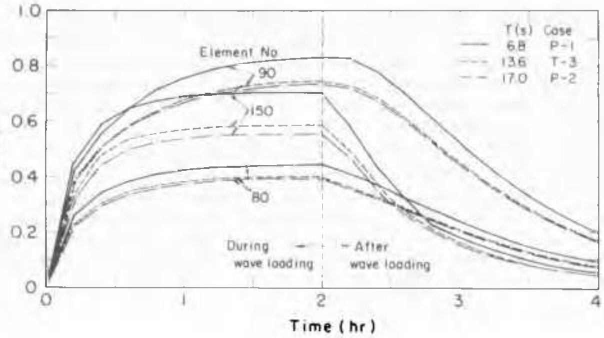

Fig.12 Influence of Loading Period

CONCLUSION

The importance of the factors k, f and L which affect the cyclic shear strength has been experimentally and analytically indicated. An advantage of the laboratory test under partially drained condition is that the potential drainage effect can be directly measured from the tests.

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