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ABSTRACT

Laboratory measurement using CCD camera was conducted to trace the sedimentation process of sand grains in a liquefied model layer. The purpose of this measurement was basically intended to obtain a visual evidence of appearance of suspended state in upper part of the liquefied soil. For this purpose, glass bead particles were used as model ground material. The test results prevailed that the glass bead grains were suspended in pore water at the instant when complete liquefaction was brought about to the layer, then they began to settle in the water. The measured pore water kept high value until grains ceased moving. And the moving velocity was far slower than that estimated by Stokes equation for sedimentation of single particle. From these findings, a predicting method was proposed to obtain the compressibility of liquefied sand layer and the continuation time of suspended state of grains.

INTRODUCTION

Soil liquefaction has caused serious damage to structures during past earthquakes. When it takes place, foundation ground for structures deform largely causing failure of structures. If soil liquefaction takes place at backwards ground behind waterfront structures, permanent displacement of backwards ground was caused for fairly long distances from waterfront line along with a lateral displacement of waterfront structures (Ishihara 1997). And it is also well known that if soil liquefaction is caused beneath an inclined ground, the ground surface moves largely in lateral direction even though the inclination is very gentle. All these phenomena are attributed to large deformation of liquefied layer. Therefore it is essential to minimize the deformation of ground during the liquefaction to prevent serious damages to structures. However, the mechanism which causes the large deformation of liquefied layer is not yet thoroughly clarified.

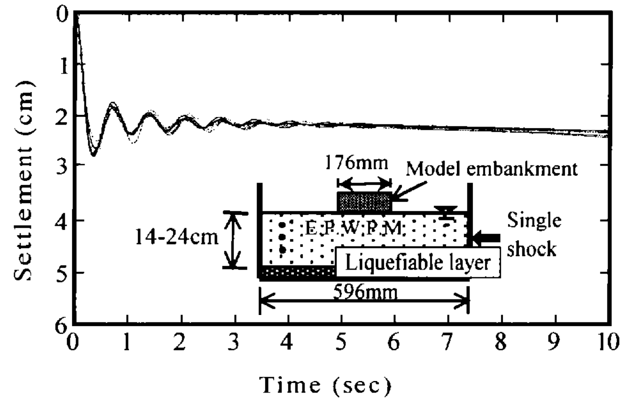


Fig. 1. Oscillating mode during embankment settlement

Thus, during past few years, a series of model tests was conducted to study the deformation process and the soil properties after liquefaction. Among the test results, vertically oscillating mode continuing for several seconds was observed during the settlement of model embankment as illustrated in Fig. 1 (Sasaki et al. 1999). This kind of behavior of liquefied layer is hard to explain other than that the soil property has changed to liquid-like.

Although there are indirect evidences, which suggest the appearance of a suspension state in a liquefied layer, no direct evidence has yet been presented. Therefore an attempt was made to trace the particle movements in a liquefied layer by conducting a small model test to obtain the direct evidence and to clarify the process of suspension in post-liquefaction soil. The duration of the state of suspension and the compression of liquefied layer were also examined.

MEASUREMENT OF PARTICLE SEDIMENTATION IN LIQUEFIED LAYER

In order to reproduce the liquefied state in a model ground, cylindrical container illustrated in Fig. 2 was used. Model ground was liquefied instantaneously by a single shock to the sidewall of the container as in the case of the test in box type container. By instantaneous liquefaction, the ground deformation only in post-liquefaction state can be measured by avoiding the excess deformation during the liquefaction process. Glass bead particles were used as the material for model ground. Nominal particle sizes of the used glass bead were 0.1, 0.2 and 0.4 mm. Specific gravity of the glass bead is

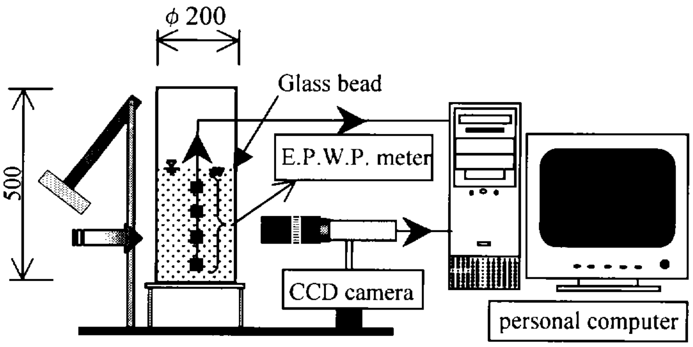


Fig.2. Schematic illustration of testing apparatus

2.485. These particles were used separately for model ground to form uniform particle size cases and also used as mixture to form a distributed particle size cases. Figure 3 shows the particle size distributions of each case. And Tables 1 and 2 show the tested cases and the physical properties of glass bead. CCD camera system was employed to monitor the movement of glass bead grains after the model ground was liquefied. In order to make it easier to distinguish a particular grain when tracing its movement, some of the particles were colored. Image pictures of grains were optically enlarged by about 30-50 times. The pictures were stored into a computer memory by 1/15-sec intervals. Recorded image pictures were later analyzed to find out locus, or moved distance and moving duration of colored particles. The recorded time is synchronized with the record of pore water pressure. Since it is necessary to enlarge the grain image for analysis, obtained area of picture is limited. Therefore for obtaining records of particle movement at different depth for a same case in Table 1, it was needed to repeat tests by changing the monitoring depth. The pore water pressures were also recorded at four depths in the model ground. And the final settlement of the ground surface was measured.

Figure 4 shows an example of the recorded locus of moved particle during liquefaction. In case of uniform size cases, all the particles moved downwards, whereas in case of mixed size cases, some of the 0.1 mm grains were observed to move upwards. These pictures are considered to provide a direct evidence of the phenomenon where the liquefied soil becomes suspension.

Figure 5 shows an example of the time history of the 0.2 mm

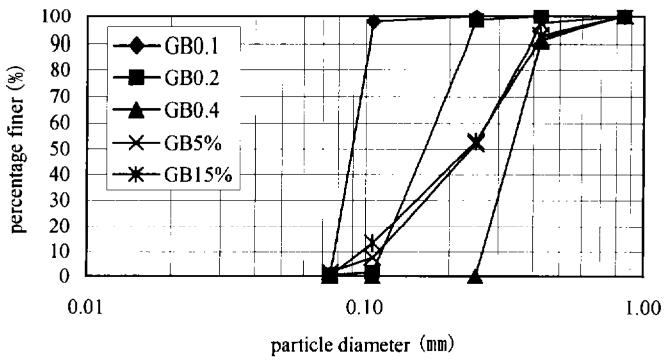


Fig. 3. Particle size distribution of used glass beads

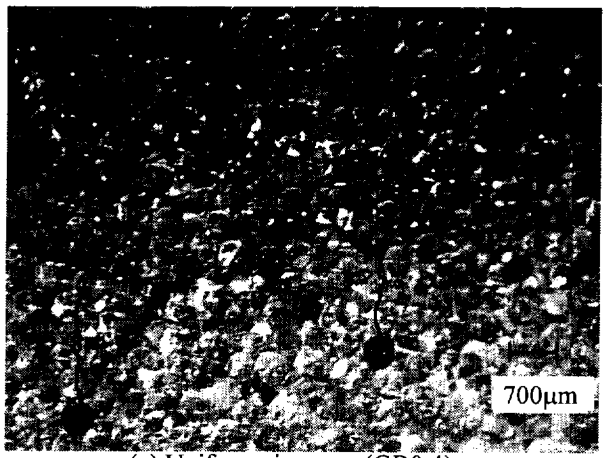
Table 1 Test cases

Case		10cm	20cm	25cm	27cm	30cm
GB0.1	CCD	9	22	0	12	0
		10	10	10	0	0
GB0.2	CCD	0	19	0	0	0
		10	10	0	0	10
GB0.4	CCD	0	17	0	0	0
		10	6	10	0	0
GB5%	CCD	0	16	0	0	0
		0	0	0	0	0
GB15%	CCD	0	12	0	0	0
		0	0	0	0	0

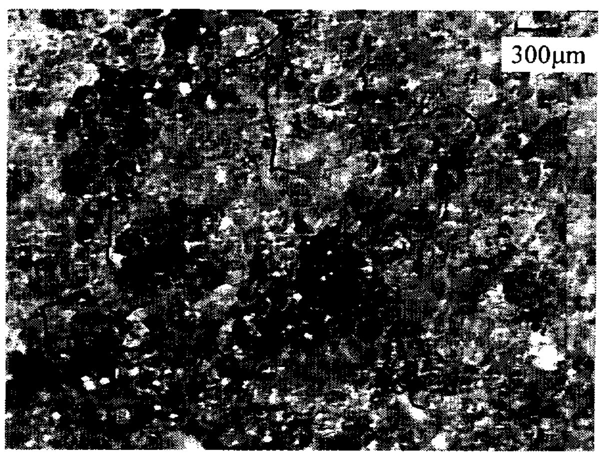
Numeral shows the number of case

Table 2 Physical properties of glass bead

	GB0.1	GB0.2	GB0.4	GB5%	GB15%
D_{50}(mm)	0.089	0.163	0.334	0.241	0.234
dw(mm)	0.089	0.158	0.336	0.194	0.186
Uc	1.195	1.558	1.337	2.471	2.833
Uc'	0.965	0.915	0.944	0.876	0.866
ρ_{dmax}(g/cm^3)	1.566	1.604	1.587	1.632	1.667
ρ_{dmin}(g/cm^3)	1.411	1.409	1.432	1.479	1.464
ρ_s(g/cm^3)	2.485	2.485	2.485	2.485	2.485
e_{max}	0.761	0.764	0.735	0.68	0.698
e_{min}	0.586	0.549	0.566	0.522	0.491



(a) Uniform size case (GB0.4)



(b) Distributed size case (GB5%)

Fig.4 Image picture of glass bead and their locus

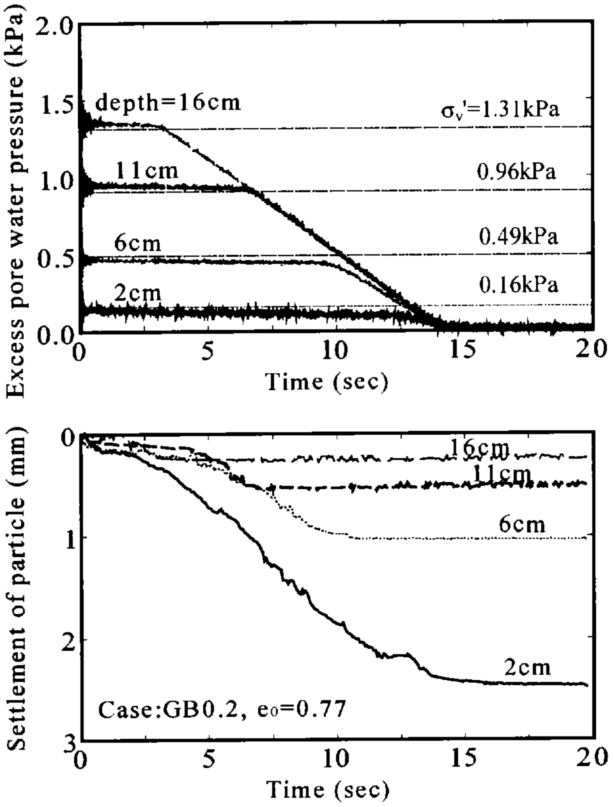


Fig. 5. Example of time history of grain sediment and P.W.P.

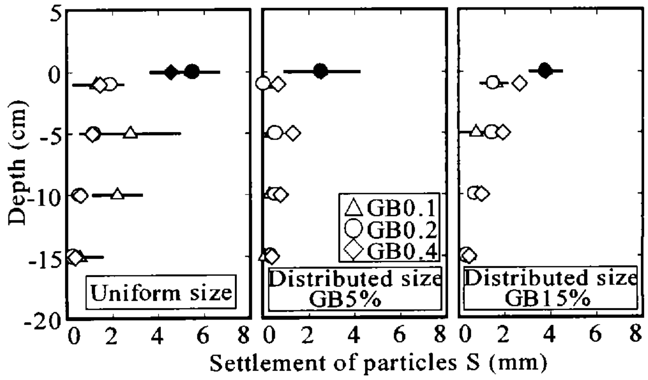


Fig. 6. Moved distance of glass bead grains

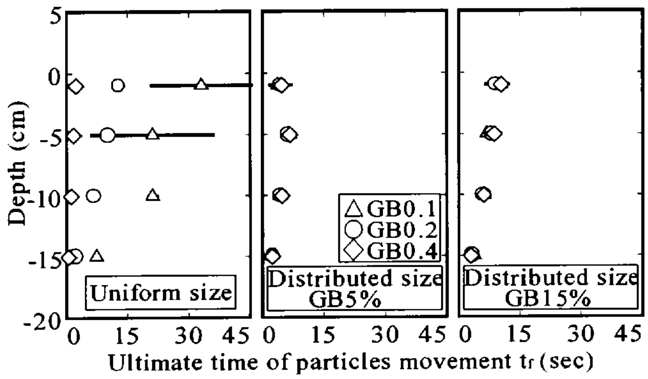


Fig. 7. Moving time of glass bead grains

glass bead grains in case of uniform size. The recorded movements of grains at four depths are compared with the time history of the measured pore water pressure. As illustrated in this figure, the measured pore water pressures at four depths show that the model ground was instantaneously liquefied at any depth as intended. The raised pore water pressure maintains for several seconds and then started to dissipate. The pore water pressure begins to decrease from deeper portion in the ground than shallower depth. During this liquefied state, monitored glass bead particles begin to move downwards for a while and then ceased moving around the same time when pore water pressure begins to decrease.

It is noticed from this figure that almost all the glass bead grains move downwards while the pore water pressure maintains the value of initial effective overburden pressures at any depth. Moved distances of each depth and the duration of high water pressure differ from each other among their depth. This means that all the particles are suspended in pore fluid during the state of high pore water pressure. When the particles dropped for enough distance to touch the below particles, the pore water pressure started to dissipate. Therefore, it is found that the soil particles in the completely liquefied state are suspended in pore water without having any effective stress, which results the state where the soil layer behaves like liquid. This suspended state of grains continues for longer period at shallower depth than at deeper depths, and thus the deeper portion of the layer recovers its strength in shorter period.

Figures 6 and 7 summarize the moved distances and time for moving of particles at each depths respectively. In these figures, empty symbols illustrate mean values of all tested cases and horizontal bar shows the range of observed value. The solid symbols at uppermost place in Fig. 6 show the measured settlement of ground surface after the dissipation of excess pore water pressure. Although there is some discrepancy between settlement at surface and the moved distance at 1 cm below the surface in some cases in Fig. 6, it is found that the moved distance is generally large at shallow depths. It should be noticed that most of the settlement is caused by the particle sedimentation than by consolidation.

From these measurement in Figs. 6 and 7, it is possible to obtain the mean velocity of glass bead movement.

Figure 8 shows the velocities of settlement against glass bead grain size. Solid symbols in this figure represent the average velocity calculated from the moved distance and moving time. Empty symbols denote the maximum velocity in the course of settlement. While solid lines represent the calculated velocities for two initial conditions considering the mutual interference between particles obtained as follows.

By examining the sediment velocity of single grain of glass bead in water, it was found that the equation (1) proposed by Rubby is better fitting to the measured value than Stokes equation (2) as illustrated in Fig. 9. This coincides with the finding by Sugii (Sugii et al. 1997).

$$\frac{v}{\sqrt{(G_s-1)gd}}=\sqrt{\frac{2}{3}+\frac{36\eta^2}{(G_s-1)gd^3}}-\sqrt{\frac{36\eta^2}{(G_s-1)gd^3}} \qquad (1)$$

where v: particle velocity, d: particle diameter, Gs: specific

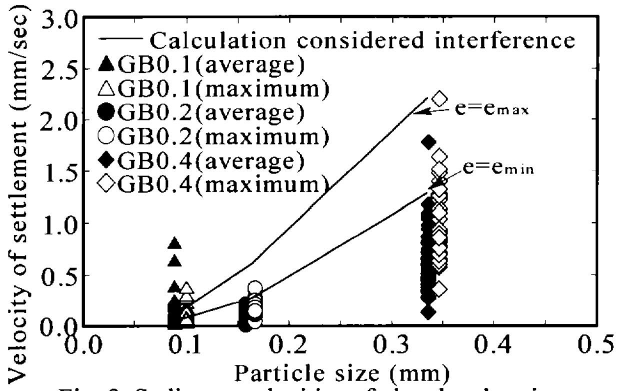


Fig. 8. Sediment velocities of glass bead grain

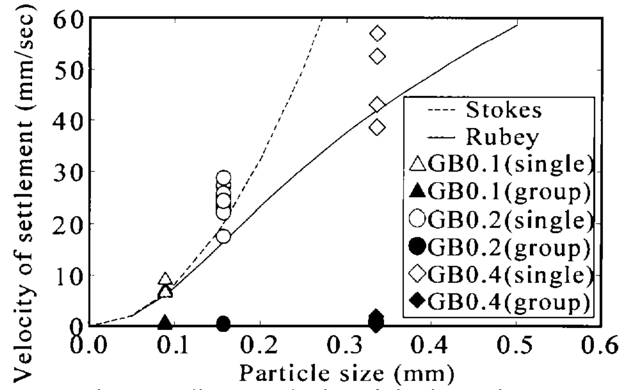


Fig. 9. Sediment velocity of single particle

gravity of solid, η: kinematic viscosity, g: acceleration of gravity.

$$v = \frac{1}{18\eta} g(G_s - 1)d^2 \qquad (2)$$

It was also found that the velocity of a single grain is much faster than that in the Fig. 8, which is the settling velocity of a particle under mutual interference condition. For this kind of condition, effect of the interference is given by Richardson as follows (Richardson et al. 1954).

$$v_m = n^{\alpha} \cdot v \qquad (3)$$

where v_m: settling velocity of particles in suspension, n :porosity

The mutual interference effect is expressed by symbol α in equation (3), which is related to the particle diameter and Reynolds number as follows.

$$\alpha = 4.65 + 19.5 \cdot d/D \qquad (R_e < 0.2) \qquad (4\text{-}1)$$

$$\alpha = (4.36 + 17.6 \cdot d/D) \cdot R_e^{-0.03} \qquad (0.2 < R_e < 1.0) \qquad (4\text{-}2)$$

$$\alpha = 4.45 \cdot R_e^{-0.1} \qquad (1.0 < R_e < 500) \qquad (4\text{-}3)$$

$$\alpha = 2.39 \qquad (500 < R_e < 7000) \qquad (4\text{-}4)$$

where D: diameter of testing cylindrical tube. The value of d/D is small so that the effect of tube wall can be neglected.

From the comparison in Fig. 8, as the calculated velocity coincides fairly well with the observed one, following equation is proposed to predict the sediment velocity.

$$v_m = n^{\alpha} \left\{ \sqrt{(G_s - 1)gd} \left(\sqrt{\frac{2}{3} + \frac{36\eta^2}{(G_s - 1)gd^3}} - \sqrt{\frac{36\eta^2}{(G_s - 1)gd^3}} \right) \right\} \qquad (5)$$

As Reynolds number is approximately equal to 0.5-15 for glass bead and Toyoura sand, α is given by equation (4-2) or (4-3).

COMPRESSIBILITY OF LIQUEFIED LAYER

It was found from Figs. 5 and 6 that the most of the compression of the liquefied layer is caused by the grain sedimentation. And this is caused during the high pore water pressure. Prior to examine the amount of compression, variation of the duration of the high water pressure was plotted against initial void ratio.

Figure 10 shows the relation between duration of the high water pressure and initial void ratio, which is summarized from the data of all the cases shown in Table 1. There is a tendency that the duration of the high water pressure of 0.4 mm uniform grain case is the shortest while that of 0.1 mm is the longest. For mixed size cases, where the representative diameter is almost the same as 0.2 mm case, the duration is slightly larger than in case of 0.2 mm uniform diameter case.

The final settlement of the model ground is varied with the initial void ratio. Figure 11 shows the relation between volumetric strain and initial void ratio. In this figure, volumetric strain is expressed by the ratio of settlement caused by liquefaction to initial thickness of the layer. The data on Toyoura sand is also plotted in this figure. It is found that when it becomes loose, volumetric strain reaches about 3-4 % for both glass bead and sand grains layers.

It is also seen that there is no apparent relation among the different sizes though it was observed for duration. Therefore, the relations between volumetric strain and initial void ratio are read from this figure as mean relations of all the data as expressed by following equations.

For glass bead,

$$\varepsilon_v = 0.85 \cdot e_0^{11.7} \qquad (5)$$

and for Toyoura sand,

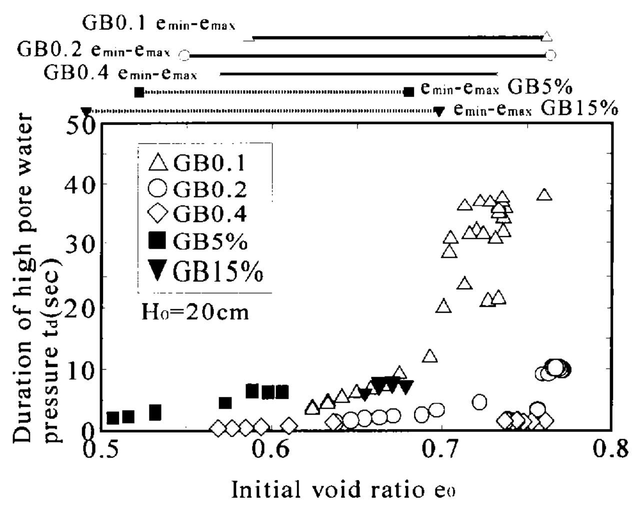


Fig. 10. Comparison of sediment time

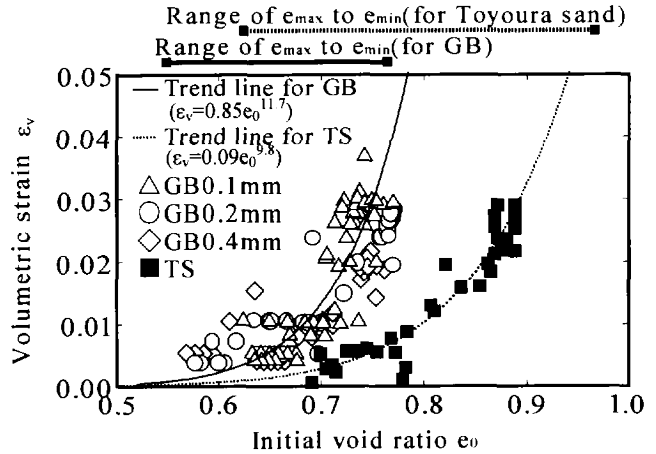


Fig. 11. Compressibility of glass beads and Toyoura sand

$$\varepsilon_v = 0.09 \cdot e_0^{9.8} \qquad (6)$$

The compressibility of Toyoura sand after liquefaction was once compiled into a coefficient of volumetric compression m_v* elsewhere (Ohbayashi et al. 2000). In that occasion, it was found that m_v* obtained through following equation was about 1000 times larger to m_v under usual consolidation.

$$\Delta H = \int_0^{H_0} m_v^* \cdot \Delta u dz = \int_0^{H_0} m_v^* \cdot \gamma' z dz$$

where m_v^*: apparent coefficient of volume compressibility, Δu: excess pore water pressure, ΔH : settlement, H_0: initial thickness of liquefiable layer, γ' : submerged unit weight.

However since it was found here that most of the volumetric decrease is ceased at the end of the suspension state, and though there are only the final settlement value in Toyoura sand cases, same tendency is assumed to be applicable to the sand. So the volumetric compression here is summarized as the function of initial void ratio as above equation.

ESTIMATION FOR DURATION OF LIQUID-LIKE STATE

In post-liquefaction state, the pore water has to begin to flow upwards due to raised pore water pressure. Liquefaction induced hydraulic gradient can reach marginal to but not overcome the critical hydraulic gradient. However, soil grains were boiled just after the liquefaction is triggered as shown by the picture in Fig. 4. This fact can be interpreted by force balance of each grain. Assuming that the soil consists of uniform size grains expressed d_w, since the submerged weight of soil grain is balanced to drag force by critical seepage flow of v_c,

$$F = \frac{\pi \cdot C_D}{8g} d_w^2 v_c^2 \gamma_w$$

where F: drag force, C_D: drag coefficient, v_c: critical velocity of pore water, γ_w: unit weight of water.

$$W_s' = \frac{\pi \cdot d_w^3}{6}(G_s - 1) \cdot \gamma_w$$

from F=Ws', diameter of particle which can stand for the seepage flow is as follow

$$d_w = \frac{3C_D}{4g} \frac{1}{(G_s - 1)} v_c^2 \qquad (7)$$

where v_c can be estimated followingly by using the Kozeny-Donart equation,

$$v_c = \frac{1}{n} k \cdot i_c \qquad k = \frac{C}{\mu} \frac{n^3}{(1-n)^2} d_w^2 \quad (8)$$

where k: coefficient of permeability, μ: coefficient of viscosity.

In this condition, the soil skeleton is marginal to be broken.

If the soil consists of different grain sizes d_w should be replaced by following value.

$$1/d_w = p_1/d_1 + p_2/d_2 + p_3/d_3 + \cdots$$

where p_i percent weight of particle d_i.

If there are grains smaller than that expressed by eq. (7), these particles will forced to move upwards.

Therefore, even if there is no disturbance, soil skeleton will be broken by the seepage force resulting suspension.

Once soil becomes suspended, each particle begins to drop. Sediment distance can be predicted from the movable distance, which is estimated from the change of interval of particles before and after the liquefaction.

Therefore the duration of suspended state of liquefied layer is given as follows.

Assuming that the soil, H_0 thick, consists of uniform size grains, d_w, and its initial void ratio is e_0, then number of grains included in unit volume of this soil is given as,

$$N_0 = \frac{6}{\pi \cdot d_w^3 \cdot (1 + e_0)}$$

Where the grains are packed uniformly, then the initial interval distance of each grain becomes,

$$h_0 = \frac{1 - d_w \cdot N_0^{1/3}}{N_0^{1/3}}$$

If these N grains becomes densely packed and the void ratio becomes to e_1, then the interval will be,

$$N_1 = \frac{6}{\pi \cdot d_w^3 \cdot (1 + e_1)} \qquad h_1 = \frac{1 - d_w \cdot N_1^{1/3}}{N_1^{1/3}}$$

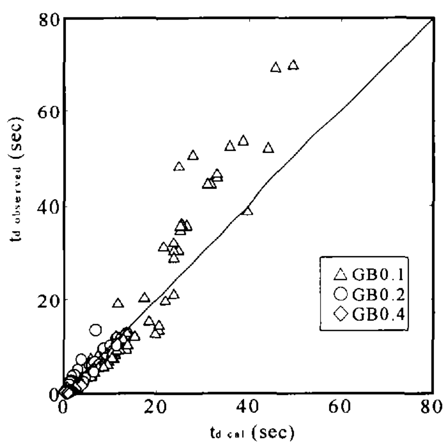


Fig. 12. Sediment time of glass bead

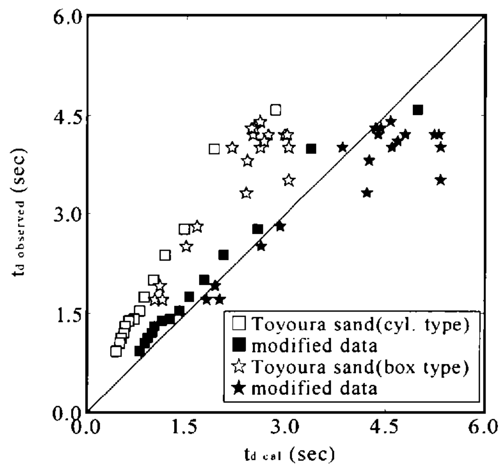


Fig. 13. Sediment time of Toyoura sand

Therefore movable distance for each particle at depth z from top is given by,

$$\Delta h(z) = (h_0 - h_1) \cdot \frac{(H_0 - z)}{(d_w + h_0)} = \varepsilon_v (H_0 - z) \quad (9)$$

Thus the duration of suspended state at depth z is given as follows, by using v_m from equation (3),

$$t_d(z) = \Delta h(z) / v_m \quad (10)$$

The calculated duration by this equation is compared in Figs. 12 and 13 for glass bead case and Toyoura sand respectively. From these figures, it is found that the equation (10) is valid for glass beads, but not for Toyoura sand. The reason of discrepancy is considered due to the grain shape. Though the glass bead is almost spherical, the shape of actual sand is not so. Therefore, if this effect is assumed to be modified linearly as follows then it is shown that the equation (11) can well estimate the duration for Toyoura sand as illustrated in Fig. 13.

$$t_{d\,\mathrm{mod}} = 1.76 \cdot t_{dcal} \quad (11)$$

Thus the duration of liquid-like state of sand layer after liquefaction can be evaluated from its initial thickness and the initial void ratio by the chart in Fig. 14.

CONCLUSION

From the results of small model tests, direct evidence was obtained showing that the soil in post-liquefaction state is suspended for a while. It was also prevailed that most of the compression of soils after liquefaction takes place while the effective stress is equal to zero or the pore water pressure keeps to be effective overburden pressure. This compressibility is much larger than that for sand due to increase of effective stress by consolidation, and was formulated as a function of initial void ratio. It is found that while the suspended soil grains drop, moving velocity is less than that estimated from Stokes equation due to mutual interference. The velocity is affected by the initial void ratio. Finally by examining the sedimentation process, the way to estimate the duration of suspended state was proposed.

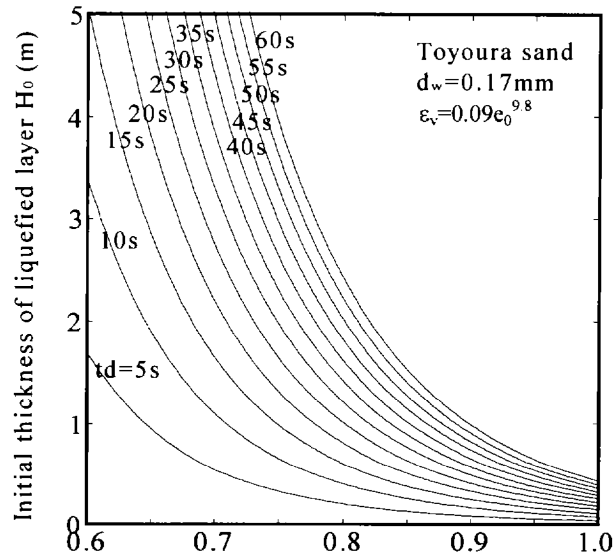


Fig. 14. Chart to estimate the liquid-like duration

ACKNOWLEDGEMENT

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