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Experimental study on reliquefaction potential of saturated sand deposit

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ABSTRACT: There exists a fact that the reliquefaction of saturated sand deposit mostly occurred in which the seismic acceleration is smaller than that for past liquefaction. In order to confirm this fact, the reliquefaction potential of the saturated sand deposits which reliquefied during the 1983 Nihonkai-Chubu earthquake and the 1989 Loma Prieta earthquake is evaluated using a simplified method of liquefaction analysis. Furthermore, the shaking table tests are carried out to clarify the effect of the acceleration, the duration of vibration and the amplitude of shear strain induced in the sand layer during first liquefaction on the reliquefaction potential of the saturated sand layer. In the tests, Kjellman's type simple shear box is used.

1 INTRODUCTION

It is reported that the saturated alluvial or reclaimed sand deposits which had liquefied once in the past reliquefied during the 1983 Nihonkai-Chubu earthquake and the 1989 Loma Prieta earthquake(S.Yasuda and I.Tohno (1988), N.Yoshida and K.Wakamatsu(1990)). Because it is known that the acceleration induced in the sand ground during the reliquefaction is smaller than that induced in the same sand layer during the past liquefaction, it has been thought that the reliquefaction potential of the saturated sand deposit is considerably large.

It is found by the experiments that the reliquefaction potential of the saturated sand layer is affected by the factors such as the amplitude of shear strain induced in the sand layer during first liquefaction, and the magnitude of residual strain and the density increase of the sand layer induced after first liquefaction, and the drainage condition. However, a unified opinion on their effects has not necessarily been obtained as yet.

It is very important to know the reliquefaction potential of saturated sand for the aseismatic foundation engineering.

In this paper, first, the reliquefaction potential of the sand deposits reliquefied during the above-mentioned two earthquakes is evaluated using the simplified method of liquefaction analysis, in order to support the occurrence of reliquefaction of these sand deposits numerically.

Next, the shaking table tests are carried out in order to clarify the effect of the acceleration and duration of vibration t_{LS} acted on the saturated sand layer during first liquefaction on the reliquefaction potential of the saturated sand layer. In the tests, Kjellman's type simple shear box is used. Furthermore, the effect of the amplitude of shear strain induced in the sand layer during first liquefaction on the reliquefaction potential of the sand layer is examined.

2 EXAMINATION OF RELIQUEFACTION POTENTIAL OF SATURATED SAND DEPOSIT

The reliquefaction potential of the saturated sand deposits which reliquefied during the Nihonkai-Chubu earthquake(1983) and the Loma Prieta earthquake(1989) was examined using the simplified method of liquefaction analysis(Y.Yoshimi(1991)). The analysis was made on the sand grounds at four sites of which the ground condition and the maximum acceleration α_{max} induced on the ground surface during first liquefaction and reliquefaction are comparatively well known.

As shown in Table 1, since α_{max} of most grounds induced on the ground surface during the reliquefaction are smaller than those during the past liquefaction, it is considered those saturated sand grounds easily reliquefied.

In the analytical method, the dynamic shear stress ratio τ_d/σ_v' induced in the ground during earthquake can be calculated using Eq.(1).

$$\tau_d/\sigma_v' = 0.65\alpha_{max}/g \cdot \sigma_v / \sigma_v' \cdot \gamma_d \qquad (1)$$

in which τ_d:dynamic shear stress, σ_v':verti-

Table 1 Result of analysis of reliquefaction potential of the sand deposits reliquefied during the 1983 Nihonkai-Chubu earthquake and the 1989 Loma Prieta earthquake.

Site	Liquefaction history	Earthquake	M	α_{max} (gal)	Sand ground analyzed	τ_d/σ_v'	$(\tau_\ell/\sigma_v')_M$	Judgment
Niiyamoto (Akita)	Past lique. Relique.	Niigata(1964) Nihonkai-Chubu M(1983)	7.5 7.7	90.6 150	N-value=0∿6 (z<6m)	0.08 0.13	0.08 0.08	Lique. Relique.
Nakazato (Aomori)	Past lique. Relique.	Nihonkai-Chubu M(1983) Nihonkai-Chubu A(1983)	7.7 7.1	278 109	N-value=7∿8 (z=2∿6m)	0.33 0.13	0.13 0.135	Lique. Possibly relique.
Aomori (Aomori)	Past lique. Relique.	Tokachioki(1968) Nihonkai-Chubu M(1983)	7.9 7.7	213 116	N-value=4∿17 (z=3.5∿8.3m)	0.38 0.21	0.12 0.12	Lique. Relique.
San Francisco	Past lique. Relique.	San Francisco(1906) Loma Prieta(1989)	8.3 7.1	300 150	N-value=10 (z<5m)	0.39 0.19	0.17 0.19	Lique. Possibly relique.

cal effective stress, σ_v:vertical total stress, γ_d:stress reduction factor(=1-0.05z), z:depth.

The in-situ liquefaction resistance $(\tau_\ell/\sigma_v')_M$ of the ground for earthquake with magnitude M is given by Eq.(2).

$$(\tau_\ell/\sigma_v')_M=\gamma_m\cdot(\tau_\ell/\sigma_v')_{M7.5} \quad (2)$$

in which $(\tau_\ell/\sigma_v')_{M7.5}$:in-situ shear stress ratio for earthquake of M=7.5 which read off Fig.1, γ_m:correction factor of the liquefaction resistance for N-value of the ground.

It is clarified in the 1964 Niigata earthquake that though the density and N-value distributions of the grounds in the depth direction before and after the earthquake are considerably different, both the average values in the depth direction are not so different(Y.Koizumi(1966), Y.Ohsaki(1966)). Since the change of both values which appeared in the grounds before and after the earthquakes shown in Table 1 is not clear, we calculated the reliquefaction potential using the typical values of the grounds(S.Yasuda and I.Tohno(1988), N.Yoshida and K.Wakamatsu (1990)).

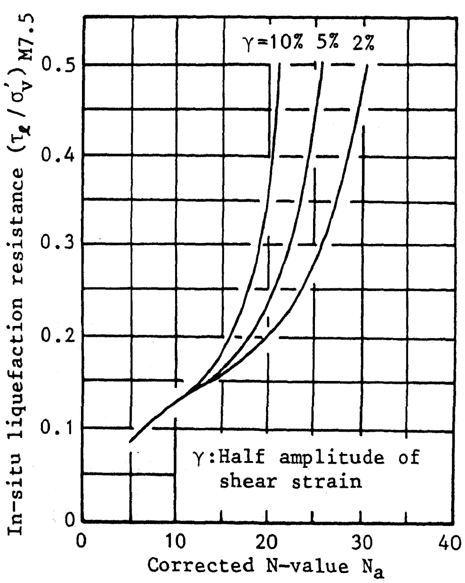


Fig.1 In-situ liquefaction resistance (after Y.Yoshimi(1991)).

The values of τ_d/σ_v' and $(\tau_\ell/\sigma_v')_M$ obtained for each sand ground are shown in Table 1. Also, both calculated values for the past liquefaction are shown in Table 1.

Let us take the ground at Aomori city by way of example to see its reliquefaction potential. From Eq.(1), we obtain τ_d/σ_v' = 0.65·(1.16/9.8)·(13.5/4.5)·0.91=0.21. Also, since the corrected N-value N_a is $6/\sqrt{0.45}$= 8.9, $(\tau_\ell/\sigma_v')_{M7.5}$ for this N_a-value is 0.12. Instituting this value and γ_m=0.98 in Eq.(2), we obtain $(\tau_\ell/\sigma_v')_M$=0.98·0.12=0.12.

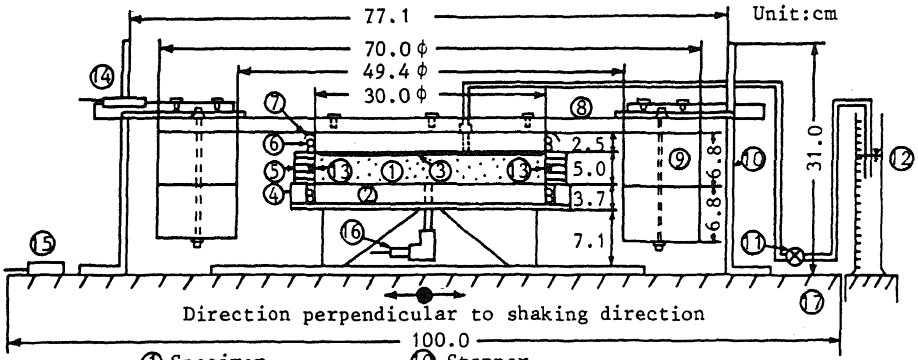
It may be judged in Table 1 that since τ_d/σ_v' is larger than $(\tau_\ell/\sigma_v')_M$ for the all sand grounds, those reliquefaction potentials are considerably large. This analytical result agrees well the fact that those sand grounds easily reliquefied. Furthermore, it is found in Table 1 that the liquefaction potential of those grounds for tne past liquefaction is quite large.

3 EFFECT OF ACCELERATION, DURATION OF VIBRATION, AND SHEAR STRAIN ACTED ON SAND LAYER DURING FIRST LIQUEFACTION ON RELIQUEFACTION POTENTIAL OF SATURATED SAND LAYER

3.1 Test apparatus and procedures

In the tests, Kjellman's type simple shear box which was fixed on the shaking table was used as shown in Fig.2. This has been used in the liquefaction tests on the saturated sand layer and in the tests measuring the horizontal stresses induced in the sand layer during cyclic shear(S.Ōhara and T.Yamamoto(1989), T.Yamamoto et al. (1991)).

Because the details of the test apparatus were described in our previous papers above mentioned, we shall describe them only briefly in this paper. To prevent the lateral



① Specimen
② Rim plate
③ Rib plate
④ Supporting plate
⑤ PV chloride rings
⑥ O-rings
⑦ Rubber membrane
⑧ Loading plate
⑨ Lead weight
⑩ Stopper
⑪ Drainage valve
⑫ Meßzylinder
⑬ Pressure transducers
⑭ Displacement transducer
⑮ Accelerometer
⑯ Pore water pressure transducer
⑰ Shaking table

Fig.2 Kjellman's type simple shear box.

expansion of the sand layer and to induce the simple shear deformation, five polyvinyl chloride rings ⑤ are stacked around the sand layer which was covered with rubber membrane ⑦ of 0.23mm in thickness. Each ring is 1.0cm in thickness, and the inner and outer diameters are 30.2cm and 35.0cm, respectively.

A vertical stress of σ'_{v0} =49kPa was applied to the surface of the sand layer by the loading plate ⑧ and the lead ring weight ⑨ . Cyclic shear stress is applied to the sand layer by the horizontal inertia force of the sand layer, the loading plate, the lead ring, and polyvinyl chloride rings during the vibration.

The saturated Toyoura sand layer is prepared by carefully pouring wet sample into water stored in a rubber membrane fixed around a rim plate ② . Subsequently the surface of the sand layer is compacted by a tamper to obtain the sand layer with a relative density D_r of 55%. The sand layer size is 30cm in diameter and about 5.0cm in height. The properties of Toyoura sand are G_s=2.642, D_{max} =0.84mm, D_{50}=0.21mm, U_c=1.7, e_{max}=0.933, e_{min} =0.628.

Thereafter, the loading plate is set on the sand layer, and the first liquefaction test which applies sinusoidal vibration with a constant acceleration and a period of 0.33 sec to the sand layer was carried out under the undrained condition until liquefaction occurs. The drainage valve ⑪ was opened after immediately first liquefaction occurred, and the vibration was continued under the drainage of pore water in the sand layer. The drainage was allowed from the center of the surface of the sand layer.

The duration of vibration t_{ES} acted on the sand layer during first liquefaction was varied in the region of about 0sec to about 30sec. The double amplitude of shear strain γ_D induced in the sand layer during liquefaction was controlled to be 13.4% by the stopper ⑩. Thereafter, the reliquefaction test was carried out on the same sand layer completed the drainage.

Considering the magnitude of accelaration induced in in-situ ground during first liquefaction and reliquefaction, we decided to apply seismic coefficient $(k_h)_1$=0.20 to the sand layer during first liquefaction test, and $(k_h)_2$=0.15 to the sand layer during reliquefaction test. The subscripts 1 and 2 denote the first liquefaction and the reliquefaction, respectively.

Also, the tests with $(k_h)_1$=$(k_h)_2$=0.15 were performed. In this case the tests applying γ_D=5.0% as well as 13.4% to the sand layer during first liquefaction were carried out to clarify the effect of the amplitude of shear strain induced in the sand layer during first liquefaction on the reliquefaction potential of the sand layer.

During the testing we measured the amplitude of shear deformation, the pore water pressure, the horizontal stresses induced in the sand layer, and the acceleration of the shaking table. The pickups for these measurements were, respectively, the displacement transducer ⑭ (capacity:10mm), the pore water pressure transducer ⑯ (capacity:980 kPa), the small type pressure transducers ⑬ (capacity:196kPa), and the strain gauge type accelerometer ⑮ (capacity:5g), as shown in Fig.2.

These measurements were recorded on a pen-written oscilloscope.

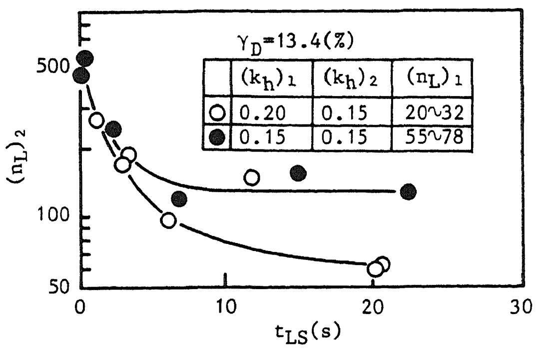


Fig.3 Variation of $(n_L)_2$ with t_{LS}.

3.2 Results and considerations

Fig.3 shows the variation of number of cycles of cyclic shear required to cause the reliquefaction $(n_L)_2$ with t_{LS}. Symbols ● and ○ show the test results with $(k_h)_1$=0.15 and 0.20, respectively. Both sand layers were subjected to γ_D=13.4% during first liquefaction.

In first liquefaction test, the liquefaction is accompanied with the rapid increase of the shear strain induced in the sand layer at a number of cycles, and the pore water pressure becomes equal to the initial effective vertical stress σ'_{vo}. On the other hand, in the reliquefaction test, because the density of the sand layer increases owing to the drainage after liquefaction, the shear strain increases gradually with increasing number of cycles owing to cyclic mobility, and the pore water pressure becomes equal to σ'_{vo} temporally. Thus, a difference between the increase of the pore water pressure and shear strain induced in the sand layer during first liquefaction and reliquefaction is recognized. Furthermore, we defined that liquefaction occurred when γ_D becomes equal to 5.0%.

It is found in Fig.3 that $(n_L)_2$ values for both sand layers are quite large at t_{LS}≒0sec and decrease with increasing t_{LS}. Namely, though in the case of t_{LS}≦2sec, $(n_L)_2$ values for both sand layers are in the range of about 250 to 500 cycles, $(n_L)_2$ value for the sand layer subjected to $(k_h)_1$=0.20 monotonously decreases with t_{LS} thereafter. On the other hand, $(n_L)_2$ value for the sand layer subjected to $(k_h)_1$=0.15 decreases gradually with t_{LS} until t_{LS}=8sec, and thereafter takes constant value of about 120 cycles at t_{LS} above 8sec.

As shown in the column for explanation of symbol in Fig.3, number of cycles required to cause first liquefaction $(n_L)_1$ value for the sand layer subjected to $(k_h)_1$=0.15 is in the range of 55~78cycles. Also, $(n_L)_1$ value for the sand layer subjected to $(k_h)_1$=0.20 is in the range of 20~32 cycles. Because $(n_L)_2$ value for the sand layer subjected to $(k_h)_1$=0.15 is larger than $(n_L)_1$ value in the range of 55~78 cycles in whole range of t_{LS}, it can be considered that the reliquefaction potential of the sand layer liquefied by the action of relatively small seismic acceleration during first liquefaction becomes quite small as compared with the first liquefaction potential. On the other hand, $(n_L)_2$ value for the sand layer subjected to $(k_h)_1$=0.20 is about 60 cycles at t_{LS}=20sec, which is in the range of scatter of $(n_L)_1$ value for the sand layer subjected to $(k_h)_1$=0.15. So, it can be considered that the reliquefaction potential of the sand layer subjected to large seismic coefficient and the vibration with relatively long duration during first liquefaction is almost the same or becomes a little larger as compared with the first liquefaction potential.

The variation of relative density D_r of the sand layers subjected to $(k_h)_1$=0.20 and $(k_h)_1$=0.15 with t_{LS} is shown in Fig.4. It is seen in this figure that degree of the

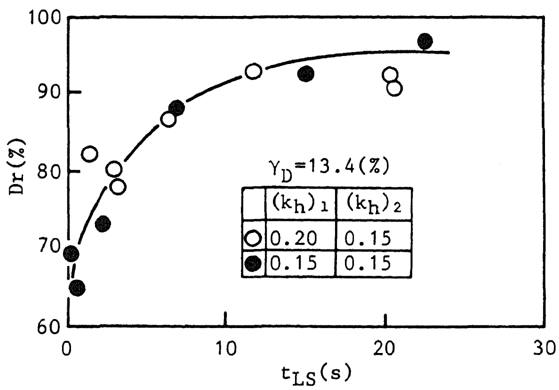


Fig.4 Variation of Dr of sand layer after first liquefaction with t_{LS}.

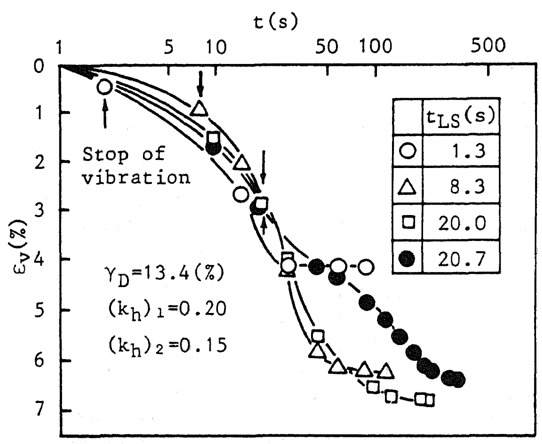


Fig.5 Variation of volumitric strain ε_v of sand layer with time t.

increase of relative density of the sand layers owing to the increase of t_{LS} is the same for both sand layers. Especially the relative density increases rapidly up to t_{LS}=8sec, and thereafter increases gradually with the increase of t_{LS}.

Fig.5 shows the variation of volumetric strain ε_v of the sand layer with time t, induced by the drainage performed during first liquefaction and after stop of vibration. This is the result in the case of $(k_h)_1$=0.20. In this figure the arrows show the time when stopped the vibration immediately after the occurrence of first liquefaction. It is found in Fig.5 that ε_v of the sand layer induced by the drainage of the pore water after first liquefaction is about 4% in the case of t_{LS}=1.3sec, and is in the range of 6~7% in the case of t_{LS}=8.3~20.7 sec. Also, the result in the case of $(k_h)_1$= 0.15 was almost the same as this result.

Fig.6 shows the variation of K_o-value of the sand layer reformed after first liquefaction with t_{LS}. K_o-values for t_{LS}=0sec are the average values of six measurements obtained before first liquefaction. It is found in Fig.6 that no difference between K_o-values for the sand layers subjected to $(k_h)_1$=0.15 and $(k_h)_1$=0.20 is recognized. That is, though K_o-value becomes temporally slightly larger than the initial K_o-value for t_{LS}=0sec after first liquefaction, thereafter it decreases and finally becomes constant when t_{LS} becomes larger.

In the test results, our previous test results(S.Ōhara and T.Yamamoto(1982,1984)) are reconfirmed. That is, it is reconfirmed that the reliquefaction potential of the sand layer becomes small owing to the density increase by the drainage performed after first liquefaction. This result was obtained by the experiments for the case of $(k_h)_1$= $(k_h)_2$=0.15.

It is shown from the test results for the case of $(k_h)_1$=0.20 and $(k_h)_2$=0.15 that the respective reliquefaction potential is not changed or becomes a little larger when the seismic coefficient and duration of vibration

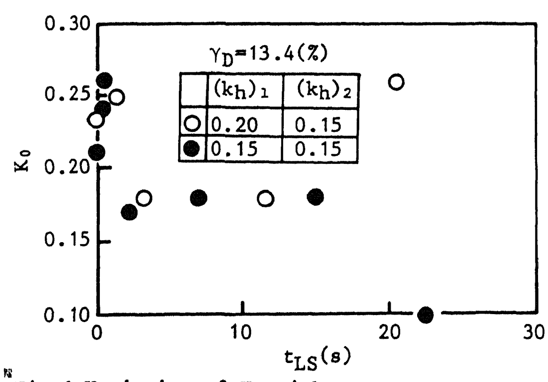


Fig.6 Variation of K_0 with t_{LS}.

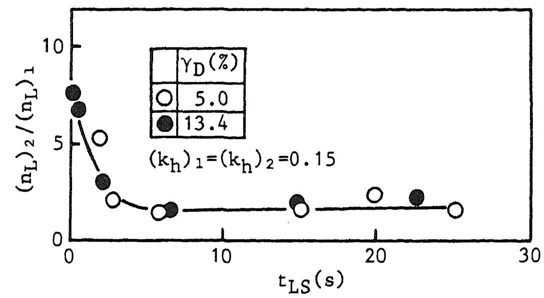


Fig.7 Effect of amplitude of shear strain on $(n_L)_2/(n_L)_1$.

acted on the sand layer during first liquefaction becomes larger. That is, it is considered that in such case since the loose sand structure is apt to partially reform in the sand layer by the drainage performed after first liquefaction, the reliquefaction potential becomes large.

To confirm this fact the cone penetration test was performed on the sand layers which were reformed after first liquefaction. As a result, no difference of the cone resistances for these sand layers could be recognized.

Fig.7 shows the variation of $(n_L)_2/(n_L)_1$ with t_{LS} for the sand layers subjected to γ_D of 5.0% and 13.4% during first liquefaction. Both results are obtained from the tests in the case of $(k_h)_1=(k_h)_2$=0.15. Symbols ● and ○ show the results for γ_D= 13.4%(same as that in Fig.3) and γ_D=5.0%, respectively. γ_D=5.0% corresponds to the double amplitude of shear strain defined as the onset of liquefaction.

It is clear from Fig.7 that $(n_L)_2/(n_L)_1$ values are independent of the amplitude of shear strain. Namely, the reliquefaction potential of the sand layer was not affected by the amplitude of shear strain. Though both $(n_L)_2/(n_L)_1$ values are 7.0 at t_{LS}≒0sec, they decrease with increasing t_{LS} and take constant value of 1.7 at t_{LS} above 8.0sec. We considered that this fact is related to that degree of the increase of the density of the sand layer decreases at t_{LS} above 8.0sec(Fig.4). This value is the same as that obtained in our previous study (T.Yamamoto et al.(1991)).

Furthermore, the variations of relative density and K_o-value with t_{LS} for the sand layer subjected to γ_D=5.0% were the same as those subjected to γ_D=13.4% as shown in Fig.4 and Fig.6, respectively.

4 SUMMARY

There is a fact that the reliquefaction of the saturated sand deposit occurred by the ground acceleration smaller than that during the past liquefaction. In order to clarify this fact we examined the reliquefaction potential of the sand deposits which reliquefied during the 1983 Nihonkai-Chubu earthquake and the 1989 Loma Prieta earthquake using the simplified method of liquefaction analysis.

Furthermore, we examined the effect of the acceleration and duration of vibration, and the amplitude of shear strain induced in the sand layer during first liquefaction on the reliquefaction potential of the sand layer using Kjellman's type simple shear box which was fixed on the shaking table.

The conclusions obtained in this study are as follows.

(1)It is clear from the results obtained by the conventional method that the reliquefaction potential of the prototype sand deposits reliquefied in past earthquake is almost larger than that for first liquefaction.

(2)The reliquefaction potential of the saturated sand layer becomes smaller compared with that for first liquefaction in the case that the seismic coefficient and duration of vibration acted on the sand layer during first liquefaction are small. However, the reliquefaction potential does not change or becomes a little larger in the case that they are large.

(3)The effect of the amplitude of shear strain induced in the sand layer during first liquefaction on the reliquefaction potential is not recognized in the range of γ_D=5.0%~13.4%.

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