AN EXPERIMENTAL STUDY OF LIQUEFACTION OF SATURATED SANDS

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SYNOPSIS

Loose saturated sand was placed in a rigid box, covered with an impervious membrane, and subjected to horizontal vibration while a surcharge was applied on the membrane. The pore water pressure measured at various depths during vibration showed that the process leading to a completely liquefied state consisted of two stages: (1) a period in which the pore pressure at different depths increased uniformly and simultaneously while the sand remained stable, and (2) a very rapid rise in the pore water pressure reaching the value approximately equal to the total stress.

The second stage (termed "sudden liquefaction" process) occurred when the effective stress was reduced to a certain value as a result of the first stage (termed "initial compaction" process). The critical effective stress immediately before the sudden liquefaction increased with an increase in the applied acceleration, and the duration of the initial compaction process increased with increasing surcharge and with decreasing acceleration.

INTRODUCTION

It has been observed during several major earthquakes that liquefaction of saturated sands caused considerable damage to structures and slopes.^{1)**} Previous laboratory experiments to study the liquefaction phenomenon may be divided into the following two groups:

- (1) A box containing saturated sand is subjected to vibration or impacts²⁾.
- (2) A cylindrical specimen of saturated sand in a triaxial compression apparatus is subjected to cyclic variation in the deviator stress while the ambient pressure is kept constant.^{3), 4)}

All the tests that belong to the first group have been run with a pervious upper boundary. Florin and Ivanov²⁾ showed that the presence of a pervious surcharge on the surface greatly reduced the duration of the liquefied state.

The laboratory tests that belong to the second group have been conducted as undrained tests, and each cylindrical specimen has been supposed to represent an element

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within a soil mass. Seed and Lee⁴⁾ showed that in their stress-controlled tests, complete liquefaction with large deformations was preceded by a period of gradual increase in the pore water pressure while the deformation remained negligible, and that the number of cyclic stresses required for complete liquefaction increased with an increase in the confining pressure.

In a stratified soil deposit, saturated sands are often found sandwiched between less pervious soil strata such as silt and clay. Even a thin layer of silt can act as an impervious boundary during a relatively short duration of an earthquake. Although there have been a number of laboratory tests to study the liquefaction phenomenon of saturated sands, none has been able to show adequately the influence of impervious boundary. It is the object of the present paper to study qualitatively the factors that influence the conditions producing liquefaction in a saturated mass of loose sand within impervious boundaries.

DESCRIPTION OF LABORATORY TESTS

As shown in Fig. 1, saturated sand was placed in a rectangular box fixed on a shaking table. The box is of welded steel construction with interior dimensions of 50 cm $\times$ 25 cm $\times$ 27 cm, having a porous plate in the bottom and a glass window in a side wall.

Five pore pressure gages (semiconductor pressure transducers Model MPC manufactured by Kyowa Dengyo, Tokyo) are mounted as shown and connected to a strain meter (Model DPM-6AT manufactured by Kyowa Dengyo, Tokyo) and an

Fig. 1. Sand box and pressure cells

oscillograph (*Visigraph* FR-102 manufactured by San'ei Sokki, Tokyo). In the design of the pore pressure measuring and recording system, an effort was made to minimize time lag by reducing the head loss, the volume change, and the inertia of the galvanometers.

An accelerometer (Type 120A-2D manufactured by Kyowa Dengyo, Tokyo) is secured on the shaking table and connected to the oscillograph.

The properties of the sands used in the investigation are given in Table 1 and Fig. 2. The Niigata sand contained some clay fraction and light particles of the sand size which made it difficult to prepare a saturated mass of uniform density and grain-size distribution. The use of the Niigata sand, therefore, was discontinued after a few preliminary tests, and zircon sand was used for most tests. The zircon sand was selected primarily because of its cleanness and uniformity which facilitated the preparation of identical specimens.

The following steps were taken to prepare a specimen of saturated sand and apply a predetermined effective stress:

- (1) Fill the box with sand to the rim while upward flow of water is maintained. Determine the original void ratio, e_0 .

Table 1 Properties of Sands

	Grain size		$\frac{D_{60}}{D_{10}}$	Specific Gravity of Solids	Max. and Min. Void Ratios			
	D_{10} mm	D_{60} mm			Oven-Dry		Submerged	
					$e_{\max}$	$e_{\min}$	$e_{\max}$	$e_{\min}$
Zircon sand	0.10	0.17	1.7	4.67	0.82	0.53	0.83	0.45
Niigata sand	0.11	0.21	1.9	2.66	1.08	0.72	1.36	0.66

Fig. 2. Grain-size distribution curves

- (2) Place a rubber membrane on the sand and close the cover.
- (3) Zero the pore pressure gages when the pore pressure is hydrostatic (atmospheric at the top of sand).
- (4) Apply a surcharge, p (air pressure), on the rubber membrane while the excess hydrostatic pressure is kept zero. Measure the volume of overflow and compute the initial void ratio, e_i .

With all the valves closed, the box was subjected to horizontal vibration in the longitudinal direction of the box, and the pore pressure and acceleration were recorded on the oscillograph.

Table 2. Range of Test Data

	Number of Liquefied Samples	Void Ratios			Relative Densities*		Sur-charge p cm H ₂ O	Vibration	
		Before Sur-charge e_0	Before Vibra-tion e_i	After Vibra-tion e_f	Before Vibra-tion R_{di} %	After Vibra-tion R_{df} %		Acceler-ation cm/sec ²	Fre-quency c/sec
Zircon sand	62	0.68-0.69	0.67-0.69	0.51-0.61	45-52	72-107	0-600	130-960	4-8
Niigata sand	4	0.91-0.93	0.90-0.92	0.77-0.81	45-50	75-86	0-60	200-300	3

* Based on e_{max} and e_{min} in Oven-dry condition (see Table 1).

Fig. 3. Typical oscillograph records

Fig. 4. Excess pore pressure vs time

The values of the initial void ratio, e_i , and the initial relative density, R_{di} , are given in Table 2. The vertical effective stress in the sand before vibration can be given by

$$\sigma'_i = p + \gamma'_i z \dots \dots \dots (1)$$

where p is the surcharge, z is the depth, and γ'_i is the initial submerged unit weight of the sand.

MEASURED PORE WATER PRESSURE

Typical oscillograph records of the table acceleration and the pore water pressure at the side wall (PC 1 to PC 3) are shown in Fig. 3. It is seen in the figure that the amplitudes of the dynamic pore pressure are relatively small. Figures 4(a) to 4(c) are obtained by replotting oscillograph records. Figure 5 is plotted from Fig. 4(c) to show several isochrones of the excess pore pressure.

All the pore pressure data for both Niigata sand and zircon sand show clearly that the u vs. t curves can be represented by idealized curves of Fig. 6. Each curve in Fig. 6 representing a certain depth in the sand consists of five distinct stages which will be identified in this paper as follows :

Fig. 5. Excess pore pressure isochrones

Fig. 6. Idealized pore pressure curves during vibration

AB....Initial compaction process;
 BC and B'C'....Sudden liquefaction process;
 CD and C'D'....Liquefied state;
 DE and D'E'....Consolidation process;
 EF....Stabilized state.

LIQUEFIED STATE

When the pore pressure curve reaches a plateau (CD and C'D' in Fig. 6), the effective vertical stress becomes nearly zero, and the upward hydraulic gradient nearly equals the critical value given by

$$i_{cr} = \frac{G-1}{1+e_z} \dots\dots\dots(2)$$

Fig. 7. Distribution of maximum excess pore pressure

This is demonstrated in Fig. 7 which gives the distribution of the maximum pore pressures for the data of Fig. 4. The measured hydraulic gradients for the three tests vary from 1.9 to 2.15, whereas the theoretical critical gradient computed from eq. (2) is 2.18

During the tests on the Niigata sand large deformations were observed through the glass window when the sand liquefied. Although the plain texture of the zircon sand precluded such visual confirmation of large deformations, it is inferred from the pore pressure data that the sand did liquefy.

INITIAL COMPACTION

The process of initial compaction (curve AB in Fig. 6) is characterized by the fact that the u vs. t curves at different depths in the sand are identical, i.e., at a given time the excess pore pressure is constant throughout the depth (see curves for 10 sec and 26 sec in Fig. 5). This shows that there is negligible flow of water in the vertical direction.

The equilibrium of vertical forces acting between the rubber membrane and the sand surface requires that during the process of initial compaction the surcharge, p ,

which is originally carried by the soil skeleton is being transferred to the pore water. It is postulated that such transfer of load from sand to water is caused by a reduction in the contact area between the rubber membrane and the sand, which in turn is caused by a slight compaction of the sand skeleton.

It must be pointed out that the total volume of sand plus water is maintained constant, and that there is nothing to prevent compaction of sand skeleton. In this respect, the test should really be called a "constant total volume test" rather than an undrained test.

It is conceivable that only a slight amount of compaction may be sufficient to cause a significant reduction in the effective stress in the sand. In their pulsating load tests on cylindrical specimens of saturated sand in the undrained condition, Seed and Lee⁴⁾ observed a gradual build-up of the pore pressure while the sand showed no noticeable deformation. The phenomenon can also be explained by the above-mentioned hypothesis of initial compaction.

The duration of the initial compaction process, t_{ic} , is plotted against the surcharge, p , in Fig. 8. For a given acceleration there seems to be a limiting surcharge below

Fig. 8. Duration of initial compaction vs surcharge

which liquefaction occurs instantly. The curves for the acceleration of 230 and 300 cm/sec² suggest the presence of an upper limit of surcharge above which liquefaction cannot occur at a given acceleration.

Figure 8 shows that at a given surcharge the duration of initial compaction increases with decreasing acceleration. The same tendency was observed by Seed and Lee⁴⁾ between the number of stress cycles to cause failure and the pulsating deviator stress at a given initial confining pressure.

SUDDEN LIQUEFACTION

The process of sudden liquefaction (curve BC and BC' in Fig. 6) is characterized by a sharp rise in the pore pressure. Unlike the preceding initial compaction process, the u vs. t curves at different depths diverge to reach different levels. This is demonstrated in Fig. 9 which shows typical u vs. t curves for the period between the initial compaction process and the liquefied state. (The original data were recorded with a paper speed of 4 cm per sec.) Despite the differences in p , t_{ic} and a , these curves are remarkably similar. The pore pressures at the three depths seem to increase simultaneously at approximately the same rate. Although the pressure at the deepest gage (PC 3) reaches the peak value somewhat later than the pressure at the top gage (PC 1), the time lag is only a fraction of a second. On the other hand, the time lag is more pronounced in Fig. 4(a) which represents a test with zero surcharge, and even greater time lag has been reported by Florin and Ivanov²⁾ for the case of free surface.

The vertical effective stress at the sand surface just before sudden liquefaction may conveniently be defined by

$$\sigma'_{lo} = p - u_b \dots \dots \dots (3)$$

Fig. 9. Pore pressure development during sudden liquefaction

Fig. 10.

Fig. 11. Effective stress vs acceleration

Fig. 12. Surcharge vs acceleration
for $t_{ic}=5$ sec

Fig. 13.

in which u_b is given by the excess pore pressure at point B in Fig. 10.

In Fig. 11 the values of σ'_{lo} are plotted against the table acceleration, a . The tests for which t_{ic} is less than 10 sec are excluded from the plot because of the difficulty in defining the point B of Fig. 10. For the tests in which liquefaction occurred within 10 sec, the surcharge corresponding to $t_{ic}=5$ sec in Fig. 8 is plotted in Fig. 12 against the acceleration.

Figures 11 and 12 show clearly that greater accelerations are required to cause

liquefaction at greater confining pressures. This agrees with Seed and Lee's observation⁴⁾ that greater pulsating deviator stresses are required to cause liquefaction and failure at greater confining pressures.

The data in Fig. 11 show further that the relationship between σ'_{lo} and a is nearly independent of the duration of the initial compaction process, t_{ic} , provided that t_{ic} is not less than 10 sec.

Table 3. Effective Stress before Sudden Liquefaction

Test No.	p cm H ₂ O	σ'_{lo} cm H ₂ O	Effective Stress at		Ratio of Effective Stresses at PC 3 & PC 1
			PC 1	PC 3	
ZU-0	0	0	8.7	52	6
ZU-6-3	150	53	62	105	1.7
ZU-10-1	250	59	68	111	1.6

Let us examine the u vs. t curves in Fig. 4 in the light of the effective stress distribution in the sand. As shown in Table 3 the ratio of the effective stress at the bottom pore pressure cell (PC 3) to that at the top cell (PC 1) is 6 for the unloaded test, but less than 2 for the loaded tests. The time lag in the build-up of pore pressure at the bottom cell in the unloaded test may be explained by the relatively large confining stress there compared to the shallower zone, whereas the apparent lack of such time lag in the other tests may correspond to the relatively small variation in the effective stresses.

CONSOLIDATION

After a mass of saturated sand is completely liquefied the sand grains settle down to a denser and more stable packing. This process involves dissipation of excess pore water pressure, and has been recognized by Terzaghi⁵⁾ as a form of consolidation process. Unlike the consolidation of a uniform clay stratum, however, the excess pore pressure distribution curve during the consolidation of a liquefied sand consists essentially of two straight lines as shown in Fig. 13 with a demarcation between the stabilized zone where the hydraulic gradient is zero and the fully liquefied zone where the hydraulic gradient equals $(G-1)/(1+e)$. The consolidation process continues until the entire mass of sand is stabilized, and the hydraulic gradient vanishes.

This phenomenon has been observed by Florin and Ivanov²⁾ in their shaking table tests on a saturated sand with a free surface, and their finding seems to be confirmed by the present test series, except for the excess pore pressure at the top of the sand which was absent in their tests.

When the upper boundary is impervious as in the author's tests, a layer of water forms between the upper boundary and the surface of the sand, thus making the surcharge literally float on the layer of water. The average depth of the surface water is 1.6 cm which is approximately 6% of the initial height of sand.

INFLUENCE OF IMPERVIOUS SURCHARGE ON LIQUEFACTION

On the basis of the preceding discussions of the test data, the following phenomena seem to be the most significant consequences of the impervious surcharge in connection with liquefaction of loose saturated sand during vibration :

- (1) Complete liquefaction is preceded by a period of gradual build-up of the pore pressure with negligible hydraulic gradient (the " initial compaction " process);
- (2) A layer of water forms between the sand and the upper boundary after the consolidation process.

It should be recognized that considerable differences may exist between field conditions during earthquakes and the laboratory test conditions reported here, particularly with respect to the boundary configurations and the manner in which stress waves propagate.

It is interesting to note, however, that a phenomenon similar to the author's initial compaction process was also observed in the triaxial pulsating load tests by Seed and Lee⁴⁾ despite the greatly different boundary restraints of their samples. It is conceivable, therefore, that such a phenomenon may occur in the field during earthquakes or due to other sources of dynamic disturbance.

If one assumes that the results of the present tests can be qualitatively extrapolated to field conditions, one can say that a stratum of loose saturated sand sandwiched between impervious boundaries can liquefy if the ratio between the acceleration and the initial effective stress is sufficiently great, and/or duration of vibration is long. This is in agreement with previous studies^{3), 4)}.

CONCLUSIONS

On the basis of the pore water pressure in initially loose saturated sand measured during vibration, the following conclusions may be made :

- (1) When the sand undergoes complete liquefaction, the process leading to the liquefied state consists of two stages : initial compaction and sudden liquefaction.
- (2) During the initial compaction process the pore pressures at different depths increase uniformly and simultaneously while the sand remains stable. The duration of the initial compaction process increases with increasing surcharge and with decreasing acceleration.
- (3) Sudden and complete liquefaction occurs when the effective stress in the sand is reduced to a certain value as a result of the initial compaction. The effective stress at the onset of the sudden liquefaction increases with an increase in the applied acceleration.
- (4) In a region where the variation in the initial effective stress is small, sudden liquefaction occurs almost simultaneously at all depths.

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NOTATION

The following symbols have been used in this paper:

- a : maximum acceleration of the shaking table;
- D : grain size of the sand;
- e : void ratio;
- f : subscript pertaining to the final state after vibration;
- G : specific gravity of solids;
- i : hydraulic gradient; or subscript pertaining to the initial state immediately before vibration;
- p : surcharge pressure;
- PC: pore pressure cells;
- R_d : relative density;
- t : time;
- t_{ic} : duration of initial compaction process;
- u : excess pore water pressure;
- z : depth;
- γ' : submerged unit weight;
- σ' : vertical effective stress.

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