LIQUEFACTION OF LARGE SAMPLES OF SATURATED SAND EXCITED ON A SHAKING TABLE

by

W.D. Liam Finn(I), J.J. Emery(II), and Y.P. Gupta(III)

SYNOPSIS

When large samples of saturated sand, 72 in. x 18 in. x 7 in. are excited on a shaking table the observed behaviour is similar to that of small specimens in cyclic loading triaxial and simple shear tests. The resistance to liquefaction increases in a non-linear way with increased surcharge pressure and decreases as the acceleration amplitude increases. The depth and range of movement of sand grains during liquefaction can be observed through special viewing windows.

INTRODUCTION

Much of the damage which occurred in the Chilean earthquakes of May 1960 (15)(IV), and the 1964 earthquakes in Niigata, Japan, (7, 12, 16) and Alaska (6, 14), was caused by the liquefaction and subsidence of foundation soils or by liquefaction induced landslides. Usually the degree of damage was closely related to the properties of the foundation soils. For instance, at Niigata (16) the soil formations in the areas seriously damaged by the earthquake consisted of recent alluvial deposits or recently deposited artificial fills of relatively uniform, loose saturated sands. The vibrations due to the earthquake induced the liquefaction of these loose saturated deposits and caused much damage to earth structures and foundations. This damage due to liquefaction has focused attention on research to determine the significant parameters affecting the liquefaction potential of saturated sands (5, 11).

Most experimental studies on the liquefaction of saturated sands have involved cyclic loading triaxial tests (8, 9, 13, 17) and cyclic loading simple shear tests (4, 10). The main conclusions derived from these studies are that (a) the larger the cyclic stresses, (b) the looser the samples, and (c) the lower the effective confining pressure, the fewer are the number of cycles of a given stress required to cause liquefaction. Finn, Pickering and Bransby (4) have shown that the important variable controlling the incidence of liquefaction in a given number of cycles for an undrained saturated sand at a particular void ratio in cyclic loading tests is the initial effective stress ratio. This effective stress ratio is defined as the ratio of the peak alternating shear stress to the initial effective mean normal stress. It appears that only the numerical value of the ratio is important and not the

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particular values of the shear and mean normal stresses. Comparisons between triaxial and simple shear data indicate equal resistances to liquefaction when the different stress condition in the two types of tests are accounted for.

This paper reports data from a current research project aimed at determining whether the behaviour of small specimens in triaxial and simple shear tests described above can be considered representative of much larger samples, and ultimately of sand deposits in the field. Preliminary studies reported elsewhere (3) indicated that when large specimens of saturated sand are vibrated on the shaking table the pattern of pore pressure response is similar to that noted in cyclic loading triaxial and simple shear tests. The resistance to a liquefaction failure was found to increase in a non-linear way with increasing surcharge pressure. Thus, the observed behaviour for the large samples with low surcharge pressures was qualitatively the same as for small samples in the triaxial and simple shear tests.

Unfortunately, it was difficult to prevent leakage with the plexiglass sample container used in the preliminary studies and, to avoid damaging the container, only low surcharge pressures (less than about 1 psi) were permitted. Also, it was not possible to apply back-pressure to this container and full saturation could not be guaranteed. For these reasons, a new sample container was fabricated to which back-pressures could be applied together with surcharge pressures up to 50 psi.

ADVANTAGES OF USING LARGE SAMPLES AND A SHAKING TABLE

The liquefaction studies of large saturated sand samples excited on a shaking table appear to offer the following general advantages over the usual cyclic loading triaxial and simple shear tests that are used:

1. The plexiglass viewing windows of the sample container (Figure 1) allow all phases of the process to be observed and photographed for further analysis.

2. Large homogeneous samples of saturated sand that simulate the field condition of K_0 consolidation may be prepared. The inertia effects of embedded instruments should be negligible for such large samples.

3. Uniform accelerations will be developed throughout the sample at low frequencies under plane-strain conditions which correspond to the propagation of shear waves in situ (18).

4. It is possible to use displacement, velocity, or acceleration modes of control to provide a wide range of acceleration records and frequencies for the shaking table.

5. The actual pore water pressure distribution in a large mass of saturated sand during liquefaction can be traced.

6. Pressures of up to 50 psi can be applied to the sample surface to simulate the effect of a surcharge. This is equivalent to approximately 100 ft of saturated overburden.

TEST EQUIPMENT AND SAMPLE PREPARATION

The shaking table, together with the sample container and other ancillary equipment is shown in the photographs of Figures 1 to 4. The shaking table is 9 ft long by 6 ft wide and unloaded weighs 1000 lbs. It is constrained to move in one horizontal direction by four horizontal, V-slotted needle bearings manufactured by Schneeberger, Switzerland, and modified at the University of British Columbia. The table is actuated by a hydraulic ram mounted on the fixed base frame and connected to the table through a rigid link. A 3 gpm pump supplies oil at 3000 psi to the ram through an electronically controlled servo-valve. The ram is a double-acting hydraulic piston with a ±2 in. stroke, a dynamic capacity of 2500 lbs and a maximum velocity of about 17 in./sec at full load.

The desired motions are transmitted to the table under the control of the MTS earthquake simulator control console shown in the background of Figure 2. It is capable of treating the input command signal from a function generator, wave follower or magnetic tape as acceleration, velocity or displacement. A servo-loop system compares a displacement-time command (integrating accelerations or velocities if required) with the actual displacement of the ram and continuously corrects the motion as necessary to maintain close correspondence with the input signal. The table accelerations are measured with a Kistler Model 305A/515 Servo Accelerometer-Amplifier system and recorded on a 12 channel B & F light-beam oscillographic recorder and/or on a Tektronic storage oscilloscope. This monitoring and recording equipment can be seen in the background of Figure 3.

The model container was fabricated from aluminum and has inside dimensions of 72 in. long, 18 in. wide and 7 in. deep. Stiffeners were used on the sample container as shown in the Figures to reduce compliance effects and the container can be used for pressures of up to 50 psi in the present configuration or up to 100 psi if high-strength bolts are used on the top lid. On one side of the container there are three viewing ports with $\frac{1}{2}$ in. thick plexiglass windows formed by a continuous sheet fixed on the inside of the container. These windows facilitate viewing and photographing the behaviour of the sand during vibration. The bottom of the sample container has a $\frac{3}{4}$ in. thick plexiglass sheet insert that was roughened by gluing sand to its top surface.

It is very important that the preparation method gives a uniform sample that is free of loose zones that may initiate early failures. To prepare the sample, an 18 in. high extension enclosure with a plexiglass side is bolted to the sample container and filled with water. A movable sand spreader box with a wire mesh bottom travels back and forth automatically on top of this extension enclosure as indicated in Figure 1. There is a perforated pipe around the lower inside of the spreader box through which a continuous flow of water passes. The water level is maintained constant in the extension enclosure about 2 in. above the bottom of the spreader box by an overflow outlet.

Sand is poured into the spreader box and the agitation of the water from the perforated pipe is just sufficient that the sand passes through the wire mesh and falls through the water in the extension enclosure to settle in the sample container as shown in Figure 1. The water flow in the sample spreader also assists in achieving a saturated sample by removing any air bubbles on the sand grains. This process is continued until the sample container is filled with sand. The sample is then carefully leveled to the required height of 7 in. by siphoning out any excess sand and the water from the extension enclosure. After leveling, the extension enclosure is removed and a thin rubber membrane 0.01 in. thick is placed over the sample insuring that there is no air in the sample. A $\frac{1}{8}$ in. thick rubber gasket is placed on the perimeter of the membrane, the lid is placed on the top of the rubber gasket, and the lid is bolted down to the sample container using a torque wrench. The membrane and gasket are shown on the sample container in Figure 2 with the lid being lowered into place. A thin vertical column of black sand is formed on the side of the sample using a thin sheet-metal mold as shown on the middle window in Figure 1. Figure 3 shows the completed assembly with the lid bolted down and the vertical column of black sand against the middle window.

The sample preparation procedure used is very similar to that described by Finn, Pickering and Bransby (4) for dynamic simple shear tests. The resulting sample is very uniform and has an initial relative density, $D_r = 27\%$, that is reproducible from test to test. The dry weight of the prepared sample is approximately 523 lbs.

SAND TESTED

Wedron silica sand was used for all of the tests. This is a uniformly graded, well rounded natural sand with the properties: specific gravity, S.G. = 2.66, maximum void ratio, $e_{max} = 0.77$, minimum void ratio, $e_{min} = 0.47$, and the 50% size, $D_{50} = 0.55$ mm.

TEST PROCEDURE

The required total surcharge pressure on the sealed sample is applied by introducing air pressure between the lid and membrane through a constant pressure regulator. The degree of sample saturation was checked during this step. The sample is then allowed to drain to the desired back-pressure which was pre-set at 15 psi for the tests described herein. At the completion of drainage, the effective surcharge pressure on the sample is the total pressure minus the back-pressure. An initial void ratio can be determined from the measured drainage to the back-pressure container. The drainage line to the back-pressure container is then turned off and the sealed sample is ready for testing with the desired excitation.

UNIFORMITY OF ACCELERATIONS

Previous work by Finn, Campanella and Aoki (2) with the shaking table and sand models had indicated that for sinusoidal acceleration frequencies of up to about 20 Hz the accelerations measured in a dry sand model (8 ft long x $1\frac{1}{2}$ ft wide x 1 ft high) were very uniform throughout the depth of the model. Preliminary studies for the present test program indicated that the accelerations were uniform throughout both dry and saturated samples of Wedron sand for frequencies up to at least 10 Hz. To measure the accelerations throughout the sample, a small Metrix piezoelectric accelerometer ($\frac{3}{4}$ in. diameter by $\frac{1}{4}$ in. thick) was placed in the sample at the desired locations and the output monitored along with the input acceleration on a dual-beam Tektronic storage oscilloscope. The ratio of the accelerations measured throughout the sample to the base input acceleration was close to one.

A theoretical analysis by Aoki (1) indicated that the surface accelerations would be uniform and equal to the base acceleration at frequencies much lower than the resonance frequency of the model. At the resonance frequency of approximately 50 Hz, the surface accelerations become non-uniform and, at some points near the model centre, are amplified by a factor of two. Similar results to those indicated by the theoretical analysis were found in tests on the shaking table. For these reasons, the maximum excitation frequency was limited to 10 Hz for the test program.

PORE WATER PRESSURE BEHAVIOUR

Pore water pressures during each test were monitored at five different locations in the middle of the sample by probes connected to transducers as indicated by the projecting Statham transducers on the right side of the sample container in Figure 4. The location of these probes along with the tracing of a typical light-beam oscillograph record for a liquefaction test is shown in Figure 5. The total applied pressure and the pre-set back-pressure were monitored using an extra transducer and were set very carefully with a Budd strain-indicator.

The degree of saturation was determined by comparing the pore water pressure increase measured in the sample by probes 1, 2, 3 and 4 with the total applied pressure measured with the extra transducer and indicated by the initial tracing for probe 5. For a degree of saturation of 100%, the pressure increase in the sample should equal the total applied pressure. The existence of leaks in the system was also checked for before testing. When the records of pore water pressure remain constant after the sample is sealed, it is clear that there are no leaks in the system and testing can proceed. This is indicated by the horizontal tracings just prior to the liquefaction test shown in Figure 5.

A surcharge pressure of 1 psi was used for the initial liquefaction test shown. As indicated by the pore pressure records, the degree of saturation was 100% and there were no leaks in the system. The excitation used for this particular test was a sinusoidal acceleration of amplitude ±0.25 g and frequency 2 Hz. Normally, the acceleration record was also monitored on the light-beam oscillograph and storage oscilloscope.

The pore pressure curves shown in Figure 5 are typical of those observed in all tests that resulted in liquefaction. Some of the features of the pore water pressure behaviour during liquefaction are as follows:

1. There is a rapid rise in the pore pressure at the beginning of the excitation and then a steady, gradual increase to about 70% of the effective overburden pressure at the level of the probe. At this point there is a rapid increase in pore water pressure to a value close to the total overburden pressure, at which point liquefaction occurs. After liquefaction, the pore water pressure decreases to the applied surcharge pressure. The various phases of the pore water pressure behaviour show up quite clearly in Figure 5. This behaviour is qualitatively the same as that observed for dynamic triaxial and simple shear tests mentioned earlier and for shaking table tests on small samples of saturated sand reported by Yoshimi (18).

2. The increase in pore pressure for each of the probes is about the same at any stage of the test and hence the final total

pore pressure increase is approximately the same for each probe at liquefaction. Since the pressure due to the weight of 2$\frac{1}{2}$ in. of saturated sand is only about 0.08 psi, the difference in elevation of probes 4 and 5 does not show up clearly in the test results.

3. Liquefaction occurred at the same time for the three middle probes (2, 4 and 5), but lags by up to $\frac{1}{2}$ cycle for the end probes (1 and 3). The 'sawtooth' pattern of the pore pressure response for the end probes is probably due to water-hammer effects from the reflection of pore water on the ends of the sample container. The pore pressure build-up and the process of liquefaction appear to occur throughout the length of the sample and within a time difference of $\frac{1}{2}$ cycle at the various pore pressure probes.

EFFECT OF SURCHARGE PRESSURE

A series of tests were carried out in which the surcharge pressure was varied from 0.25 psi to 10 psi (corresponding to about $\frac{1}{2}$ ft to 20 ft of saturated overburden) to check the effect of surcharge pressure on the resistance to liquefaction. For this series of tests the excitation record was kept constant at a sinusoidal acceleration of amplitude ±0.25 g and frequency 2 Hz. The test results are summarized on the surcharge pressure vs. log cycles to first liquefaction plot shown in Figure 6. As the surcharge pressure was increased, the number of cycles required to cause liquefaction of the saturated sand sample increased until, at a surcharge pressure of 10 psi, the sample did not liquefy in a large number of cycles. A projected figure of 15,000 cycles to liquefaction was made for the 10 psi surcharge pressure. This increasing resistance to liquefaction with increasing surcharge pressure is similar to the results reported for cyclic loading triaxial and simple shear tests, shaking table studies on small samples of saturated sand (18). It may be noted from Figure 6 how few cycles are required to liquefy the sand at low confining pressures.

A few results from a preliminary testing program using a different sample container (3) are also included in the low surcharge pressure range.

Three tests are indicated by triangles on Figure 6 that show a reduced resistance to liquefaction compared to the general trend. Initially, a $\frac{1}{16}$ in. thick rubber membrane was used for these particular tests before the very soft and flexible 0.01 in. thick rubber membrane was available. It would appear that a small portion of the applied surcharge pressure was used to stretch the thicker and stiffer membrane, and this resulted in the lower resistance to liquefaction for these three tests.

The depth of visually detectable sand movement during liquefaction was determined by observing the vertical column of black sand located in the sample against the middle window (Figures 1 and 3). In most cases, the horizontal movement of the black sand started at the top of the sample, when the pore pressure response indicated that liquefaction was imminent, and propagated downwards to a depth of approximately 5 in. The horizontal movement of the column of black sand was about ±$\frac{3}{4}$ in. at the surface of the sample and to the naked eye there was no visible horizontal movement at a depth of 5 in. There was no visible vertical motion of the black sand. When the shaking was stopped at the end of the test, the column of black sand usually remained quite straight and close to its original position in the sample. It was difficult to determine from the observed behaviour of the black sand whether the sample was now looser at the surface after shaking and liquefaction. However, in some tests, particularly those at low surcharge pressures, there appeared to be some spreading of the column near the surface which would indicate the formation of a looser surface layer.

After the initial liquefaction, the sand grains 'settle' to give a lower void ratio, the pore water pressure drops to the surcharge pressure and a layer of water approximately 0.25 in. in depth forms on the surface of the sample. There is no longer any contact between the surface sand grains and the membrane, so that it is quite possible that these surface sand grains may move at this point and a non-uniform surface layer is formed. This behaviour is again qualitatively the same as that reported by Yoshimi (18).

Coloured films of the vertical column of black sand taken with an 8 mm. movie camera during shaking are now being used to check the uniformity of the sample. Preliminary work with these films indicates that individual sand grains may move up to ±1 in. at liquefaction. Experiments are being conducted in which small specimens are removed from the sample after liquefaction by solidifying the sand with commercial gelatin. The specimens can then be checked for any variations in void ratio with depth. It is hoped that these studies will provide information on the uniformity of the sample after liquefaction.

EFFECT OF ACCELERATION AMPLITUDE

All of the test results described previously were for a sinusoidal acceleration of amplitude ±0.25 g and frequency 2 Hz. For the series of tests described in this section, the surcharge pressure was kept constant at 2 psi, and the excitation record used was a sinusoidal acceleration of frequency 2 Hz and amplitude varying from ±0.10 g to ±0.50 g. The test results are summarized on the acceleration amplitude vs. log cycles to liquefaction plot in Figure 7.

The liquefaction curve indicates that the resistance to liquefaction decreases with the increase in acceleration amplitude. Since the shear stresses induced in the sample are a function of the acceleration amplitude, this decrease in the resistance to liquefaction with increasing acceleration amplitude would be anticipated. For this particular sample and acceleration amplitudes below ±0.15 g, the saturated sand sample did not liquefy.

The behaviour of the vertical column of black sand for acceleration amplitudes up to about ±0.33 g was very similar to that observed in the test series described previously. However, at amplitudes above ±0.33 g, the column of sand moved first at the centre, and then the motion propagated upwards to the surface of the sample. The total depth of visually detectable sand movement was again about 5 in., but the horizontal movement was now somewhat greater at about ±$1\frac{1}{4}$ in. For these higher acceleration amplitudes, there was a definite spreading of the column of black sand at the surface and this would indicate that a loose surface layer was being formed.

CONCLUSIONS

The development of liquefaction during large scale tests of saturated sand samples on the shaking table appears to follow the same pattern as in cyclic loading triaxial and simple shear tests. However, not enough shaking table tests have been carried out yet to determine if the quantitative values of the variables controlling liquefaction may be correlated for all three types of tests. It seems that a very significant advantage of the large scale tests is the opportunity they afford to study the structural and density changes that take place in a sand deposit during liquefaction. These changes are likely to prove critical in determining the behaviour of a sand deposit in subsequent earthquakes.

The viewing windows on the large scale test apparatus allow the process of liquefaction to be observed directly. The movement of the sand grains can be filmed and the depth and range of movement during liquefaction can be recorded.

ACKNOWLEDGEMENTS

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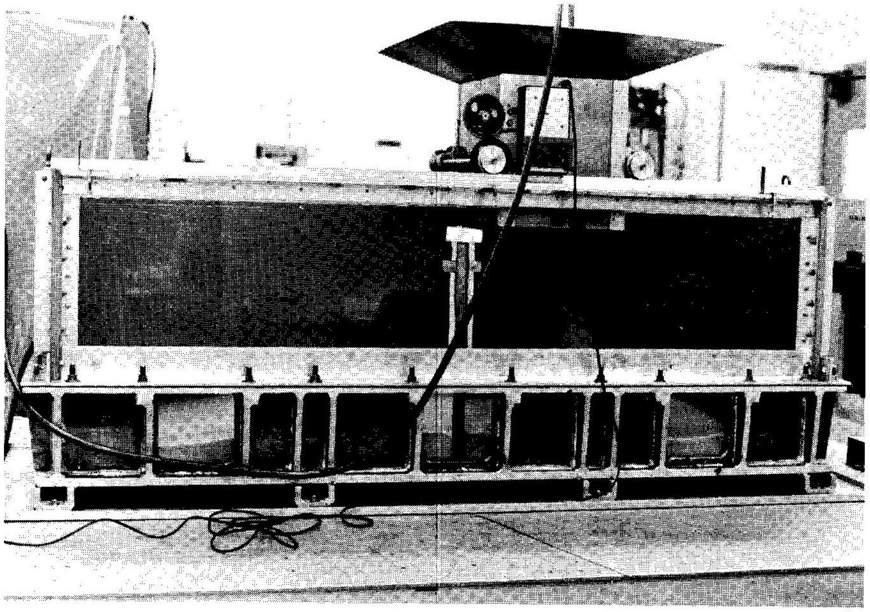

FIG. 1 SAMPLE PREPARATION. SAND BEING PLACED IN THE SAMPLE CONTAINER.

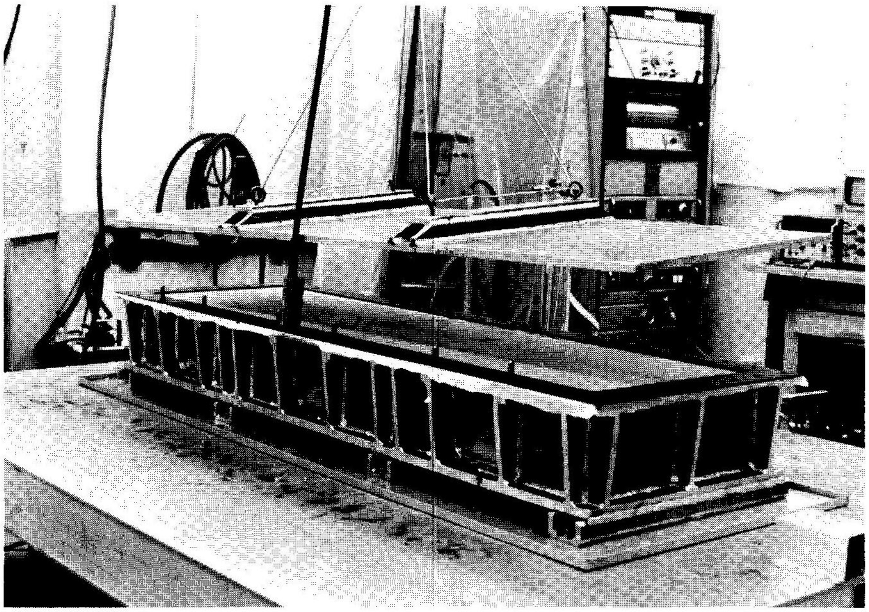

FIG. 2 SAMPLE PREPARATION. LID BEING LOWERED ON THE SAMPLE CONTAINER.

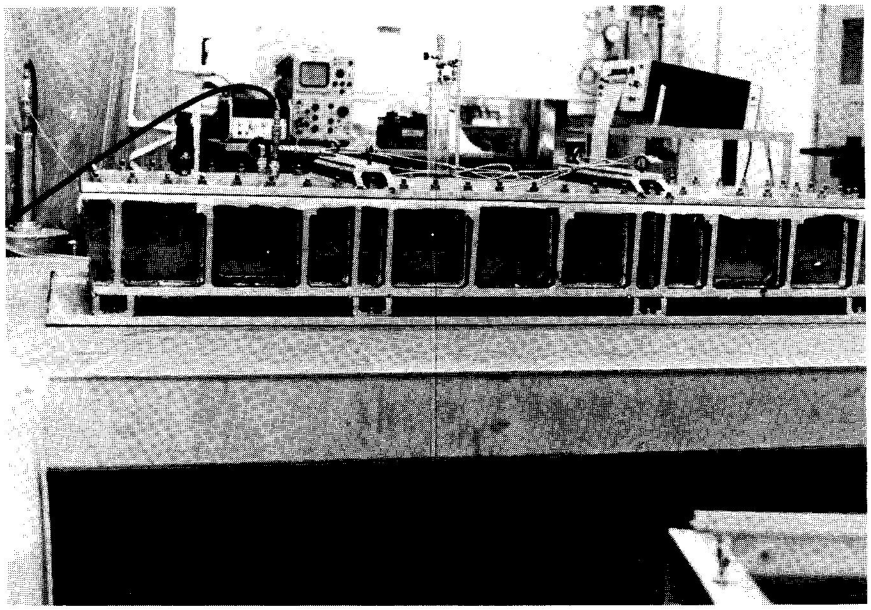

FIG. 3 LID BOLTED DOWN AND SAMPLE READY FOR TESTING.

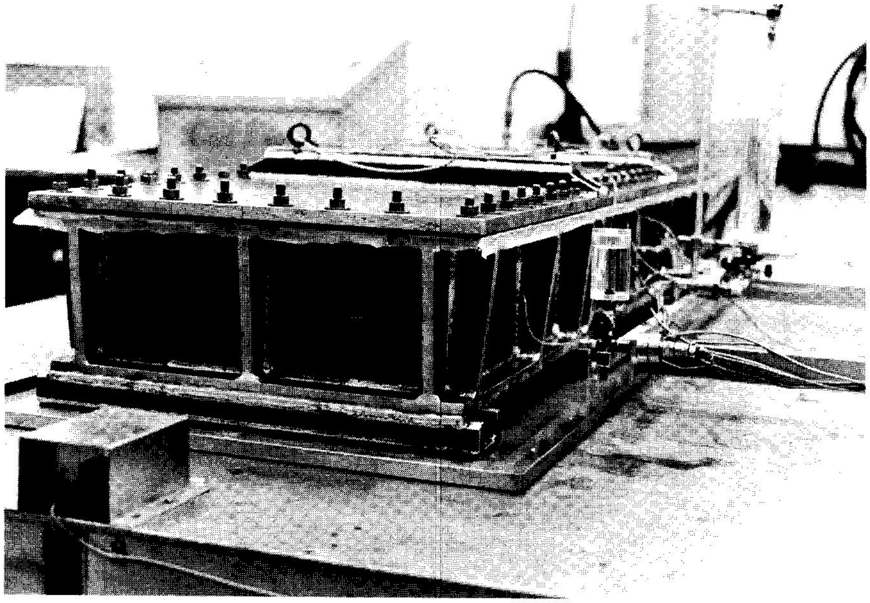

FIG. 4 LOCATION OF PORE PRESSURE TRANSDUCERS.

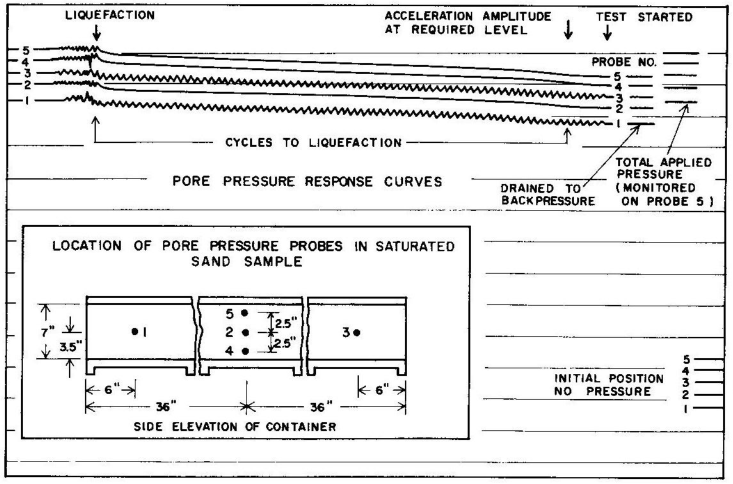

FIG. 5 TYPICAL PORE PRESSURE RESPONSE CURVES FOR FIRST LIQUEFACTION. SURCHARGE PRESSURE OF 1 PSI, SINUSOIDAL ACCELERATION OF ± 0.25 G @ 2 HZ.

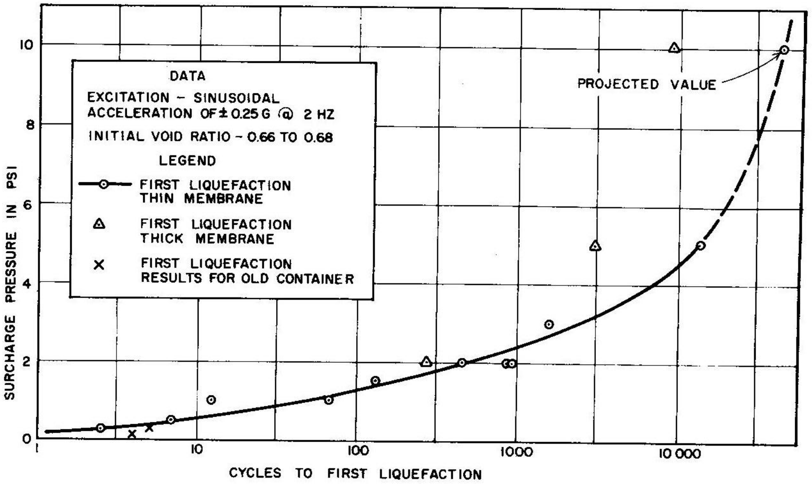

FIG. 6 EFFECT OF SURCHARGE PRESSURE ON RESISTANCE TO FIRST LIQUEFACTION.

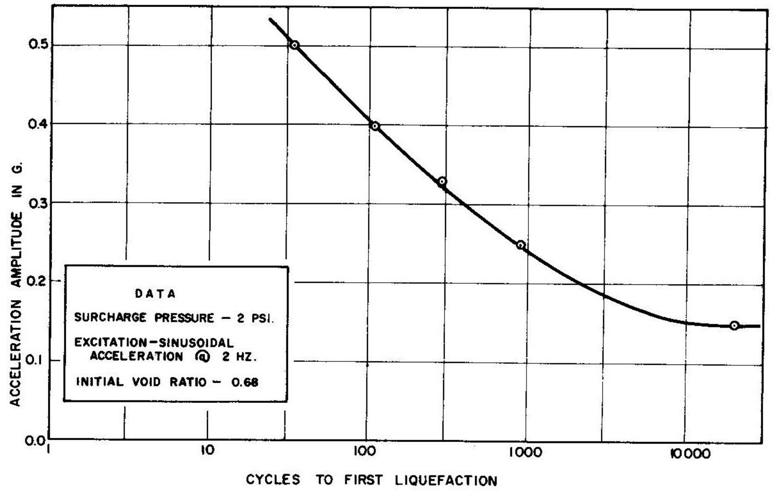

FIG. 7 EFFECT OF ACCELERATIÒN AMPLITUDE ON RESISTANCE TO LIQUEFACTION.

DISCUSSION OF PAPER NO. 6

LIQUEFACTION OF LARGE SAMPLES OF SATURATED SAND EXCITED ON A SHAKING TABLE

by

W.D.L. Finn, J.J. Emery, Y.P. Gupta

Question by: K.G. Asmis

The examples you have shown were excited by a sinusoidal input. Have you tried any experiments with actual earthquake input records?

Reply by: W.D.L. Finn

Yes, the 1940 El Centro record has been used in some preliminary studies. However, for the liquefaction tests on large samples, waveforms such as sinusoidal, sawtooth and square waves have generally been used so that this variable is controlled in the experiments. This allows for a comparison of the test results with data from triaxial and simple shear dynamic tests. By using the tape input feature of the MTS simulator, it is hoped to examine the effect of actual earthquake records in the triaxial, simple shear and shaking table liquefaction tests.

Question by: S.R. Swanson

How useful or effective would vertical pilings or "outrigger" configurations be in preventing building damage?

Reply by: W.D.L. Finn

Pilings would not be of much help once liquefaction occurred unless their capacity was not effected by the liquefaction, i.e. they extended to depths where the liquefaction did not occur or were founded on rock. They might have some beneficial side-effect in compaction of loose sands during driving.

Question by: D.A. Sangrey

In your presentation you illustrated liquefaction of a sand sample which had been consolidated after an initial liquefaction and then reloaded. Would you comment on the likelihood that this second liquefaction was a zonal effect?

Reply by: W.D.L. Finn

Continuing research indicates that there is probably a zonal effect for those samples that liquefied a second time in less cycles than required for the first liquefaction.

Question by: O.A. Pekau

In one of your slides, you showed the number of cycles required to cause liquefaction for given overburden pressure. No mention was made of the frequency of excitation. It appears to me that this may be an important parameter, just as for any dynamic response problem. Could you comment on the frequency dependence of your results?

Reply by: W.D.L. Finn

In the range of frequencies of 1-10 Hz, it would appear that there is very little, if any, frequency dependence in the results. This has also been shown by Seed in his work. The uniformity of accelerations throughout the sample has been checked and, in the frequency range 1-10 Hz, the accelerations are very uniform and equal to the base input acceleration.

Question by: W.W. Gruber

How is the external pressure applied to the sand sample? Is the sand sample drained of surplus water only or is it dried before it is liquefied the second time?

Reply by: W.D.L. Finn

The external pressure is applied at the surface on a thin rubber membrane that is sealed around the periphery and covered by the heavy lid. The air is introduced between the lid and membrane through an accurately set control valve. The back pressure to the sample is set with a similar valve. The sample is drained after the first liquefaction to the set backpressure. It is not dried or disturbed in any manner. Of course, the sample is completely removed before the next test.