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SYNOPSIS A stack of 48 rings, lined with a latex membrane, is used to confine a column of soil 12 inches high by 12 inches in diameter (300 mm × 300 mm). Both dry and saturated columns of fine sand are shaken at their base, at a centrifugal acceleration of 35.5 g. Measurements of the settlement of the surface, horizontal displacement and pore pressures show that the columns of soil are behaving essentially (although not exactly) as one-dimensional shear beams.

BACKGROUND

These are still "early days" in the dynamic testing of soils aboard a centrifuge. There have been tests modelling the behavior of gravity and pile-supported structures using cyclic loadings representing the offshore environment (Rowe et.al., 1976; Scott, 1979), but the frequencies of these loadings have been such that dynamic inertial forces are insignificant. Morris (1979) tested model towers of different sizes and found that the natural frequency for foundation rocking followed the appropriate scaling law. The quantitative portion of Morris' tests involved modest levels of strain within dry sand, although his overall program also included a few tests with large strains and saturated sand. Kutter (1979) has initiated a program of shaking tests upon models of cohesive embankments. In addition, there has been testing involving craters caused by explosions. However, despite the considerable past and current testing effort, as yet we do not have a really good handle on a number of important basic questions, such as: (a) how well can we make measurements at small scale, high frequencies and large accelerations?; (b) how well do scaling laws apply when there are large strains and high frequencies?; and (c) how can we resolve the conflicting requirements of the scaling law for inertia forces ($f \sim N$) and for consolidation ($f \sim N^2$)?

Thus there is need for a test in which a mass of soil with a simple geometry is in a simple and well-defined state of loading -- conditions which are essential if the soil "model" is to be formed in a uniform and reproducible manner, if experiments are to be carried out at several different scales so as to test the scaling laws, and if the observed response of the soil is to be compared to reliable theoretical predictions. With such a test, it would be possible to address fundamental problems in dynamic centrifuge testing, such as those listed at the end of the first paragraph.

With this goal in mind, we set out to simulate a column of soil cut from a stratum and shaken at its base (Figure 1a). For this purpose, it was necessary to create a cylindrical boundary which would:

* Prevent strains within a horizontal plane.
* Not restrict shearing strains, caused by dynamic base shaking, in vertical planes.
* Develop dynamic shear stresses in the vertical direction on the cylindrical boundary, as required to complement dynamic shear stresses on horizontal planes. Without these shear stresses, the column of soil would bend as a cantilever rather than deforming as in the stratum.

As in almost any test, it proved impossible to satisfy all of these requirements exactly. Several different schemes were considered, including wire-reinforced rubber membranes. We finally chose to use a set of stacked rings, as shown schematically in Figure 1b. This testing arrangement is similar to that used in some versions of the simple shear test, and yet it is also quite different in that the static and dynamic stresses are varying with depth. That is, a "system of soil", rather than an "element of soil", is being tested.

This paper describes the details of the stacked-ring apparatus and results from an initial series of tests with this device, carried out on the centrifuge at Cambridge University. The emphasis in these first tests was upon learning just how well the stacked-rings function. Subsequent tests, some of which will be completed prior to the Conference, will focus upon the fundamental questions of scaling.

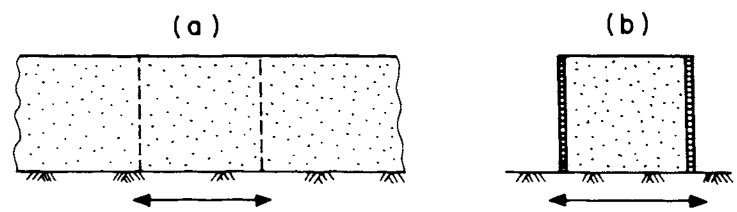

Fig. 1. Soil within stacked rings simulating a column of soil in a stratum.

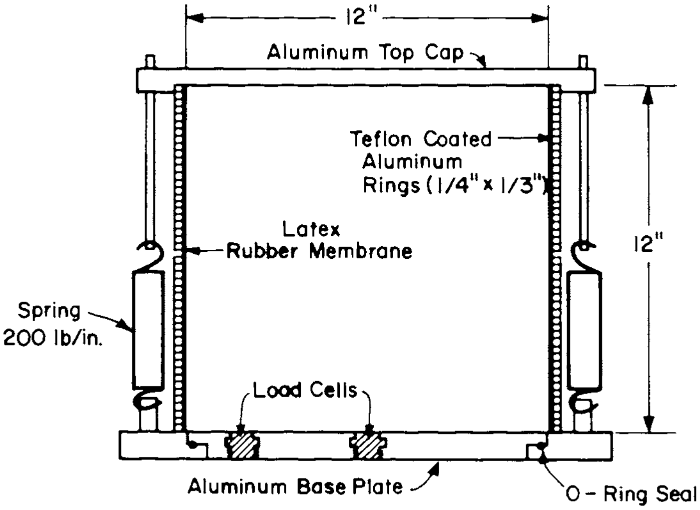

Fig. 2. Schematic of stacked-ring apparatus

STACKED RING APPARATUS

The essential features of this device are shown in Figure 2. They include: (a) the rings; (b) a membrane located inside the ring, to keep soil particles from between the rings and to provide water-tightness during tests on saturated soil; (c) a base plate, (d) a top ring; and (e) springs and adjusting screws for prestressing the rings. Also involved, but not shown, is a framework for support of certain instrumentation.

The overall size of the device was dictated by the space and weight restrictions of the suspended-box package available at Cambridge, the desire to have a height to diameter ratio that did not exceed unity, and by the availability of tubes from which the rings could be cut. Within these limitations, the largest dimensions for the column of soil were 12 inches high (305 mm) by 12 inches in diameter.

The rings were cut from an aluminum tube and machined to size: 1/4 inch (6.3 mm) thick and 0.32 inch wide (8.1 mm) in the radial direction. These dimensions were selected on the basis of several considerations: the mass of the rings should be less than 20% of the mass of the soil, the frictional resistance between rings should be less than 20% of the shear resistance of the soil on a plane through the interface between the rings, and the rings should be sufficiently stiff to almost eliminate radial strains within the soil. This final requirement also ensured that the rings would be strong enough to resist the lateral stresses from the soil. After machining, the rings were coated with Teflon-S. The full stack consisted of 48 rings.

Providing resistance to upward vertical dynamic shear between the soil and rings was an especially perplexing problem. The weight of the rings provided some resistance to uplift, but not enough to develop the dynamic shear stresses expected to occur during tests with the largest shaking accelerations. Therefore, springs were placed to prestress the rings in the vertical direction. The amount of this prestress could be adjusted from test to test, according to the anticipated dynamic shear stresses, using the nuts which secured the springs to the special top ring. Prestress could also be altered by changing the number (up to 6) and stiffness of the springs. The top ring, which weighed 4.6 lbs. (20.5 N) served in addition to anchor the top of the rubber membrane. The prestressing system gave the additional advantage of holding the stack of rings in position during placement of the soil and loading the apparatus onto the centrifuge.

It was difficult to predict in advance just how the system of pre-stressed rings and soil would behave during actual tests. In the ideal, there would be just enough shear between the rings to overcome the inertia of the rings and just enough shear stress in the soil to overcome the inertia of the soil, and no horizontal dynamic stresses would occur. In actual fact, because of differences in the density and stress-strain behavior of the rings and the soil, dynamic horizontal normal stresses would be expected to develop between the soil and the rings as necessary to make them move together. The coefficient of friction for the Teflon coating is about 0.2. Thus, with no soil and no prestress, the largest acceleration that could be transmitted up through the rings is 0.2 g. At lower accelerations one might expect that the rings would restrain the soil, while at higher accelerations the soil must push the rings. However, the actual behavior is complicated by the existence of prestress and the heavy top ring plus the fact that Teflon slips to some degree at stresses smaller than the frictional resistance. For all of these reasons, plus doubt as to just how much vertical dynamic stress would develop between soil and rings, it was necessary to study the behavior of the device during actual tests.

Instrumentation

The principal instrumentation consisted of piezoelectric accelerometers mounted upon the base plate and top ring and embedded within the soil, plus LVDT displacement transducers to measure transient displacement of selected rings and settlement of the surface of the soil. These displacement transducers were supported on a stiff portal frame alongside and over the stack of rings. In tests with saturated soil, pore pressures were measured using miniature pore pressure transducers.

Other instrumentation was included specifically to monitor the workings of the apparatus. The bolts connecting the prestressing springs to the base plate were strain-gaged so that the actual prestress force could be recorded. Two force gages were located in the base plate, one of them off-center, to record total vertical stress at the bottom of the column of soil. It had been hoped that horizontal stress could be measured by strain-gaging several rings, but this plan was thwarted by the complex and poorly-known set of forces acting upon a particular ring.

The output of the transducers was recorded, after suitable amplification and conditioning, upon a 14-track magnetic tape recorder, from which the time traces could be played back onto either an X-Y recorder or a paper strip visicorder. The mix of recorded responses varied from test to test, depending upon the principal objectives of the test.

TESTING PROGRAM

The tests were carried out in a special spring-actuated "shaking box" developed at Cambridge University by Morris (1979). A suspended box was pulled back against springs before spinning the centrifuge, and then released in flight. The resulting motion is approximately a damped sinusoid with a frequency of about 61 Hz. The nominal centrifugal acceleration during the tests was set at 38 g, although at mid-depth of the soil column the acceleration was 35.5 g. Thus the 12 inch deep model soil column corresponded to a stratum with a thickness of 35.5 feet (10.8 m) and excited with base shaking at a frequency of about 1.7 Hz. This particular centrifugal acceleration was selected so as to permit subsequent half-scale tests to be carried out at 75 g -- the rated limit for the Morris package. However, as will be discussed hereafter, subsequent smaller-scale tests will actually be performed using a different package.

The program of tests is summarized in Table I. It involved tests upon the rings with no soil, with dry sand and with saturated sand. Several "firings" were made for each specimen of soil, which necessitated stopping the centrifuge and recocking the box against the spring. It was difficult to control the peak shaking accelerations that would occur, and hence the actual sequence of peak accelerations differed somewhat from the intended pattern.

Leighton-Buzzard 120/200 sand, a uniform sand with a mean grain size of 0.1 mm (0.004 inch), was employed for these tests. A very fine sand was selected so that the time for dissipation of excess pore pressures would be long compared to the period of the exciting motion. For dry tests, the sand was pluviated at a rate which gave a relative density of about 65% (porosity of 0.44). This density proved to be quite repeatable from test to test. For saturated tests, the sand was pluviated into water and then vibrated. This procedure did not give good control of the density; indeed, the two supposedly identical specimens had relative densities of 55% and 86% (porosities of 0.45 and 0.41)!

TABLE I. Summary of Tests

Test	Soil	D_R-%	a_h/N			
			A	B	C	D
PL-2	Dry	67	0.16	0.11	0.23	--
PL-3	Sat.	55	0.17	0.17	--	--
PL-5	Sat.	86	0.14	0.12	0.25	0.24
PL-7	Empty	--	0.10	0.17	--	--
PL-8	Dry	64	0.13	0.08	0.12	0.17

Note: all tests at nominal centrifugal acceleration of 38 g (N = 35.5 at mid-depth of soil).

The program of tests was actually carried out in June 1980, and the detailed results presented by Lambe and Whitman (1980). Also included in the program were several tests in which a layer of sand was placed in the bottom of, and in contact with the side walls of, the suspended box. The ratio of the thickness of the soil to the length of the box was about 0.4 to 0.5. "Edge effects" proved to be very severe, and the strains within the central portion of the layer apparently were much smaller than those experienced in the stacked ring apparatus.

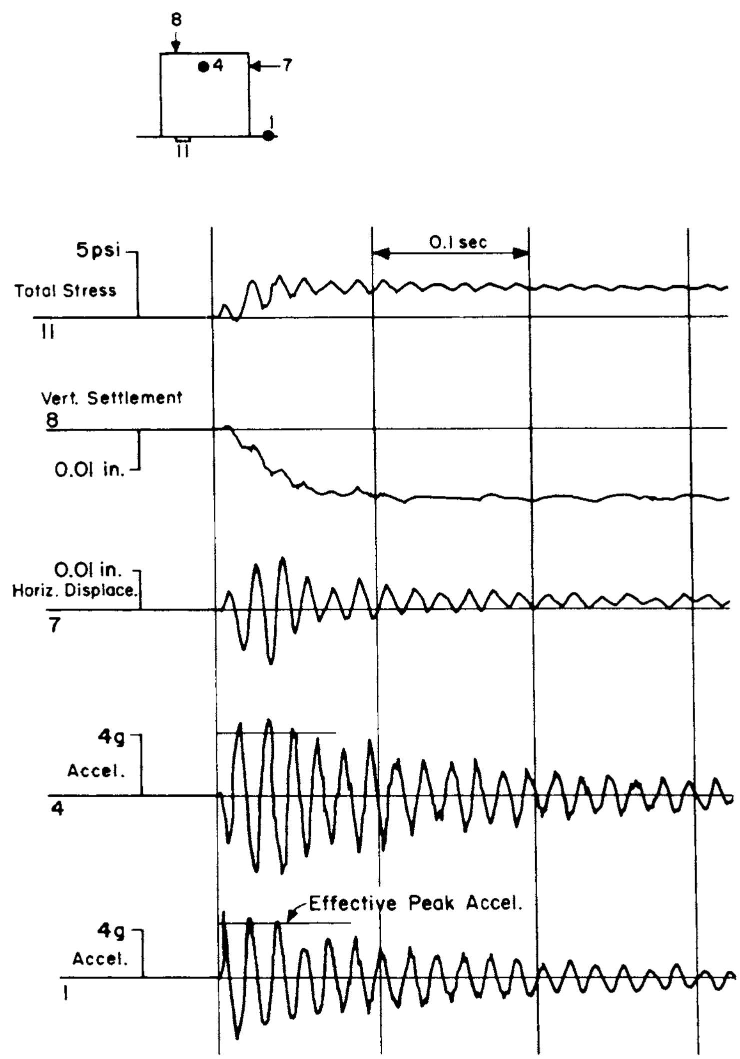

Fig. 3. Typical traces from test PL-5C on dry sand.

RESULTS -- DRY SAND

Figure 3 shows selected recordings during Test 8; they are typical of all the results for dry sand. In this test, two accelerometers were placed within the soil at mid-depth, one at the center-line and the other near the rings; very similar recordings were obtained from both.

The time-histories of acceleration, both on the base plate and within the soil, reveal high frequencies superimposed upon the basic damped sinusoid. In determining the peak acceleration at each location, these high frequency components were filtered out by eye. Typically, the peak acceleration at mid-depth was 10-20% higher than the peak acceleration at the base. The peak acceleration near the surface was less than that at mid-depth, and about equal to that at the base. Thus, overall there was very little amplification. Some slight difference in phasing between base and top could be detected during the first cycle of motion, but it was so small that no determination of wave velocity could be made.

The peak transient displacements of a ring near the top of the stack relative to the base plate are plotted against peak base acceleration in Figure 4. Also shown are the peak relative displacements calculated using the SHAKE program, a time-history of input motion actually recorded on the suspended box, and modulus and damping relations characteristic for a sand of this relative density. The recorded relative motions were similar to the predicted motions, although somewhat larger. The relative horizontal motions of the rings in the test without soil were quite similar to those observed in the tests with soil. Strains determined from the several recordings of horizontal relative displacement were in the range from 0.1% to 0.5%. Values of effective modulus were backcalculated from the observed accelerations (and thence stresses) and strains, and were found to be within the range that could be expected for this sand. Using these back-figured values of modulus, the fundamental frequency of the soil column was calculated, and found to be in the vicinity of the forcing frequency. All-in-all, it appeared that the column of sand behaved as though the presence of the stack of rings did not affect it, although extrapolation of the displacements to smaller accelerations might suggest that the rings would offer significant constraint for input accelerations (prototype scale) of 0.05 g or less.

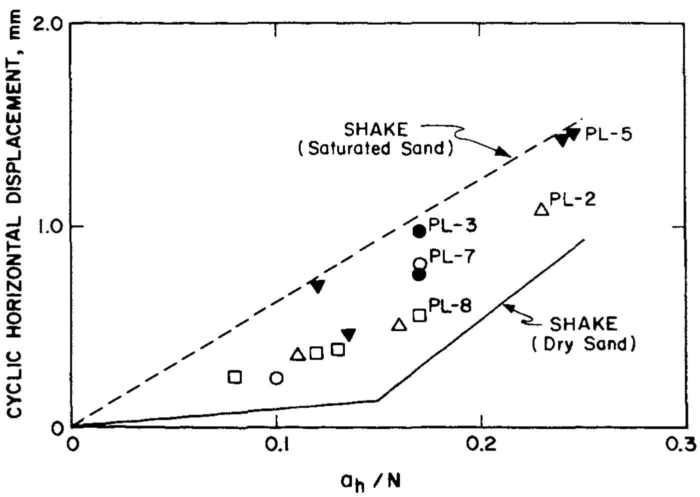

Fig. 4. Horizontal displacements vs. acceleration.

Several of the recordings showed evidences that there was some bending of the soil column. The vertical stress cell in the off-center position of the base showed a cyclic response in phase with the observed horizontal displacements. (If there were purely shear deformations, no vertical stresses would occur.) There was an observed cyclic vertical motion of the top ring, and the recording of vertical motion of the surface of the sand off-center revealed a cyclic motion superimposed upon the accumulating settlement. All of these observations suggest that there was undesirable bending deformation superimposed upon the hoped-for pure shear. However, analysis of the data indicates that bending contributed only 10% to 20% of the total deformation.

The static stresses recorded by the two load cells in the base were less, in some cases only one-half, of the theoretical stresses at the base. These recorded stresses increased as a result of each "earthquake". Such results are indicative of arching, but there is no way of knowing whether this is arching of the sand mass as a whole ("bin action") or merely local arching around the load cells.

Figure 5 is a plot of settlement of the surface as a function of the input horizontal acceleration. Also shown are settlements predicted using data (Silver and Seed, 1972) for a sand of this relative density and the cyclic strains predicted by the computer program SHAKE. Considering that the observed strains were somewhat larger than the predicted strains, the predicted and observed settlements are in reasonable agreement.

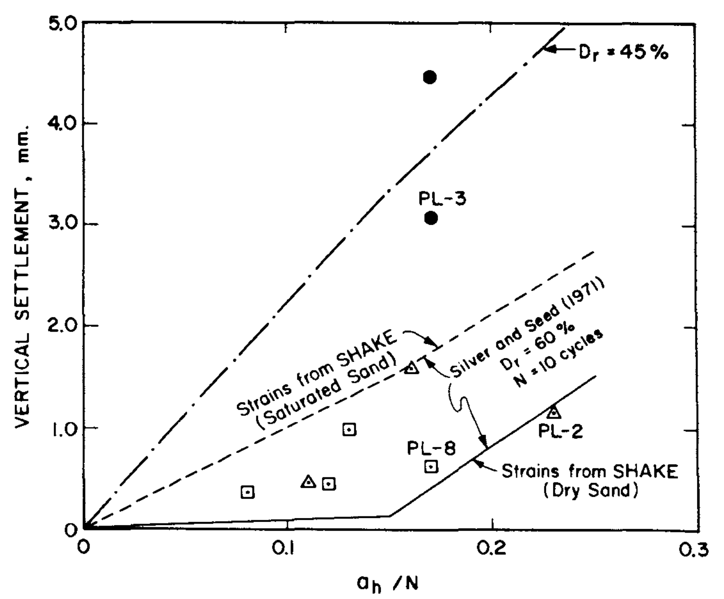

Fig. 5. Settlement vs. acceleration.

RESULTS -- SATURATED SAND

Figure 6 portrays selected readings during Test 3, which involved the looser of the saturated specimens of sand. The pore pressure increases to reach the total vertical stress after 2 cycles and remains at this level during the next about 20 cycles. The beginning of the subsequent dissipation may be seen in the trace for the transducer at the bottom of the specimen. A corresponding set of records from Test 5, with the denser specimen, appear in Figure 7. Again the pore pressure builds-up rather quickly to the total stress (except near the base of the specimen). Now dissipation begins more quickly, and the variations in pore pressure during each cycle -- characteristic of the behavior of a dense sand -- are evident. The rapid build-up of pore pressures in these tests makes sense in view of the large values of $\tau_d/\bar{\sigma}_v$ -- 0.3 for a_h/N = 0.15 -- and the large shear strains. In Test 5, multiple transducers were placed at both intermediate elevations within the sample and the several recordings at each elevation were quite similar.

In the tests upon saturated sand, peak accelerations at mid-depth were less than those at the base. The peak accelerations at the surface of the sand are unknown, owing to the equipment failure, although peak accelerations on the top ring were slightly greater than those at the base.

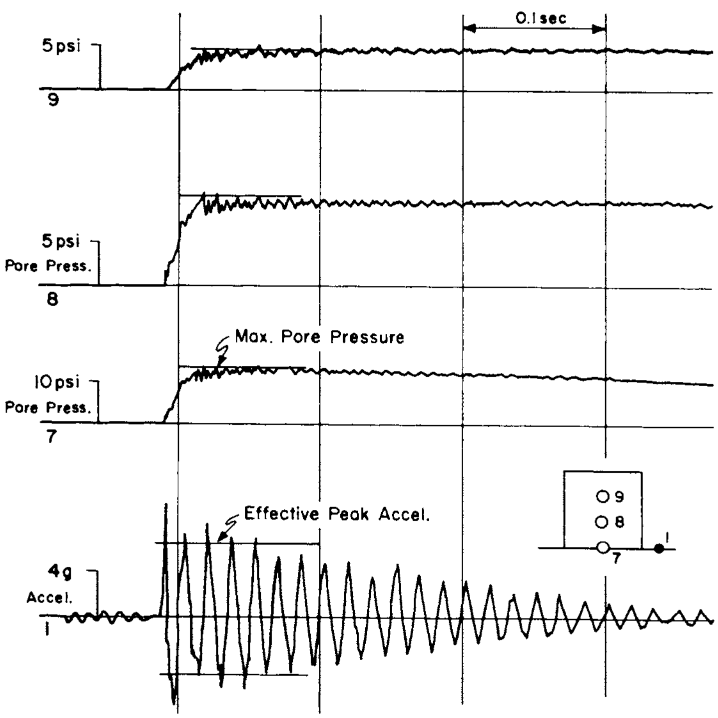

Fig. 6. Pore pressure vs. height in Test PL-3A on loose saturated sand.

The time-histories of horizontal relative displacement were quite similar to those for dry sand, although the peak relative displacements were somewhat greater -- as shown in Figure 4. The prediction for peak relative displacement, made using the SHAKE program, did not consider the effect of pore pressure increase during shaking. In Test 3, the relative displacement was concentrated in the lower portion of the specimen. In Test 5, strain was distributed more-or-less evenly with height.

Settlement of the surface was measured only in Test 3. As may be seen in Figure 5, it was considerably greater than with dry sand.

Values of coefficient of consolidation were deduced by fitting theoretical dissipation curves to the observed decay curves. The average c_v for Test 3 was about 2 ft^2/sec (0.2 m^2/s), while that for Test 5 was nearer 3 ft^2/sec (0.3 m^2/s). With Test 3, the effective beginning of dissipation (end of generation) was about 0.4 s to 0.5 s (24 to 30 cycles) into the shaking, and in Test 5 the effective beginning was after only about 0.1 s (or 6 cycles).

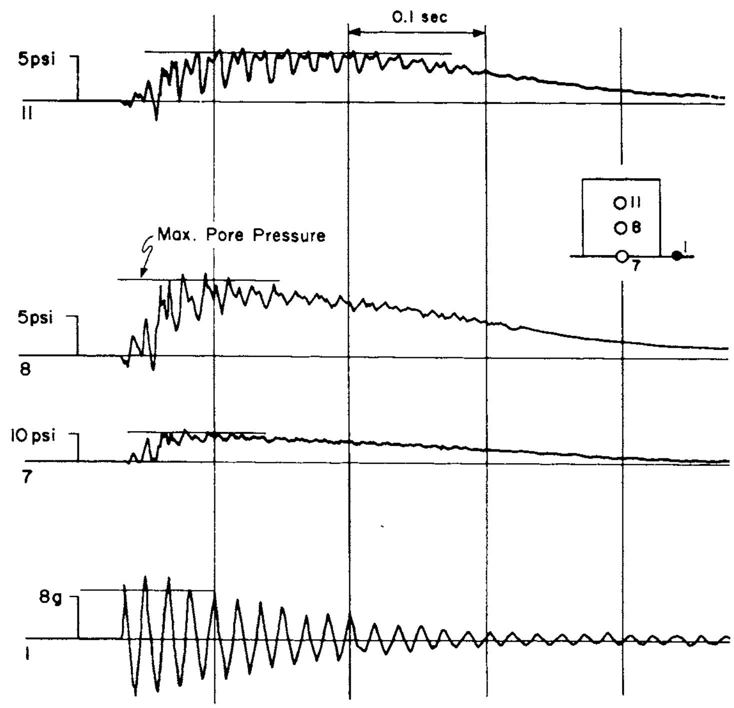

Fig. 7. Pore pressure vs. height in Test PL-5C on dense saturated sand.

CONCLUSIONS

The observations reported in the previous sections; plus other more detailed analyses, lead to the conclusion that the stacked-ring apparatus performed in a reasonably satisfactory manner. That is, while there were evidences of deviations from the desired state of simple shear, on the whole the performance was quite close to that expected. In particular, the horizontal relative displacements, excess pore pressures and the settlements were very much in line with anticipated values. Furthermore, acceleration and pore pressure were reasonably uniform over horizontal cross sections. Thus, it was judged appropriate to continue with further development and use of the apparatus.

FUTURE TESTS

Tests with a smaller stacked-ring apparatus, with a height and diameter of 5.25 inches (133 mm), are now scheduled for January 1981. This smaller apparatus and the contained soil will represent a 1:2.25 scale model of the earlier "prototype" tests. Accordingly, the excitation frequency will be $61 \times 2.25 = 137$ Hz, and the centrifugal acceleration at mid-depth of the specimen will be $35.5 \times 2.25 = 80$ g. In order to preserve scaling for the dissipation of excess pore pressure, a mixture of glycerol and water -- leading to a c_v which is 2.25 times that for the "prototype" soil -- will be used as pore fluid. These tests will be performed using the "bumpy road" excitation system described in the paper by Schofield to this conference. Thus, these second tests will involve a different time history of excitation than the earlier tests, and consequently will not exactly be "models of the model". However, results from the first tests -- modified as appropriate to account for the effect of the different time history -- have been used to predict responses expected in the smaller scale tests. Comparison of predicted and observed response will give at least a preliminary indication as to the validity of scaling. A third series of tests, using the larger apparatus and bumpy road excitation, so as to be properly scaled versions of the second tests, is tentatively scheduled for the summer of 1981.

All of these tests will have focussed primarily upon the response of the stacked-ring apparatus and upon the correctness of scaling, rather than upon the study of the behavior of a soil system. Rather, the observed response of the soil has been compared with theoretical predictions as a means of verifying the performance of the apparatus. Assuming that subsequent tests continue to indicate that the apparatus does satisfactorily approximate the case of a column of soil within a stratum, it may then be used to study problems for which theoretical solutions are either unsatisfactory or have not been validated -- such as generation/dissipation in layered systems, settlement of foundations as a result of pore pressure build-up, etc.

ACKNOWLEDGEMENTS

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SYMBOLS

a_h: Effective peak "horizontal" acceleration.

N: Centrifugal acceleration.

τ_d: Effective peak dynamic shear stress.

$\bar{\sigma}_v$: Vertical effective stress.

c_v: Coefficient of consolidation.