SOIL LIQUEFACTION IN
CYCLIC CUBIC TEST APPARATUS

by

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INTRODUCTION

Although many studies have been made on soil liquefaction due to cyclic loading, the laboratory tests have always been limited to two directional plane or axisymmetric boundary conditions. In 1967-68, Ko and Scott described a cube type of laboratory device which was capable of subjecting a test specimen to three directional type of normal static stresses (3,4,5). The study described herein used essentially the same equipment, but adapted for cyclic loading liquefaction tests on loose saturated sand.

TEST APPARATUS AND SOIL CONDITIONS

The cubic test apparatus (Fig. 1) consisted of an outer rigid box which held a 4 in cubic sample of soil bounded on all 6 sides by a thin rubber membrane. Thin steel dividers separated these membranes at the edges. Fluid pressure could be applied in the 3 opposing chambers between the rigid box walls and the sample to create the four types of cyclic normal stress illustrated in Fig. 2. Shear stresses could not be applied to the boundary faces.

Approximate cyclic strain measurements were made by noting the amount of water which flowed into or out of the three opposing chambers. Internal pore water pressures were monitored by a thin tube which entered the sample through one corner. The excess pore pressure data were used to define liquefaction failure.

The soil tested was a clean uniform medium subrounded quartz sand known locally as Monterey 20-30 sand, the same sand used by Peacock and Seed (10) (D_{50} = 0.62 mm, C_u = 1.2, e_{max} = 0.85, e_{min} = 0.53). The samples were prepared by wet raining after boiling to saturate and then vibrated to the required density. All tests were performed at 50% relative density where initial liquefaction and large cyclic strains occur almost simultaneously (7).

All samples were isotropically consolidated to σ_c = 15 psi. Symmetrical, uniform cyclic normal stresses were applied at 0.5 Hz. According to the reasoning of Seed and Lee (12), Series A, B and C tests should give the same results. Series D represents a cyclic plane stress test, impossible to simulate in the triaxial apparatus. The large surface area of the sample, and the large grain size caused concern that membrane penetration into the voids at the face might affect the results. This potential problem was partially investigated in Series E and F. Thin brass plates were glued to

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the rubber membranes on the faces subjected to the stress pulsations to reduce the possible membrane penetration effect. For comparison purposes, two sets of cyclic triaxial tests, using 1.4 and 2.8 in dia. samples, were also performed on this sand at the same density and confining pressures as for the cubic sample tests.

The sample response in all series of tests was qualitatively the same as observed from ordinary cyclic triaxial tests on clean loose saturated sand. Transient and permanent pore pressures built up progressively with each cycle to the value of the confining pressure at which point large cyclic strains occurred. The cyclic stress level and the number of cycles required to produce this state of instability was taken as the cyclic strength or initial liquefaction (12) for that test. In general, each test was stopped and the sample dismantled within 5 to 10 cycles after initial liquefaction. For some samples, after the first test, the sample was reconsolidated and retested.

FIRST LOADING CYCLIC LIQUEFACTION TEST RESULTS

The results of all first loading tests in the cube apparatus are shown in Fig. 3. The data indicate no difference between tests with or without plates. The combined data from all cyclic cube tests are shown to the same scale for comparison purposes in Fig. 4a. Data from all but the plane stress Series D tests lead to one fairly well defined curve. Data from Series D form another fairly well defined curve some 40% stronger than the other data.

Initial liquefaction data points from the 1.4 and 2.8 in diam. cyclic triaxial tests showed about the same amount of scatter as the data in any one series of cyclic cubic tests. The best fit strength curves from these cyclic triaxial tests are shown by dashed lines in Fig. 4b. The 2.8 in diam. samples indicated a lower strength than the 1.4 in diam. samples. The cube curves are somewhat steeper than the triaxial curves and intersect the triaxial strength curves. The Series D strength curve is located above both of the cyclic triaxial test curves except for very large numbers of cycles.

No obvious explanation is available concerning the observed variations in cyclic strength with different test conditions. A number of experimental factors may affect the results. Green (2) has criticized the Ko-Scott cube apparatus because of the difficulties at the edges and the corners, which restrict and impede large strains. However, since the pre-liquefaction strains were less than about 1%, the large strain difficiency in the apparatus would not be important. Furthermore, recent comprehensive studies using cyclic triaxial equipment have shown that significant differences in cyclic strength may be obtained from small variations in test procedure (6,9). Nevertheless, the data from all the series of tests, except Series D, were consistent within themselves. This consistency tends to confirm the hypothesis extended from that proposed by Seed and Lee (12) that these three types of tests should give the same results. Although the cube data do not fall directly on the triaxial curves, they are, for all but Series D, sufficiently close to suggest that differences might be due partly to minor experimental apparatus differences and partly to fundamental differences in stress patterns.

The observation that Series D test results were significantly stronger than the other Series tests is demonstrated by a fairly large number of tests performed by the first two named writers over a period of about 1 year. Thus, the writers are led to conclude that the cyclic strength in plane stress conditions is significantly greater than in other forms of 3 directional loading.

CYCLIC TESTS ON RECONSOLIDATED SAMPLES

In 1970 Finn, Bransby and Pickering (1) published results of cyclic triaxial tests giving data for first loading liquefaction and for tests on the same samples after reconsolidation. They showed that if the first loading test was stopped before liquefaction occurred, involving cyclic strains less than ± 0.5% single amplitude, then on retesting after reconsolidation the sample would be stronger than measured during first loading tests. Data showing a similar beneficial effect from reconsolidation after previous non-liquefaction cyclic loading were obtained by Lee and Focht (8). Seed et al (13) have also presented similar data from shaking table tests. In contrast, Finn et al (1), found that if the cyclic loading triaxial test was continued beyond initial liquefaction then reconsolidated, an identical cyclic test on the same specimen always caused liquefaction in the first or second cycle, regardless of how many stress cycles were required for liquefaction to occur on the first loading. This observation led Finn et al (1) to suggest that the severe reduction in cyclic strength in reliquefaction tests indicated certain basic changes in the intergranular soil fabric.

Similar results have also been observed by the writers with cyclic triaxial tests. Nevertheless, it was reasoned that this weakening effect must be only a laboratory phenomena and not appropriate for field conditions, otherwise any site which has experienced liquefaction once in the past would reliquefy again at the beginning of every small earthquake. Historical data from Niigata, Japan (11) indicate that this is not the case. It was therefore reasoned that there must be some laboratory influence which produces such an apparent metastable structure after first liquefaction. Possibly this could be due to boundary effect, such as necked samples, which remain after reconsolidation. It could also be caused by internal change in the intergranular packing.

Several reloading tests were performed on the cubic samples after they had first been liquefied. To insure seating after the first liquefaction, the consolidating sample was subjected to 4 stress pulses of the same intensity as the previous test, after which the drain line was closed and the second liquefaction test was performed as usual. During initial liquefaction the volume decreased by about 0.4 to 1.1% corresponding to an average increase in relative density, $D_r < 5\%$. No consolidation volume change was observed as a result of the 4 drained cycles.

The results of the reliquefaction tests are shown in Fig. 5. There is a significant increase in cyclic strength in the reliquefaction tests as compared with the first loading tests. For reference purposes, a dashed curve has been drawn to show the average strength increase to be expected from a linear increase in relative density of 5%, without any change in interparticle fabric.

Qualitatively, it seems reasonable that if particles bear on each other through sharp asperities, or if large open voids develop during reconsolidation, the soil should be more prone to liquefaction than if the particle contacts were on stronger flat faces and the void distribution was fairly uniform. Small amounts of cyclic loading under drained conditions would wear away sharp and very weak contacts leaving the soil in a more stable structure at essentially the same density. Vibratory compaction in the initial sample preparation should also wear away asperity contacts and lead to a more uniform density distribution than obtained originally by sedimentation from a fluid state. Since these studies were performed, additional comprehensive data by Ladd (6) and Mulilis et al (9) have shown that the cyclic strength of sand may be influenced by as much as 100% by the type of compaction used to prepare test specimens.

In the field, strong earthquake shaking is followed by less intense shaking as part of the same event or as aftershocks. This subsequent shaking should have the tendency of restabilizing the soil following an initial liquefaction so that it would not be as weak as suggested from laboratory tests performed on preliquefied samples without prior drained cyclic loading.

CONCLUSIONS

A limited study has been made on the cyclic liquefaction strength of one loose sand tested in a cubic apparatus and the data compared with data from cyclic triaxial tests. First liquefaction results showed that for all but one of the few possible uniform symmetric normal cyclic stress patterns, the cyclic strengths were the same and were in reasonable agreement with the data from cyclic triaxial tests. For the one cyclic load pattern which simulated a plane stress condition, the cyclic strength was about 40% greater than for the other patterns.

Although samples which have been liquefied and reconsolidated may have a very low resistance to cyclic loading, the reconsolidated cube samples were first subjected to a few cyclic stresses under drained conditions and the apparent metastable structures were destroyed. The samples exhibited greater strength than when first tested. These data along with other recent data suggest that interparticle soil fabric is of considerable importance in the cyclic strength of sands. Field evidence shows that pre-liquefied sand in the field is not as weak as suggested from the laboratory tests performed on pre-liquefied soil without prior drained cyclic stabilization. However, questions still remain unanswered as to what laboratory sample preparation and testing methods are appropriate to simulated field conditions.

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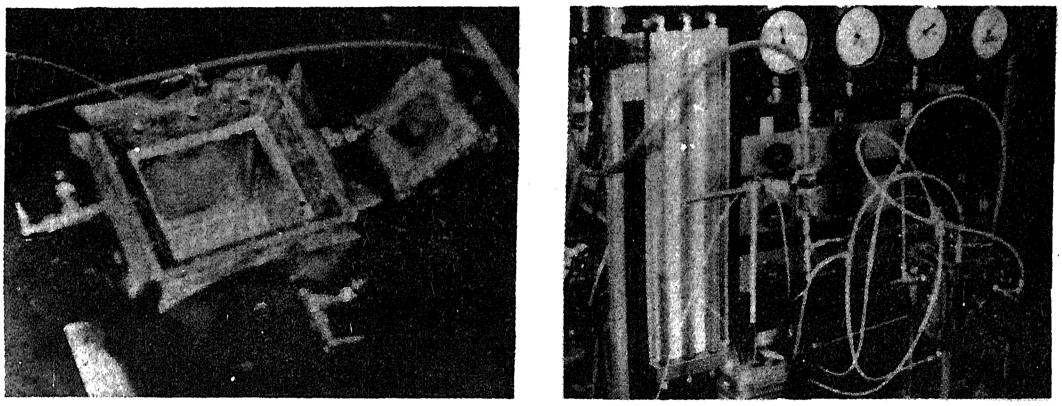
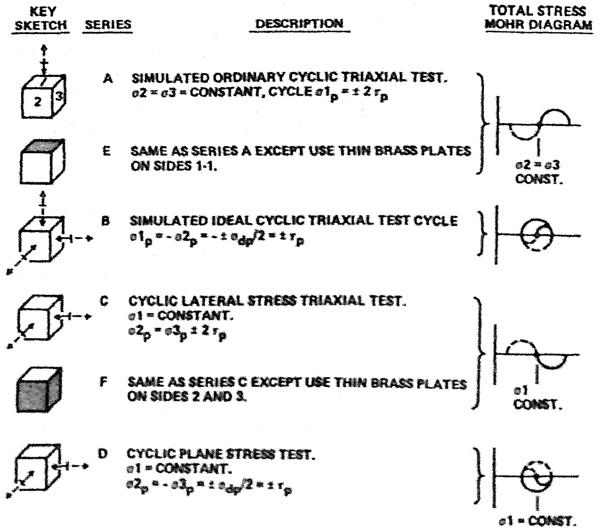


Fig. 1. Photographs of cube cyclic testing apparatus.



KEY SKETCH	SERIES	DESCRIPTION	TOTAL STRESS MOHR DIAGRAM
	A	SIMULATED ORDINARY CYCLIC TRIAXIAL TEST. $\sigma 2 = \sigma 3$ = CONSTANT, CYCLE $\sigma 1_p = \pm 2 \tau_p$	$\sigma 2 = \sigma 3$ CONST.
	E	SAME AS SERIES A EXCEPT USE THIN BRASS PLATES ON SIDES 1-1.	
	B	SIMULATED IDEAL CYCLIC TRIAXIAL TEST CYCLE $\sigma 1_p = -\sigma 2_p = -\pm \sigma_{dp}/2 = \pm \tau_p$	
	C	CYCLIC LATERAL STRESS TRIAXIAL TEST. $\sigma 1$ = CONSTANT. $\sigma 2_p = \sigma 3_p \pm 2 \tau_p$	$\sigma 1$ CONST.
	F	SAME AS SERIES C EXCEPT USE THIN BRASS PLATES ON SIDES 2 AND 3.	
	D	CYCLIC PLANE STRESS TEST. $\sigma 1$ = CONSTANT. $\sigma 2_p = -\sigma 3_p = \pm \sigma_{dp}/2 = \pm \tau_p$	$\sigma 1$ = CONST.

Figure 2. Types of Cyclic Tests Performed on Cubic Samples. All Tests, $K_c = 1.0$.

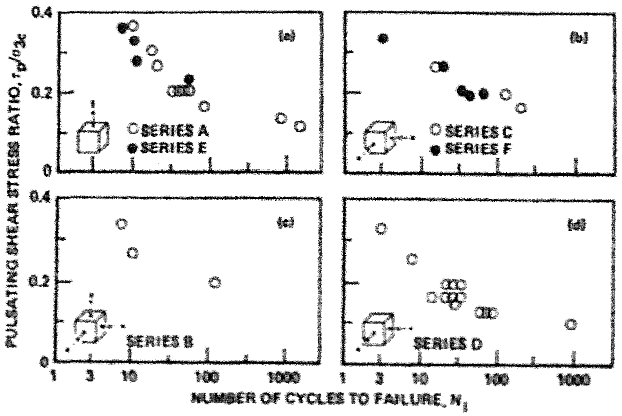


Figure 3. Initial Liquefaction Cycle Strength of Cubic Samples.

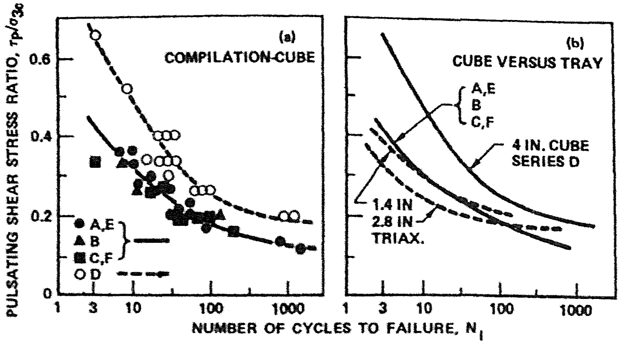


Figure 4. Summary of Initial Liquefaction Cyclic Strength Data.

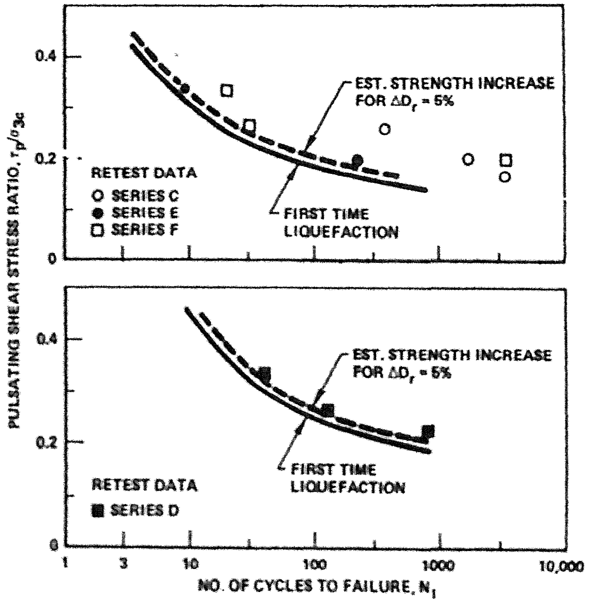


Figure 5. Cyclic Strength After Previous Liquefaction.