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Seismic liquefaction under three-dimensional loading

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ABSTRACT: Seismic liquefaction could cause havoc in the form of structural damages and human lives. Identification of the liquefaction potential of vulnerable soil deposits has become an important issue. A more realistic evaluation of liquefaction potential can be achieved only if true field earthquake loading conditions are considered either in testing or analysis. A new servo-controlled three-dimensional cyclic loading device has been developed and used to study the mechanism of seismic liquefaction. The study also examines the stress path that could be severe to cause liquefaction. The conventional devices are observed to overestimate the resistance of soils to liquefaction. Furthermore, Cyclic Rotational Circular and Cyclic Rotation Elliptic stress paths are seen more severe than Conventional Cyclic Triaxial and Cyclic Pure Shear Stress paths.

1 INTRODUCTION

During dynamic disturbances like earthquakes, the shaking of ground may cause many detrimental effects. One of them is called soil liquefaction. Due to ground oscillations, soils lose their strength and liquefy resulting in flow failures or lateral spreads or sand boils. The catastrophic damages they cause make it imperative to make a more realistic evaluation of potential danger to liquefaction. Many experimental studies have been based on the principle of subjecting representative soil elements to the same kind of loading conditions in the laboratory as they would encounter in the field, and assessing the probable field performance from the resulting behavior of the laboratory test specimens. However, concensus exists that there are significant limitations of the parameters determined in the laboratory that are used in liquefaction risk analysis, due to the inability to simulate the field loading conditions in the laboratory.

Current laboratory procedure like cyclic triaxial test allows for only unidirectional evaluation, but stresses are multidirectional in such occurrences as earthquakes. A new servo-controlled cyclic multiaxial testing device has been built to simulate the earthquake loading conditions in the laboratory. The device provides a more realistic simulation of site performance and an improved evaluation of the shear stress causing liquefaction. A comprehensive series of tests have been run on samples of Monterey 0/30 sand following different stress paths. Effect of stress path and multidirectional loading on seismic liquefaction is reported and discussed.

2 NARRATIVE

The conceptual and theoretical understanding of the phenomenon of liquefaction has been addressed adequately. Field and laboratory test procedures to evaluate liquefaction potential are refined to minimize the error with limited success. Multidirectional loading on a soil element as experienced in an earthquake would be more severe than one directional loading and pore pressures would build up faster than under unidirectional stress conditions. While it is known that the potential for soil liquefaction is greater when the soil is loaded in simple shear stress path, there are many factors that are not understood. During earthquakes, the soil element could be

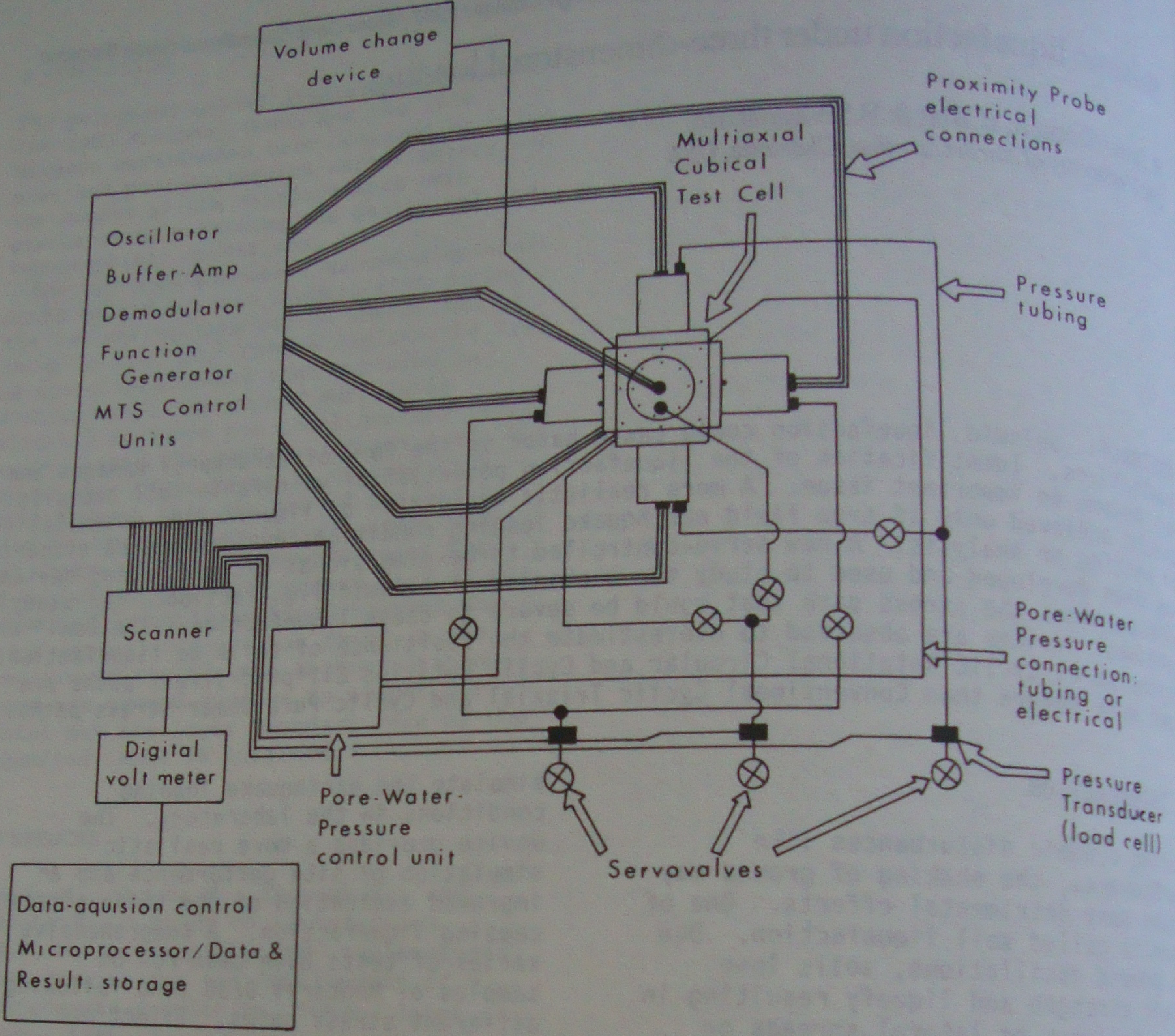

FIGURE 1. CONTROL SYSTEM FOR THE NEW CYCLIC LOADING TRULY TRIAXIAL DEVICE

subjected to loading along any possible stress path. It has not been known whether any other stress path loading could be more severe than the simple shear stress path. Cyclic triaxial compression tests, cyclic simple shear tests and torsional shear tests have limitations to address this question. It is the objective of this research to address these issues.

(i) Define the behavioral response of soil under a three-dimensional loading environment.

(ii) Study the response of soil under different stress paths, and

(iii) Verify bias in the test results from conventional tests by comparing results from this research by Monterey 0/30 sand.

3 SERVO-CONTROLLED MULTIAXIAL DEVICE

The device is a stress controlled one, capable of simultaneously applying independently controllable three-dimensional loading to the sample. Both static and cyclic loadings are possible. Normal strains and pore pressures can be measured during testing. Tests can be conducted on 4 inch (10.16 cm) cubical sample following any stress path. The testing unit consits of (1) a multiaxial cell, (2) a cyclic loading mechanism, (3) pressure sensing transducers and deformation detecting transducers, (4) electronic control units, and (5) a data acquisition system. The general layout of test setup is shown in Figure 1. A cross-sectional plan of the test

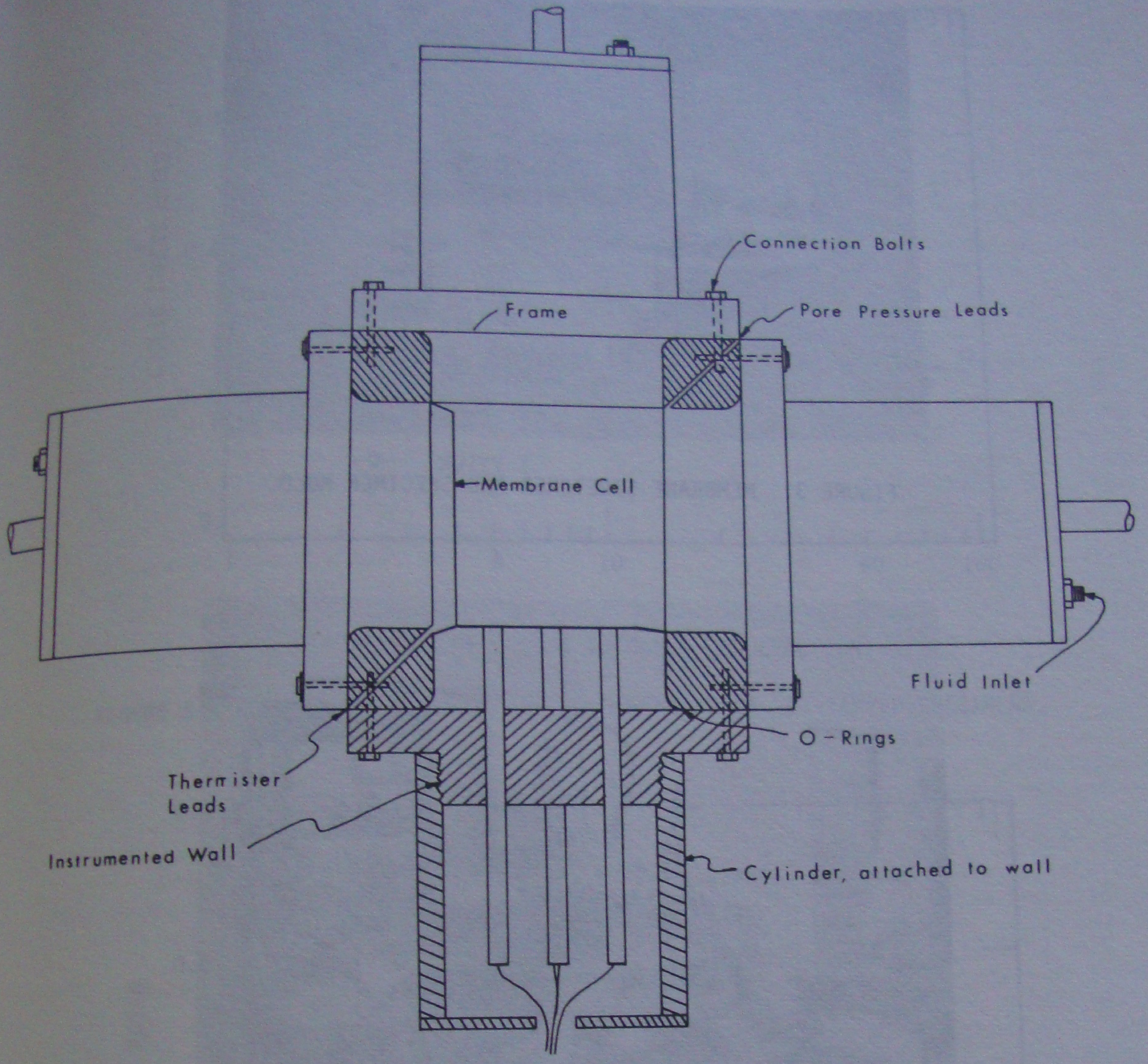

FIGURE 2. CROSS-SECTIONAL VIEW OF LOADING AND DEFORMATION MEASURING MECHANISM

cell is shown in Figure 2. The pressure vessel on each face, housing three linear variable Differential Transducers (LVDT), is designed for 1500 psi (1.03x10^4 kpa) fluid pressure. The loads are applied to soil sample through pressurized flexible membranes. A hydraulic pump supplies the required pressure input.

An electronic servo-control system controls the flow of fluid into the pressure vessels through servo-valves. The pressure transducer fitted in the closed loop electronic servo-control system gives feedback as it monitors. A function generator provides the desired frequency of cyclic loading on the sample. Tests have been conducted following cyclic conventional triaxial compression, cyclic sample shear, cyclic rotational elliptic and cyclic rotational circular stress paths.

4 TESTING

Soil samples are prepared is a special sample preparation mold. The mold serves to contain the sample to the desired relative density and also serves as a membrane stretcher. The soil is rained into the mold when as

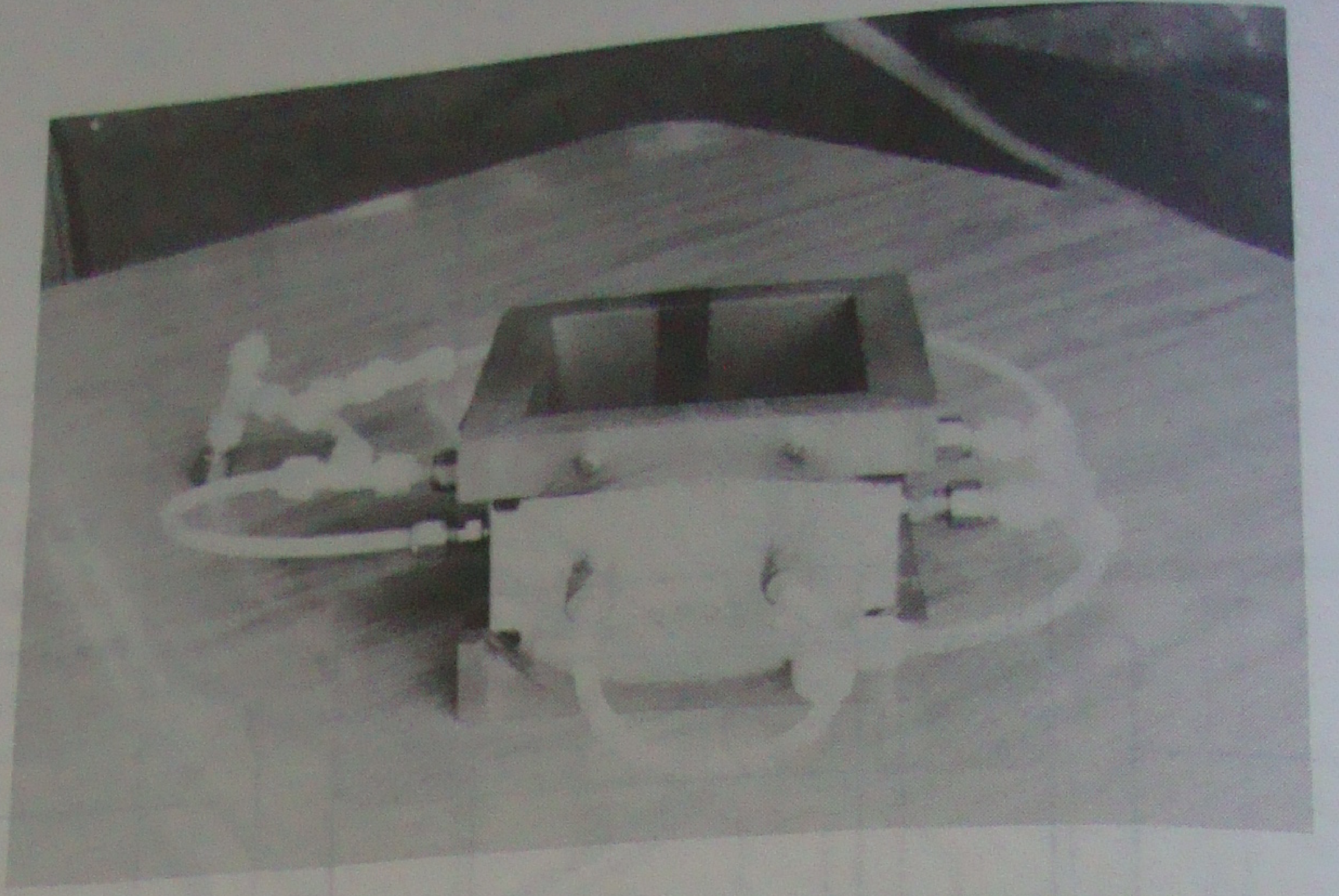

FIGURE 3. MEMBRANE STRETCHER AMD SPECIMEN MOLD.

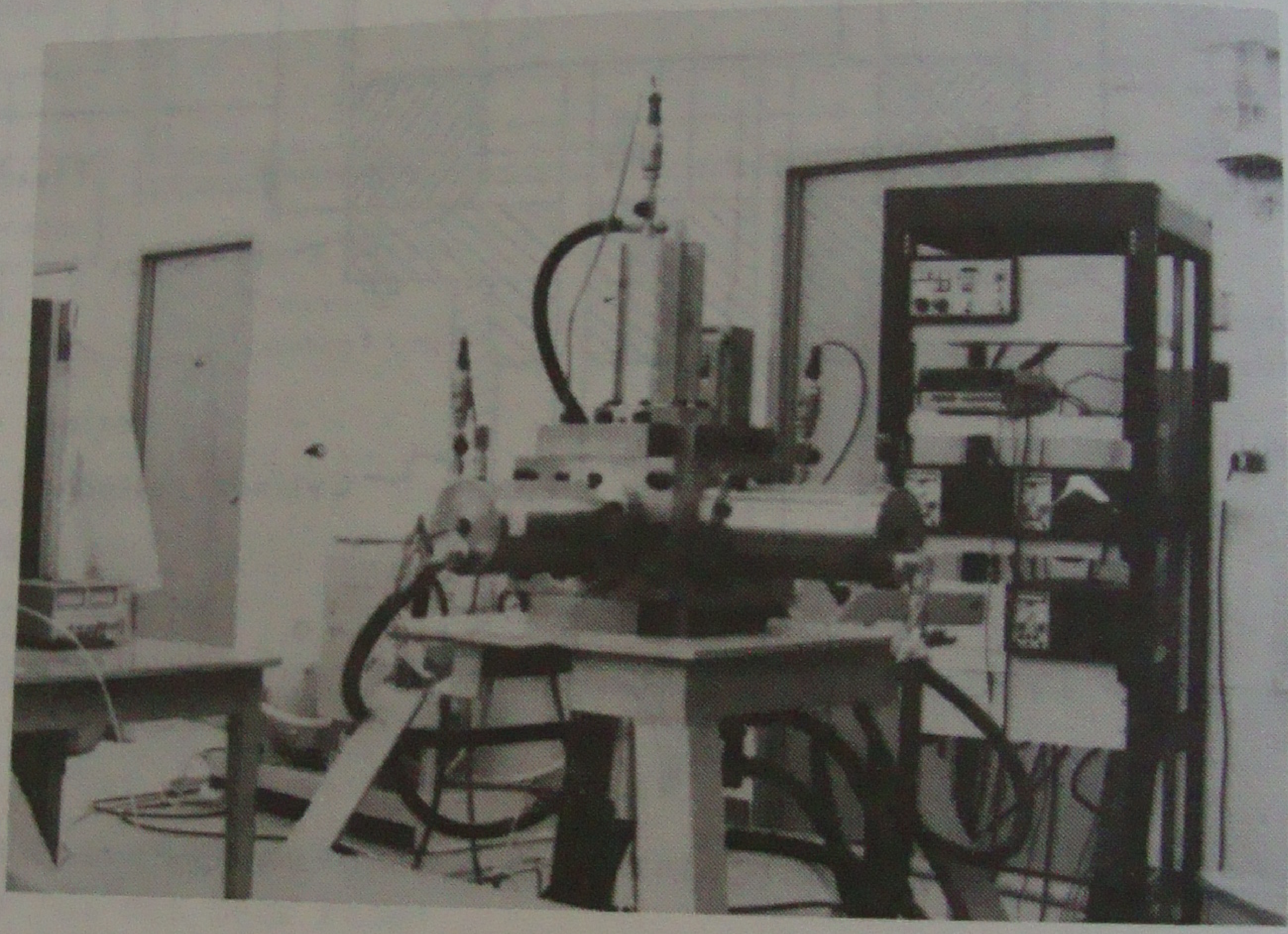

FIGURE 4. ASSEMBLED VIEW OF THE TEST SETUP.

applied vacuum keeps the membrane well stretched as shown in Figure 3. The sample is slided into the cubical cavity of the cell frame and tested. An assembled view of the test cell is shown in Figure 4. The soil sample is saturated by back pressure technique. For effective saturation, carbon dioxide is passed through the sample followed by water. Saturation is continued till the porepressure transducer registers pressure equal to the confining pressure. Sample is then allowed to consolidate before the load is applied.

The earthquake random loading is represented by sinusoidal loadings. A frequency of 1 Hz (1 cycle/second) is chosen for load application. As the test is performed, the pore pressures and displacements of the faces of the soil are monitored and recorded by the microcomputer. The data for each test is stored on a floppy disk, and can be immediately displayed for visual inspection. Subsequently, the data are

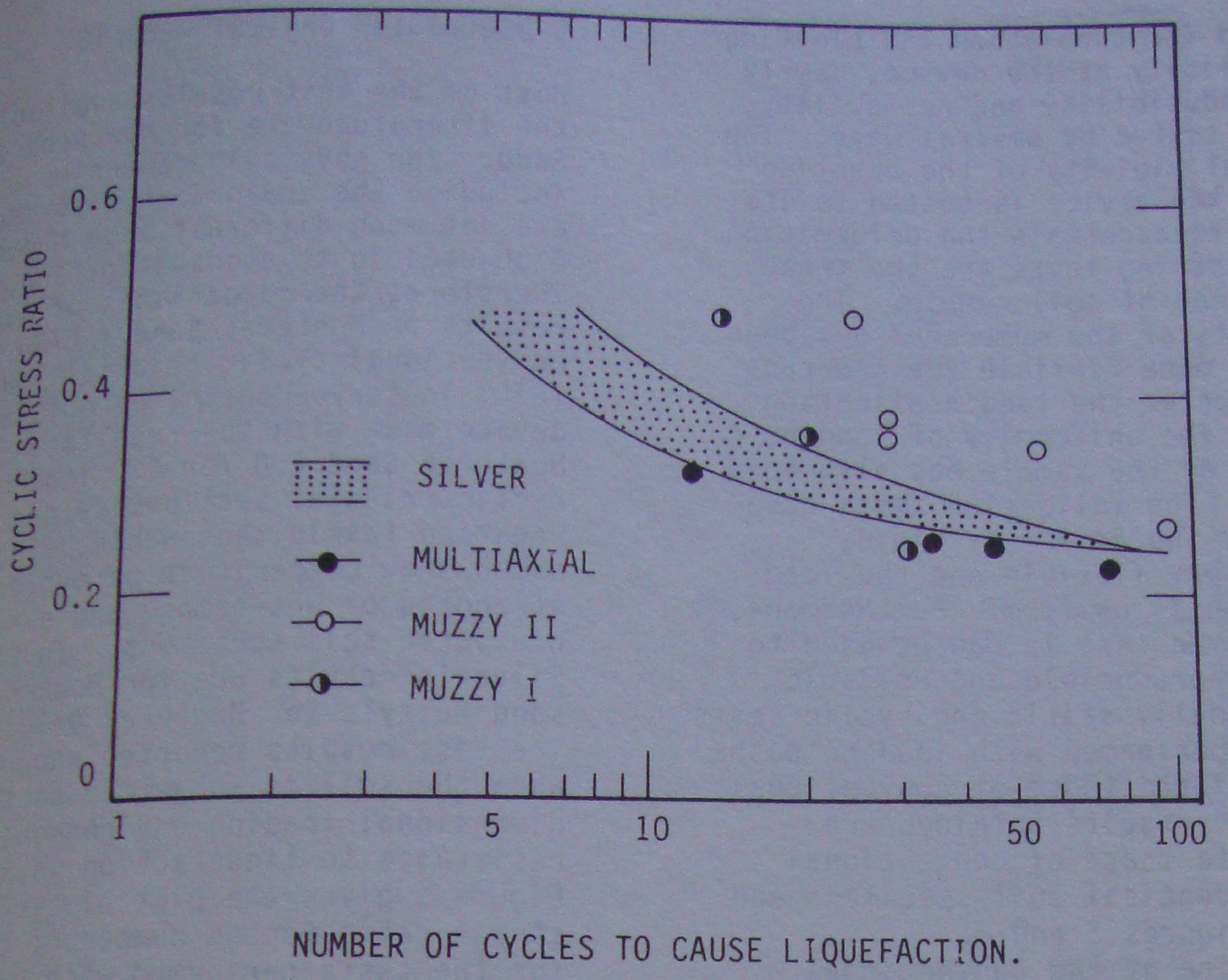

FIGURE 5. COMPARISON OF CYCLIC SHEAR STRENGTHS OF WET-TAMPED SPECIMENS.

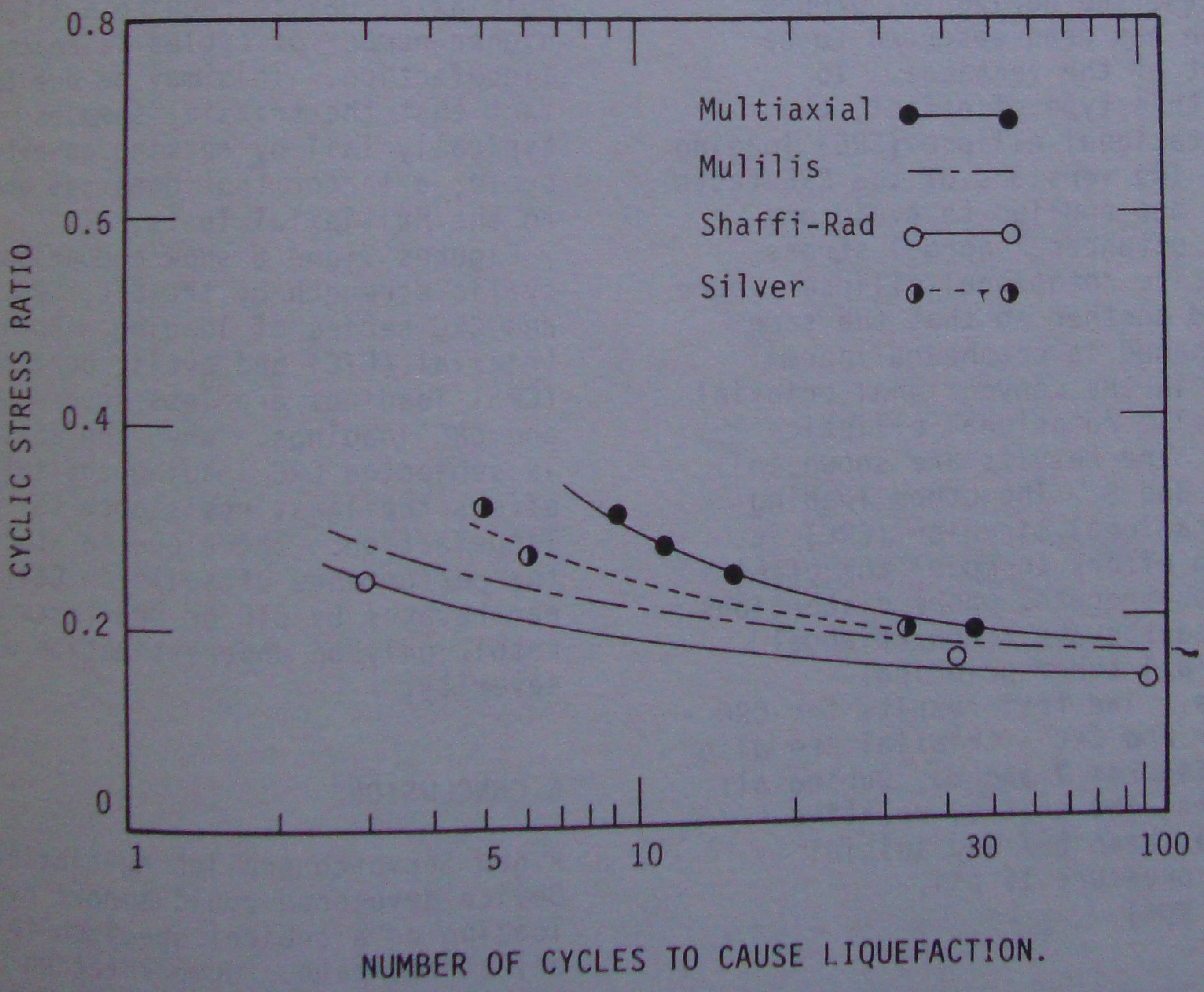

FIGURE 6. COMPARISON OF CYCLIC SHEAR STRENGTH OF AIR-PLUVIATED SPECIMENS.

processed for tabulation and plotting.

The validity of the device, namely its reproducibility and reliability, has been tested by several ways. The structural rigidity of the reaction frame of the device is tested to its capacity to ascertain the deformation recorded during tests are the true deformations of soil sample. The flexibility of the membranes has been tested as more flexible the membrane is, the better the load application will be. The uniformity of loading on the faces of the sample has also been examined. The validation tests have shown that the device is rigid, membrane very flexible and the load application is uniform. Furthermore, it has proved that it can be used to generate reproducible and reliable tests. Finally static and cyclic tests have been performed with loading paths which simulated those of conventional tests. The results obtained are comparted to those of conventional tests on identical soil specimens and shown in Figures 5 and 6.

In addition ot the conventional stress paths, tests have also been conducted following cyclic rotational ellipse and cyclic rotational circular stress paths. In many California earthquakes, the horizontal ground distortion has been observed to be twice that of the vertical. To simulate this type of effect, the cyclic rotational ellipse (CRE) loading is used. Two versions of the CRE tests are used, one applied to avoid any change in octahedral normal stress called cyclic rotational ellipse - pure shear, and another so that the same type of change in octahedral normal stress as in the conventional triaxial called cyclic rotational elliptic-triaxial. The results are shown in Figures 7 and 8. The other loading cyclic rotational circular (CRC) is used in an effort to model the effects of those earthquakes where distortions from the earthquake reach at equal levels in all three principal directions. The test results for CRC - pure shear and CRC - triaxial are also shown in Figures 7 and 8. During all these tests, the initial relative density has been 60% and initial confining pressure 15 psi. (1.03×10^2 kpa)

5 DISCUSSION OF TEST RESULTS

Most of the test results available in the literature are for Monterey # 0 Sand. The physical properties including the grain size distribution are not much different from Monterey # 0/30 used in this investigation. Therefore, the comparisons of test results on Monterey Sand # 0/30 for conventional cyclic triaxial loading (CTC) in servo-controlled multiaxial device made with the results on Monterey Sand # 0 for CTC loading in cyclic triaxial test device can be regarded fairly reasonable. Figures 5 and 6 show comparisons of cyclic strengths of wet-tamped and air pluviated soil specimens. In Figure 5, Silver's results are for Monterey "0" sand Muzzy's for Monterey 0/30 sand. The test results reported show that when the soil is subjected to three-dimensional loading environment, the resistance to liquefaction is smaller. Figure 6 gives the plot of cyclic stress ratio versus number of cycles for the tests performed with a relative density of 60%, along with those from other similar investigations using pluviated samples. The soil specimens tested in the servo-controlled Multiaxial Device require a slightly higher number of cycles to reach liquefaction. This may be due to the fact that the triaxial samples typically fail by necking on extension cycle, a factor that does not enter in to the Multiaxial Tests.

Figures 7 and 8 show comparison of cyclic strength by the CTC, CPS, CRE and CRC series of loading. Both cyclic triaxial (CTC) and cyclic pure shear (CPS) loadings are less severe than CRE and CRC loadings. When the soil sample is subjected CRC loading the soil offers the least resistance to liquefaction. Therefore, a study on the performance of soils in California earthquakes by CTC or CPS tests would result only on underestimation of the severity.

6 CONCLUSIONS

A new Servo-controlled Multiaxial Device developed could impart cyclic loading on a cubical specimen following any stress path. Jump rotation of principal stresses by 90 degrees is possible in this stress controlled device. Transient loading conditions

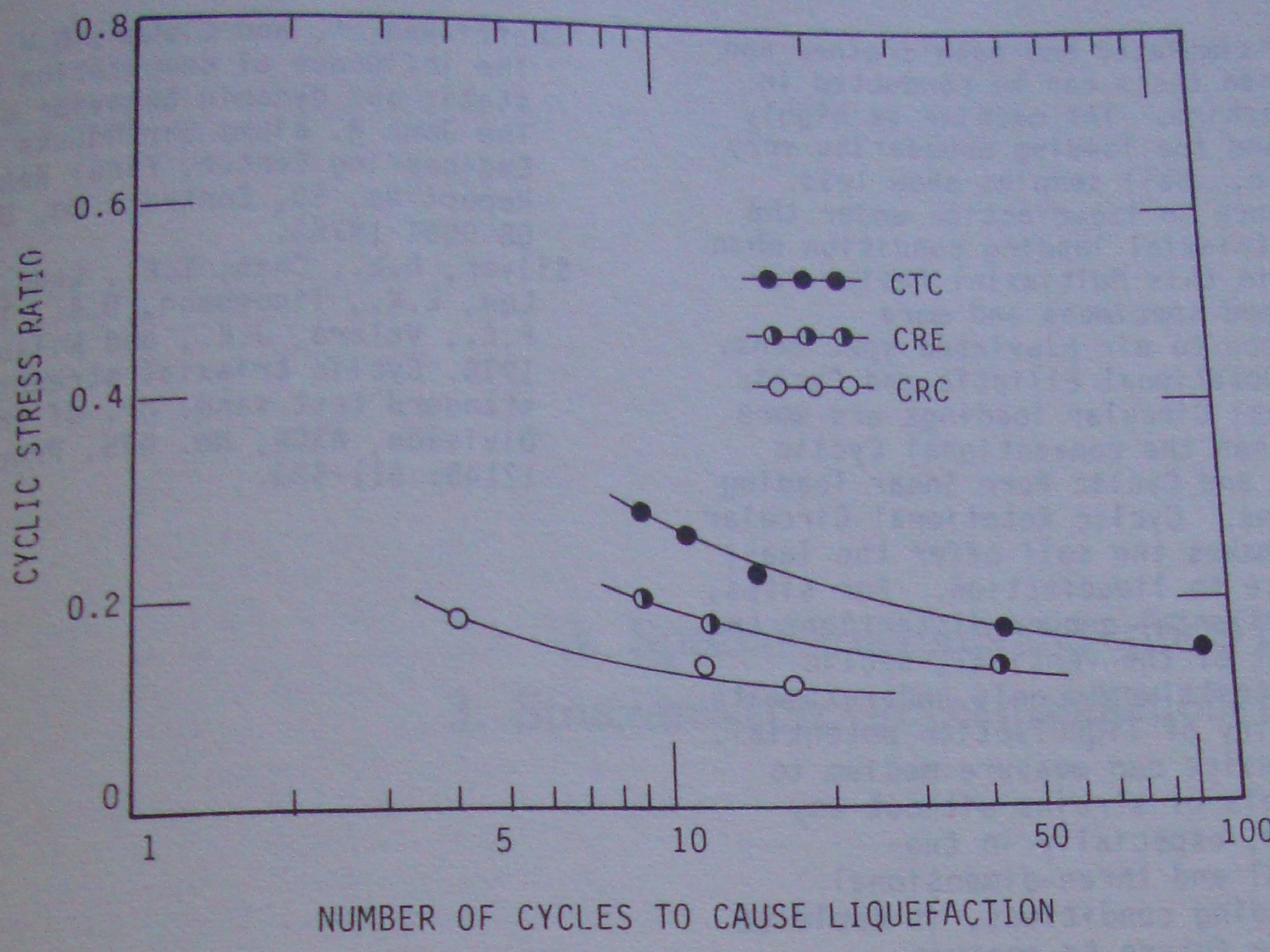

FIGURE 7. EFFECT OF STRESS PATH ON CYCLIC SHEAR STRENGTH.

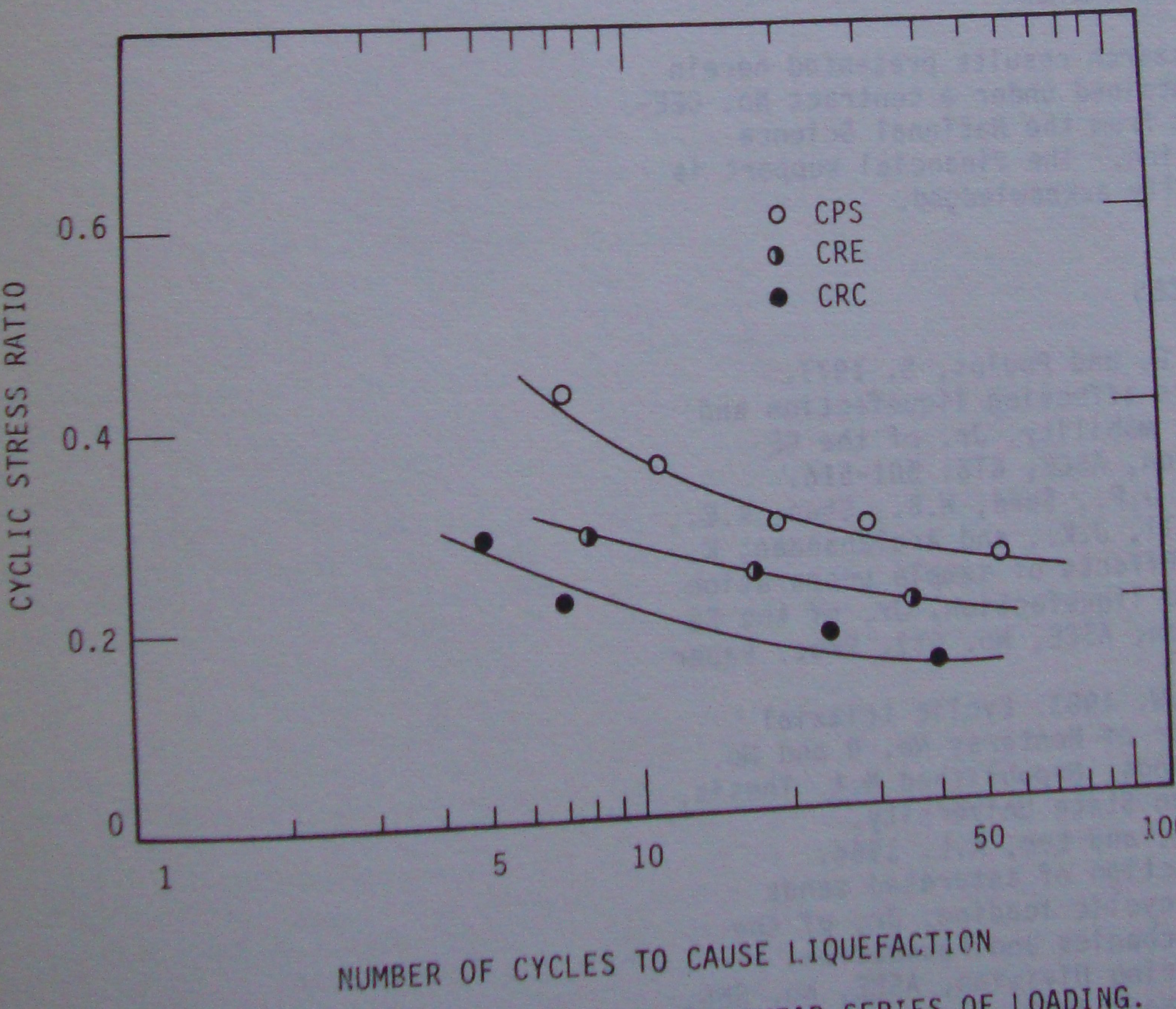

FIGURE 8. CYCLIC STRENGTH BY THE PURE SHEAR SERIES OF LOADING.

can be simulated and both drained and undrained tests can be conducted in this machine. The machine is highly rigid and the loading boundaries very flexible. Soil samples show less resistance to liquefaction under the cyclic triaxial loading condition when tested in this Multiaxial Device for wet-tamped specimens and more resistance to air pluviated specimens. Cyclic Rotational Elliptic and Cyclic Rotational Circular loadings are more severe than the conventional Cyclic Triaxial and Cyclic Pure Shear loading conditions. Cyclic Rotational Circular loading makes the soil offer the least resistance to liquefaction. For sites, where horizontal ground distortions are twice that of the vertical, Cyclic Triaxial tests would only underestimate the severity of liquefaction potential. As this device can measure medium to large levels of strains without any difficulty, especially in two-dimensional and three-dimensional cyclic loading conditions, it could be used in the future to measure cumulative permanent deformations due to successive shocks.

7 ACKNOWLEDGEMENT

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