RICE UNIVERSITY

THE DEVELOPMENT OF A PERIODIC LOADING APPARATUS FOR TRIAXIAL TESTING

by

SIH-KONG DJOU

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

Thesis Director's signature:

Houston, Texas

May, 1964
This dissertation is concerned with the development of a periodic loading apparatus for testing soil specimens under triaxial loading conditions. To attain this objective an intensive survey of the literature has been conducted in order to evaluate the characteristics of similar apparatus developed in the past. In the light of the experiences of others, a new design is proposed which will enable most effectively the study of the behavior of soil specimens under periodic loading conditions. The proposed apparatus is quite versatile. It is possible to apply a periodic deviator stress as well as a periodic confining stress and to vary the pattern of stress applications quite readily. The same apparatus could be utilized to test soil samples under static triaxial loading conditions also.
TO MY PARENTS

Mr. and Mrs. G. G. Djou
ACKNOWLEDGEMENT

The writer wishes to express his most sincere appreciation to Dr. George E. Triandafilidis for his guidance and encouragement in completing this thesis.

Special thanks to Professor Wayne A. Dunlap of Texas A. & M. University for discussing and demonstrating a similar periodic loading apparatus developed at Texas A. & M. University, and his valuable comments in connection with the design of the proposed apparatus.

The writer also appreciates very much the assistance of Mrs. Dorothy R. McCall and Mrs. Barbara G. Walther in typing this manuscript.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I.</td>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>II.</td>
<td>SCOPE</td>
<td>4</td>
</tr>
<tr>
<td>III.</td>
<td>BACKGROUND</td>
<td>10</td>
</tr>
<tr>
<td>A.</td>
<td>First Triaxial Periodic Loading Apparatus developed at the University of California.</td>
<td></td>
</tr>
<tr>
<td>B.</td>
<td>Second Triaxial Periodic Loading Apparatus developed at the University of California.</td>
<td></td>
</tr>
<tr>
<td>C.</td>
<td>Triaxial Periodic Loading Apparatus developed by Larew and Leonards.</td>
<td></td>
</tr>
<tr>
<td>D.</td>
<td>Triaxial Periodic Loading Apparatus developed at Texas A. &amp; M. University.</td>
<td></td>
</tr>
<tr>
<td>IV.</td>
<td>DESIGN CONSIDERATIONS</td>
<td>31</td>
</tr>
<tr>
<td>A.</td>
<td>Triaxial Cell.</td>
<td></td>
</tr>
<tr>
<td>B.</td>
<td>Pressure Cylinder.</td>
<td></td>
</tr>
<tr>
<td>C.</td>
<td>Air Pressure Reservoirs, Air Pressure Regulators and Air Pressure Gages.</td>
<td></td>
</tr>
<tr>
<td>D.</td>
<td>Solenoid Valves.</td>
<td></td>
</tr>
<tr>
<td>E.</td>
<td>Electric Timer.</td>
<td></td>
</tr>
<tr>
<td>F.</td>
<td>Load, Deformation and Pressure Transducers.</td>
<td></td>
</tr>
<tr>
<td>G.</td>
<td>Recording Instruments</td>
<td></td>
</tr>
<tr>
<td>H.</td>
<td>Control Board.</td>
<td></td>
</tr>
<tr>
<td>I.</td>
<td>Supporting Framework</td>
<td></td>
</tr>
<tr>
<td>J.</td>
<td>Tubing.</td>
<td></td>
</tr>
<tr>
<td>V.</td>
<td>TYPICAL TESTING PROCEDURE</td>
<td>40</td>
</tr>
<tr>
<td>VI.</td>
<td>SPECIAL FEATURES</td>
<td>44</td>
</tr>
<tr>
<td>A.</td>
<td>Maximum Confining Pressure and Maximum Deviator Stress.</td>
<td></td>
</tr>
<tr>
<td>B.</td>
<td>Maximum and Minimum Frequencies.</td>
<td></td>
</tr>
<tr>
<td>C.</td>
<td>Variation of Principal Stresses.</td>
<td></td>
</tr>
<tr>
<td>D.</td>
<td>Static Tests.</td>
<td></td>
</tr>
<tr>
<td>VII.</td>
<td>RECOMMENDATIONS</td>
<td>48</td>
</tr>
<tr>
<td>APPENDIX I</td>
<td>List of Commercially Available Parts.</td>
<td>49</td>
</tr>
<tr>
<td>APPENDIX II</td>
<td>Bibliography.</td>
<td>51</td>
</tr>
</tbody>
</table>
I. INTRODUCTION

In a broad sense a foundation consists of structural elements that transfer the loads from the superstructure to the underlying soil. These structural elements are proportioned in such a manner as to transmit the applied loads with an adequate factor of safety. In view of the type and usage of structure it is also important to realize the necessity of independently assessing the order of magnitude of the resulting deformations and when necessary to modify the design to keep the deformations within tolerable limits.

In this process of selection and proportioning, it is necessary to determine the loads for which the foundation element will be proportioned and also to evaluate the pertinent physical strength characteristics of the underlying soil.

The applied loads are divided into two major categories. First, those which are of permanent nature (dead loads) and act at all times on the foundation, and second, those which are of temporary nature (live loads) and act periodically on the foundation.

The variation of intensity of ordinary live loads occurs so slowly with respect to time, that for all practical purposes they are treated as static loads. Under these circumstances, the foundation contact stresses are always balanced
with the applied loads and the physical strength characteristics of the underlying soil are determined by means of conventional static laboratory testing procedures.

However, when the live loads are applied very rapidly it is no longer possible to neglect the time dependency of the applied live loads and it becomes necessary to introduce principles of dynamics in the analysis of the foundation. The physical strength characteristics of the underlying soil can no longer be determined by conventional static tests and it becomes necessary to study the influence of periodic stresses and the accompanying strain rate effects on the strength characteristics of the underlying soil medium.

Among a great variety of problems of this latter category it will probably suffice to mention only few typical examples. For instance, the dynamic effect of the applied live load cannot be neglected in the design of pavements subjected to rapidly moving wheel loads, in the design of foundations supporting vibrating machinery, in the design of all kinds of foundations in regions of intense earthquake activity and in the design of foundations for structures which are subjected to blast loading conditions.

It is apparent that the time dependent loads mentioned in the above examples do not all belong to the same category. For instance, an earthquake disturbance produces impulses of random intensity and frequency, while the rotating parts of a vibratory machine will produce periodic impulses of uniform intensity and frequency. In contrast the disturbance pro-
duced by a blast consists only of a single transient impulse.

The purpose of this dissertation is to design a laboratory apparatus for studying the influence of periodic loads on the stress-strain characteristics of soil samples under triaxial loading conditions.
II. SCOPE

Prior to the application of a foundation load the state of stress at any point within the underlying subsoil consists of a vertical stress equal to the overlying effective weight of soil and an all around confining stress which is a function of the vertical stress.

The shear strength of the soil is determined by extracting a representative soil sample from the field and testing it in the laboratory by simulating the same initial state of stress and providing drainage conditions that are likely to prevail and result in the most conservative strength assessment. While the confining stress is maintained constant, the axial stress is gradually increased, until the sample either fails or exhibits large amounts of axial deformation. The duration of such a conventional test ranges anywhere between 5 to 30 minutes. The stress strain relationship obtained from such a test is utilized to determine the shear strength of the underlying soil. The foundation is proportioned on the basis of an allowable shear strength which is obtained by dividing the ultimate strength by an adequate factor of safety.

The factor of safety is so chosen to provide an ample margin of safety against uncertainties in regard to loads and local variations in the subsoil as well as to safeguard against progressive deformations due to creep under
constant sustained shearing stresses. When this principle is utilized in proportioning a foundation the vertical stress in the soil underlying the foundation is increased only by a certain fraction of the ultimate shearing strength of the soil. Ordinarily the all around confining stress is assumed to be equal to the effective vertical stress, and the increase of the axial stress in excess of the confining stress is designated as the deviator stress.

The utilization of the above principles is quite satisfactory in evaluating the stability of a soil under static loading conditions but the stability of the underlying soil under periodically applied loads such as vibratory machinery, earthquakes and moving loads is not as readily apparent. If it is assumed that under periodic loads it is possible to calculate the shear stresses that are induced on the underlying subsoil, then the problem of evaluating the stability of the soil can be resolved by performing laboratory tests where the shear strength of the soil is determined under an identical periodic state of stress.

The pattern of stress application depends on the nature of the periodic load. The term periodic load as used in this dissertation will be defined as a load of constant magnitude that is periodically applied and removed from the underlying soil. For instance, a soil element under the foundation of a vibratory machinery, prior to the excitation of the machinery is subjected to a constant all around confining stress $\sigma_3$ and a sustained deviator stress $\sigma_s$. After excitation of the
vibratory machinery the soil element is subjected to periodic impulses of constant frequency and intensity. This additional periodic deviator stress is designated as $\sigma_d$. It can possess both a positive and negative phase thus creating a pulsatory effect around the sustained stress axis. The negative phase of the additional periodic deviator stress reduces the sustained deviator stress to $\sigma_s'$ as shown in FIG. 1. For a problem of this nature it is convenient to express this pulsatory stress as a constant function of the sustained stress.

**FIG. 1** STRESS VS TIME RELATIONSHIP OF A SOIL ELEMENT SUBJECTED TO MACHINERY VIBRATION.

The pattern of stress application on a soil element under a foundation subjected to earthquake loads is in essence similar to the one described above, but both the frequency and intensity of the applied impulses follow a very
random pattern. It is not within the scope of this apparatus to create random stress patterns.

The pressure influence line (1)* for a soil element under a highway pavement subjected to a moving wheel load is shown in FIG. 2. It can serve as another example of a periodic stress application, provided that a series of wheels spaced at equal intervals move along the pavement at a constant speed. The periodic stress duration of the applied impulse depends on the travelling speed of the vehicles. The intensity of the periodic stress depends on the type of vehicle. The elapsed time between successive stress applications is designated as the "interval". This interval is arbitrary and depends on the traffic density. The pattern of periodic stress application due to wheel loads moving on a soil supported pavement can be approximated by a diagram such as shown in FIG. 3. It should be pointed out that for a problem of this nature the sustained stress is of no practical significance and furthermore the periodic deviator stress \( \tau_d \) can only act in a downward direction.

It should be further emphasized that the periodic stress impulses induce an increase in the lateral confining stresses. For this reason it is considered desirable to design the periodic loading apparatus so that it would be possible to study the effect of periodic confining stresses on the stress strain characteristics of soil specimens.

*Raised numerals in parantheses refer to similarly numbered items in the list of selected bibliography.
FIG. 2 PRESSURE INFLUENCE LINE FOR A SOIL ELEMENT SUBJECTED TO A MOVING WHEEL LOAD.

FIG. 3 STRESS VS TIME RELATIONSHIP OF A SOIL ELEMENT SUBJECTED TO MOVING WHEEL LOADS.
It is anticipated that initially this triaxial periodic testing apparatus will be confined to undrained tests only.
III. BACKGROUND

The static stress-strain characteristics of soil deposits are determined in the laboratory by performing either direct shear tests, unconfined compression tests, confined compression tests or triaxial compression tests. The choice among this variety of testing techniques depends on the type of soil and also on the necessity of simulating in the laboratory the loading and drainage conditions that will actually occur in the field.

Attempts to investigate the effects of time dependent loads on the stress-strain characteristics of soils have similarly been carried out by designing special dynamic soil testing equipment for all the different types of tests mentioned above. It is not within the scope of this dissertation, however, to study the performance of equipment specifically designed for the purpose of applying transient loads and furthermore it is not the scope of this dissertation to be concerned with equipment that are not adequate for testing soils under triaxial loading conditions.

Since the basic design principles of all types of dynamic soil testing equipment have exerted a certain degree of influence towards the development of triaxial periodic loading devices, it is considered desirable to provide at least an overall perspective of the extent of available information. In the list of selected bibliography references (2 to 14)
have been introduced strictly for this purpose, and consequently no further mention to these references is anticipated in the text of this dissertation.

In order to simulate periodic stress applications under triaxial loading conditions to soil specimens in the laboratory, it is necessary to design a special kind of triaxial loading device that will possess all of the previously mentioned desirable features. Towards the development of this objective advantage has been taken of the experiences of previous investigators. It is therefore appropriate to present short summaries of a few pertinent previous efforts in this area.

A. First Triaxial Periodic Loading Apparatus developed at the University of California.

Figure 4 shows a laboratory apparatus built at the University of California at Berkeley for studying the effects of periodic loads on the stress-strain characteristics of compacted clays \( (15, 16) \). The design principle of this apparatus is very similar to the one developed at Harvard University \( (4) \), except for a few minor differences in operation. This apparatus is not directly applying a periodic load onto the soil specimen; it removes and re-applies the weights from the hanger of a conventional triaxial loading frame.

The hydraulic pressure is supplied by a constant volume vane-type pump and is regulated by a by-pass valve.
### Operation of Four-Way Solenoid Valve

<table>
<thead>
<tr>
<th>Down-Stoke</th>
<th>Up-Stoke</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Diagram" /></td>
<td><img src="image2.png" alt="Diagram" /></td>
</tr>
</tbody>
</table>

To Loading Yoke of the Triaxial Loading Frame

---

**FIG. 4** First Triaxial periodic Loading Apparatus developed at the University of California.

*(After Seed, Chan & Monismith)*
The stroke of the carriage and the load duration are controlled by a combination of a four-way solenoid valve, a two-way shut-off valve and a flow restriction valve. A micro-switch is introduced on the carriage to sense the load application and to regulate the opening sequence of the four-way solenoid valve.

The carriage of the apparatus has a total vertical travel of 3 inches. For most tests a one inch movement of the carriage is ample for many types of soil specimen. The initial setting of the carriage under the hanger depends on the stiffness of the specimen and the lever ratio of the loading beam. For highly deformable samples, the setting of the carriage becomes very critical and requires careful consideration. When a large amount of initial deformation occurs, the travel of the carriage has to be adjusted to provide a consistent stroke for subsequent successive loading cycles.

Most specimens tested with this type of apparatus were subjected to a periodic load of 1 second duration with a time interval of 5 seconds between successive cycles (10 cycles per minute). A typical periodic deviator stress vs time relationship is shown in FIG. 5. To reduce the duration of the tests, the periodic stress intensity was increased every hour throughout the test by an increment of one tenth of the static unconfined compressive strength of the soil specimen. The mechanical design of the apparatus was simplified by producing only idealized rectangular pulses.
The triaxial test specimens were prepared following standard testing procedures. Silty clay samples with a liquid limit of 37% and a plastic limit of 23% were compacted in a 6 inch inside diameter Triaxial Institute Kneading Compactor. Identical test specimens were trimmed from the compacted sample to the size of 1¼ inches in diameter and 4 inches high. The specimens possessed a degree of saturation of about 95%. They were subsequently enclosed by two thin rubber membranes prior to testing.

The deformation of the specimen was measured by a dial indicator and the number of load cycles were recorded by a counter. The magnitude of the periodic deviator stress was measured by a dynamometer and was traced as a function of time on a Sanborn recorder.

The test results indicated that under periodic load applications, less stress is required to produce the same
Percentage of strain than under sustained loading conditions. A larger deformation results under the same magnitude of loading when the load is periodically applied and removed. It was also reported that periodic load applications induce a certain amount of consolidation and thus result in an increase of the ultimate strength.

B. Second Triaxial Periodic Loading Apparatus developed at the University of California.

In order to investigate soil behavior under periodic loads of higher frequencies, a second type of periodic loading apparatus was developed at the University of California (17, 18, 19). This second type of apparatus utilized compressed air instead of oil as the pressure medium. This is a desirable feature because the higher expansion and the lower viscosity of compressed air ensures a much faster pressure build-up and decay in the cylinder.

Figure 6 shows the latest version of the second type of apparatus. It is possible to vary the lateral confining pressure in the triaxial cell simultaneously with the repetition of the deviator stress, as well as to vary the sustained load during the test by adjusting the weights and counter weights on the loading yoke.

For the application of a periodic deviator stress, the compressed air passes through a pressure regulator and is stored in an air reservoir. From the air reservoir the regulated air pressure is first delivered to a pressure cylinder
FIG. 6 SECOND TRIAXIAL PERIODIC LOADING APPARATUS DEVELOPED AT THE UNIVERSITY OF CALIFORNIA.

(After Seed & Fead)
and subsequently vented by means of a three-way solenoid valve which is excited by an electrical timing unit. The pressure cylinder consists of a cylindrical vessel and a single stroke piston which is surrounded by a synthetic rubber Bellafram and guided by a ball bushing to eliminate air leakage and energy losses due to friction. When the pressure cylinder is pressurized, it transforms the pneumatic pressure into an axial downward force which in turn is transmitted to the soil specimen through a loading yoke. When the pressure is exhausted from the cylinder through an opening in the solenoid valve, the piston rebounds due to counterweights at the end of the loading yoke. This load application continues until the electrical timing unit is disconnected. The load duration and the time interval between successive cycles is preset and adjusted by the timing unit.

Since the loading yoke and the piston are always in contact during the load applications, no impact effects are transmitted to the soil specimen. Furthermore, since there is no return spring in the pressure cylinder, the piston can freely follow the deformed configuration of the specimen.

The variation of the confining pressure in the triaxial cell is accomplished by using the same method of controlling the periodic deviator stress.

When an element of soil is subjected to an increase in deviator stress, there is a simultaneous increase in the confining stress \((17)\). A typical pressure versus time relation obtained with this apparatus is shown in FIG. 7 which simulates a probable loading condition that a surface soil
FIG. 7 TYPICAL PRESSURE VS TIME RELATIONSHIP FOR PERIODIC CONFINING & DEVIATOR STRESSES.

(After Seed & McNeill)
element will experience under a single load application. The apparatus is so designed to be able to build up the confining pressure to its full value before the deviator stress is applied. This ensures a principal stress ratio during the test which consistently simulates actual field conditions. To attain this objective it is necessary to introduce a small time delay between the sequence of operation of the two solenoid valves. The curves in FIG. 7 show that it requires 0.05 sec. to build up the confining pressure and another 0.05 sec. for the deviator stress. Then both the major and the minor principal stresses remain constant for about 0.40 sec. and they subsequently decrease to zero within 0.10 sec. The shortest load duration that can be attained with this apparatus is 0.10 sec.

During the test, the confining pressure variation is traced by a pressure transducer mounted at the top of the triaxial cell and the deviator stress is monitored by an eight strain gage dynamometer which is placed between the loading yoke and the piston of the triaxial cell. Both traces are recorded on a Sanborn recorder. The deformation of the specimen was read by a dial gage before and after a stress application. In some tests an inductance type deformation gage was used to trace the deformation as a function of time \(18,20\).

Clay and sand specimens for this investigation were prepared using the same procedure already described in Section A of this chapter.
The conclusions derived from the test results using this apparatus are very similar to those summarized in the preceding section, but further indicated that with equal periodic deviator stress applications larger deformations occur when the confining pressure is periodic rather than of sustained nature.

C. Triaxial Periodic Loading Apparatus developed by Lawre and Leonards.

Larew and Leonards have published a paper on the strength criteria under repeated loads (21). In this paper the authors present a new type of triaxial periodic loading mechanism. FIG. 8 is a schematic diagram of this new development. This apparatus is basically a combination of a conventional double bay triaxial testing unit and an electric motor driven loading device. The main shaft on the loading device has two opposite mounted eccentric cams which are linked with weights placed on hangers through cables. When the shaft is rotated by the motor, each eccentric cam will either lift or lower the weights from one hanger. Since the cams are mounted opposite to each other, the loading sequence of the two hangers is alternating in opposite direction. With this arrangement, two periodic load triaxial tests can be performed at the same time while a very small torque is transmitted to the main shaft. This device can lift or lower a maximum weight of 160 Kg. from each hanger. The motor speed and the gear ratio in the speed reducing gear box are designed to have a loading application frequency of about 20 to 22 cycles.
FIG. 8 TRIAXIAL PERIODIC LOADING APPARATUS DEVELOPED BY LAREW AND LEONARDS.
per minute. The load duration can be varied by adjusting the length of the cables with turnbuckles. The shape of the pulse can be changed by adopting cams of different shapes. A typical pattern of periodic stress application operating at a frequency of 23 cycles per minute is shown in FIG. 9.

![Graph of periodic deviator stress vs. time relationship.](image)

**FIG. 9 TYPICAL PERIODIC DEVIATOR STRESS VS TIME RELATIONSHIP.**  
*(After Larew & Leonards)*

The adjustment of the turnbuckles requires special care when testing highly deformable specimens because the cumulative initial plastic deformations of the specimens might increase the distance of the loading stroke and therefore, alter the load duration time.

A commercially available triaxial cell is used. The size of the specimen is 1.4 inches in diameter and 2.8 inches high. Three types of soil have been tested - a micaceous silt, a limestone residual clay, and a sandy clay. The details of the sample preparation procedure can be found in another publication by Leonard (22).
A constant confining pressure is applied by compressed air. Glycerine is used as a confining fluid. All tests are performed under undrained (quick) conditions. The deformation of the specimen under the repeated load application is measured by a dial gage to the nearest 0.001 of an inch. The number of load applications is recorded on a revolution counter that is connected to the main shaft.

The test results indicate that after the first few periodic load applications, the deformation vs number of load applications curve will approach a constant slope. Larew and Leonards proposed that the intensity of the periodic deviator stress which corresponds to the constant slope part of curve can be regarded as the strength of compacted clays under a periodic loading condition. Furthermore, the ratio between this critical intensity of the periodic deviator stress and the static deviator stress at failure, can be considered as a measure of the sensitiveness of the strength reduction due to the effects of periodic load applications. For highly plastic clays, the minimum ratio is usually at or near the optimum water content. This ratio further decreases with an increase in the compactive effort during sample preparation.

D. Triaxial Periodic Loading Apparatus
developed at Texas A. & M. University.

Recently, the Texas State Highway Department has sponsored a research project at Texas A. & M. University \((23,24)\), to study the strength, deformation and fatigue characteristics
of highway subgrade materials subjected to periodic traffic loads. Since the aggregates for highway subgrades can be as large as 1\(\frac{1}{2}\) inches in size, it was necessary to design a testing apparatus capable of handling specimens as large as 6 inches in diameter and 12 inches high. The assembled apparatus is shown in FIG. 10. It occupies a floor area of about 40 sq.ft. and stands 6 ft. high. It is capable of testing four specimens simultaneously.

The design principle of the periodic loading system is very similar to the first type of apparatus developed at the University of California with the exception of a few improvements. First, an 800 psi. pressure accumulator has been added on the pressure line to store the hydraulic pressure which also distributes the pressure to the four testing units. Second, in order to eliminate the loading yoke mechanism the pressure cylinder is placed directly above the triaxial cell. This arrangement does not allow the application of any sustained load, but subgrade materials are not subjected to substantial sustained loads and therefore this is not considered to be a serious disadvantage.

Each of the four loading units has a pressure regulator, a four way solenoid valve and a double-action pressure cylinder to produce periodic stresses to the soil specimens. After the apparatus was built, it was discovered that the rebound force of the specimen was large enough to push the piston up to its starting position. It was therefore necessary to block one opening of the solenoid valve and thus modify the pressure cylinder to single action only.
Specially designed 9 inches inside diameter and 18 inches high triaxial cells, FIG. 11, have been built to accommodate 6 inches in diameter test specimens. The triaxial cell is made of Plexiglass 3/8 inches thick. The stainless steel loading piston is 1 inch in diameter and is guided by two precision ball bushings.

Remolded specimens are prepared in a 6 inch steel mold using granular subgrade materials. In this investigation, commercially available opaque latex membranes proved to be inadequate in resisting the wear caused by the granular materials. A specially manufactured synthetic rubber membrane was adopted. It has a thickness of about 1/32 inch and is both air and water tight. However, the flexibility and adhesiveness of this type of synthetic rubber membrane is low and created sealing problems.

All specimens are drained from both top and bottom. A small diameter saran tube is used to inter-connect the porous plates from each end of the specimen. The water that drains out of the specimen is collected in a pore pressure measuring burette which is utilized to determine the changes of pore air pressure in the specimen due to periodic load applications. A leakage in the system or in the membrane can be detected by observing the system or in the membrane can be detected by observing the amount of water flow into the burette.
FIG. 10 ASSEMBLED VIEW OF THE TRIAXIAL PERIODIC LOADING APPARATUS DEVELOPED AT TEXAS A & M UNIVERSITY.

FIG. 11 DETAILS OF THE TRIAXIAL COMPRESSION CELL.
The constant confining pressure in the triaxial cell is applied by compressed air which is stored in an air reservoir. The pressure in the reservoir is regulated by an air regulator and is measured by a Bourdon tube type pressure gage.

Most of the tests are performed under a constant confining pressure of 11.5 psi. and a periodic axial load of 1500 pounds which corresponds to 53 psi. on a 6 inch diameter specimen. The load duration is about 0.2 second with a 1.8 second interval between consecutive load applications (30 cycles per minute). A typical load vs time relationship is shown in FIG. 12. Since the apparatus utilizes a hydraulic loading system, the pressure is built up to its maximum value rather gradually. However, after the deviator stress reaches its peak intensity, it decays very rapidly within approximately 0.003 seconds which is an undesirable feature. An attempt has been made to introduce a restriction valve on the pressure return line but this results in an exponentially decaying pulse.

![Typical Periodic Deviator Stress vs Time Relationship](image)

**FIG. 12 TYPICAL PERIODIC DEVIATOR STRESS VS TIME RELATIONSHIP.**
A dynamometer between the pressure cylinder and the triaxial cell is used to measure the magnitude of the periodic deviator stress as a function of time. The dynamometer consists of a 1 3/4 inch diameter thin wall stainless steel tube with four fully bridged SR-4 strain gages. The calibration of the dynamometer is done in a universal testing machine. Deformations are measured by a special deformation gage which is mounted on the piston of the triaxial cell. An adjustable set screw on the triaxial cell is utilized as a reference datum. In essence, the deformation gage consists of two parallel flexible steel cantilever strips which are clamped together and spaced about 3/4 inch apart. Four fully bridged SR-4 strain gages are attached on the surfaces of the two cantilever strips. When the strips deflect, two of the gages register a tensile strain while the other two register a compressive strain. This type of deformation gage was used earlier by Casagrande and Shannon (4). It consisted of a single cantilever strip and required a dummy counterpart for balancing the bridge. A dial deformation gage has also been used for back checking the cumulative deformation of the specimen.

An electronic power transformer is used to rectify, stabilize and step-down the 110 volts alternating current to a 12 volts direct current. The 12 volts direct current is further reduced to 7 volts by two universal balancing units and fed into all the four deformation gages and the
four dynamometers of the apparatus. The output signals from
the gages are monitored by the eight galvanometers of a Visi-
corder. Later the signals are translated into light pulses
and recorded on a moving strip of light-sensitive paper. The
moving speed of the paper strip can be set from 0.01 in./sec.
to 80 in./sec., so that any desirable time scale can be ob-
tained. The paper strip also registers time at 0.01 sec.
intervals which facilitates the interpretation of the traces
of the light pulse. Since there are no amplifiers in the
recording system, the output signal distortion is minimized.

Since the confining pressure is kept constant, no pres-
sure recording instrument is attached on the triaxial cell.

The number of repetitive load applications is recorded
by a panel mounted electric reset counter which is connected
in parallel with the timing unit.

The investigation being primarily concerned with the
subgrade deformation rather than the ultimate strength of
the specimen, all tests are terminated after the specimen
reaches an arbitrary strain of 5%.

Since this apparatus is operated under a high hydraulic
pressure, a "warm-up" period of approximately 15 minutes is
required prior to each test in order to build up enough pres-
sure in the accumulator. Prior to every test a steel dummy
is introduced as a substitute for the triaxial cell in order
to adjust the opening of the pressure regulator and the timing
sequence. After the triaxial cell is placed in position, the
initial deformation of the specimen requires some further ad-
justments. Otherwise, the maximum value of the deviator stress cannot be reached within a short period. Due to this difficulty it has not been possible to record the deformations that occur under the first few periodic load applications.
IV. DESIGN CONSIDERATIONS

An assembled view of the proposed apparatus is shown in FIG. 13. The main components of the apparatus consist of a triaxial compression cell, a pressure cylinder, air pressure reservoirs, an electric timer, solenoid valves, load and deformation transducers, pressure gages and regulators, a control board, electric recording equipment and a steel framework for supporting the assembled equipment and instrumentation.

In order to facilitate the design and to cut down on the time necessary to build the proposed periodic loading apparatus it was necessary to utilize commercially available parts as much as possible. From this point of view the response characteristics of the apparatus, as will be discussed later, are within the range that can be easily succeeded by readily available commercial items.

A. Triaxial Cell.

This apparatus is designed to utilize any conventional type of triaxial compression cell which accommodates 1.4 inch diameter specimens. However, the maximum height of the cell should preferably not exceed 18 inches.

B. Pressure Cylinder.

The pressure cylinder is an item of great importance and has been specially designed for the proposed periodic triaxial
FIG. 13 PERIODIC LOADING APPARATUS FOR TRIAXIAL TESTING
loading apparatus. The main function of the pressure cylinder is to transform the regulated air pressure into an axial load on the soil specimen. A cross-sectional elevation of the proposed pressure cylinder is shown in FIG. 14. The pressure cylinder has an inside diameter of 3 inches and is 5 inches high. The piston of the cylinder is sealed by means of a rolling diaphragm which is made out of teflon fabric and is commercially known as Bellofram. When the piston is displaced the Bellofram rolls on or off the piston and provides an excellent seal with a minimum amount of friction between the cylinder and the piston. The vertical motion of the piston in the cylinder is guided by a 3/8 inch round shaft of hardened steel which is specially machined to fit a precision ball bushing. The bushing fits into a recess in the cylinder and is held in position by a retainer ring. The effective pressure area of the Bellofram specified by the manufacturer is 6.25 square inches and the maximum volume of the pressure chamber is approximately 24 cubic inches. Connecting rings and a spacer disc have been designed for easy maintenance and possible adoption of different size of pressure cylinders in order to vary the maximum deviator stress. Such an arrangement also provides an easy access for changing worn out Bellofram quite readily.

C. Air Pressure Reservoirs, Air Pressure Regulators and Air Pressure Gages.

The air pressures needed for producing a confining stress, a sustained deviator stress, a periodic deviator stress and a reduced sustained deviator stress are separately stored in four air pressure reservoirs. Army surplus stainless steel oxygen
FIG. 14 PRESSURE CYLINDER

Scale: Half Full Size
tanks will be used as air pressure reservoirs. They are 10 inches in diameter, 18 inches long and approximately 1170 cubic inches in volume. These reservoirs are safe for pressures as high as 400 psi.

The pressure in each reservoir is regulated individually by an air pressure regulator. The pressure regulator has an integral air relief valve and a venturi type aspirator tube which is able to regulate the in-flow pressure to increments of 1/8 inch of water and to vent instantly the excess downstream pressure to within 0.01 psi of the set pressure.

The pressure in each reservoir is read by a 4½ inch, panel mounted, Bourdon tube type air pressure gage to an accuracy within 0.5% of its full capacity range.

D. Solenoid Valves.

Two dual pressure selection type 3 way solenoid valves have been used to control the air passage between the air reservoirs and the pressure cylinder. The solenoid valves consist of two units - a solenoid (electro-magnet) with its plunger and a flow control valve. When the solenoid is energized or de-energized by an electric input, the movement of the plunger of the solenoid forces the flow control valve to select either one of the two inlet pressures and divert it to the outlet opening.

E. Electric Timer.

An electric timer is used to actuate the opening sequence of the solenoid valves. The energizing and de-energizing
period of the solenoid can be separately selected by adjusting the two timing dials of the timer. The minimum dial division is 0.10 seconds, therefore, the maximum frequency of the solenoid operation can be set to 300 cycles per minute. When the timer is in operation it transmits the timed input electricity to the solenoid through a micro-switch.

F. Load, deformation and pressure transducers.

In measuring the intensity of the periodic deviator stress a force washer is placed between the pressure cylinder and the piston of the triaxial cell, as shown in FIG. 15. The size and shape of this force washer is similar to an ordinary bolt washer. With strain sensitive wire wound around its circumference, it can sense the change of the axial load just like an ordinary strain gage. The wiring and bridging of the force washer is also similar to an ordinary strain gage.

For measuring the deformation of the specimen during the test, an inductance type linear motion transducer is mounted on the piston of the triaxial cell and the mandrel of the transducer bears against a fixed datum on the triaxial cell. The outside dimension of the transducer is about 2 inches long and ½ inch in diameter. The transducer has a wire wound outside coil and a movable inside magnetized mandrel. The transducer follows the movement of the piston and changes its inductance - thus - creates a recordable signal. The sensitivity of this type of linear motion transducer is 0.0001 inch.

To record periodic application of confining stresses, a gage pressure transducer is directly connected to the triaxial
FIG. 15 ARRANGEMENT FOR MONITORING LOAD AND DEFORMATION OF TEST SPECIMEN.
cell. This gage pressure transducer converts the change of confining stresses into electrical signals which are fed into the recording instrumentation.

G. Recording Instruments.

The signals transmitted from the load, deformation and pressure transducers can be traced by an oscilloscope. The sweep speed of the oscilloscope should be synchronized with the frequency of the periodic stress applications. A special recording camera can be mounted on the screen of the oscilloscope to take photographs of the traces at a suitable interval.

A disadvantage of the ordinary dual beam oscilloscope is that it can trace only two signals at a time. It is, therefore, advisable to use a selection switch to choose among the three output signals. However, a Visiorder similar to the one described in Section D of Chapter III, can be used for recording all three signals simultaneously.

H. Control Board.

All the controlling instruments will be mounted on a central control board for easy operation. Besides the above mentioned pressure regulators, pressure gages and electric timer, the control board is also equipped with an electric reset counter, a main air pressure inlet valve, a central electric switch and recording instrument connectors. The 6-digit reset counter is connected in parallel with the electric timer and registers the number of periodic stress applications. The main air pressure inlet valve and the central electric switch are
used to supply the two energy sources, necessary for the operation of the apparatus.

I. Supporting framework.

The apparatus and its control board are supported by a welded steel frame which is constructed by a combination of 3 inch equal leg steel angles, steel plates and \( \frac{3}{8} \) inch plywood boards. The supporting frame is 72 inches long, 30 inches high and 21 inches wide. Half of the table is reserved for a future extension to include a second testing unit.

The four air pressure reservoirs are placed underneath the table in order to save space.

The triaxial testing bay consists of a crosswise stiffened steel reaction plate and four 1-inch round steel supporting columns. The clear distance between the testing table and the reaction plate can be adjusted to suit different types of triaxial cells. The pressure cylinder and the two 3-way solenoid valves are mounted on the reaction plate. Three screw type clamps (FIG. 13) are placed on the platform of the supporting frame to facilitate the alignment of the triaxial cell with respect to the loading axis of the apparatus.

J. Tubing.

All compressed air tubing used in this apparatus is made of 3/8 inch outside diameter vinyl plastic tubing. The details of the connecting arrangement is shown in FIG. 16.
V. TYPICAL TESTING PROCEDURE

To perform a triaxial periodic test on either an undisturbed or a remolded soil, the soil specimen is first carefully prepared according to conventional triaxial testing procedures. The size of specimen is 1.4 inches in diameter and about 3 inches high. The specimen is protected by two thin latex membranes to prevent air and water intrusion. Silicon grease may be used between the two membranes for extra sealing effects.

De-aired, distilled water is used as a confining fluid. To avoid the possibility of compressed air being dissolve in the water, a thin layer of light oil is placed above the water surface in the triaxial cell. At least $\frac{1}{4}$ inch of air space should be left above the oil level in the triaxial cell for better application of confining pressure.

Prior to placing the triaxial cell in its testing position, it is substituted by a steel dummy. This dummy facilitates the adjustment of the pressure regulators, the setting of the timer, and for checking the performance of the recording instruments. A toggle valve which is located at the entrance of the pressure cylinder is used to close temporarily the flow of air to the pressure cylinder while the triaxial cell is placed in its testing position. By following this procedure the stresses and strains during the first few periodic load applications can be recorded.
The functioning of the apparatus is schematically shown in FIG. 16. The compressed air source is connected to the apparatus through a main air pressure inlet valve. By means of the four precision air regulators, the main air pressure is regulated, diverted and stored in four air reservoirs. The pressure in each reservoir is regulated according to the required characteristics of the periodic pulse.

Air reservoir 1 is used to supply constant confining pressure to the triaxial cell. A shut-off valve is placed on the supply line for temporary isolation of the confining stress whenever it becomes necessary. Air reservoir 2 contains a medium pressure intensity for producing the sustained deviator stress, \( \sigma_s \). Reservoir 3 contains a high pressure intensity for producing the periodic deviator stress, \( \sigma_d \), while reservoir 4 contains a low pressure intensity for producing the reduced sustained deviator stress, \( \sigma_s' \). The air passage between the air reservoirs and the pressure cylinder is controlled by two 3-way solenoid valves, connected in series. When the electricity is disconnected, solenoid valve #2 is de-energized so that the opening C is blocked, while D is connected to E. Therefore, the pressure in air reservoir 2 is delivered into the pressure cylinder and simulates the sustained load condition. When the manual switch turns on the electricity, solenoid valve #2 is energized so that the opening D is blocked and C is connected to E. At the same instance, the electric timer also starts functioning. It first energizes the solenoid valve #1 according to the time...
FIG. 16 SCHEMATIC DIAGRAM OF A PERIODIC LOADING APPARATUS FOR TRIAXIAL TESTING.
setting on dial A. When the solenoid valve #1 is energized, the high pressure in air reservoir 3 is diverted to the cylinder through openings A, C and E and creates a periodic deviator stress. When the solenoid valve #1 is de-energized according to the time setting on dial B, the path between air reservoir 4 and the cylinder is opened. Since the volumetric ratio between the air reservoir and the pressure cylinder is about 50 to 1, the higher pressure in the cylinder will immediately compromise with the pressure in air reservoir 4, and the excess pressure will vent to the atmosphere through the relief valve in the pressure regulator 4. Therefore, a reduced sustained deviator stress is accomplished. The timer recycles this application indefinitely until it is disconnected again. The result of this procedure simulates a stress vs time relationship like the one shown in FIG. 1.

The number of periodic stress cycles is recorded on a reset counter. The pressure cylinder transforms the variation of pressures into periodic axial loads and applies them to the soil specimen in the triaxial cell.

The variation of axial load, axial deformation and confining stress are monitored by the force washer, linear motion transducer and gage pressure transducer, respectively and are traced on the oscilloscope.
VI. SPECIAL FEATURES

A. Maximum confining pressure and maximum deviator stress.

The proposed apparatus will be operated by laboratory supplied compressed air. The maximum intensity of the available air pressure source is about 100 psi. The maximum intensity of confining stress is governed by the type of triaxial cell and normally does not exceed 100 psi.

The intensity of the maximum deviator stress depends on the ratio of the cross-sectional area of the soil specimen and the effective pressure area of the pressure cylinder. For this particular apparatus, the area ratio between the 1.4 inch diameter soil specimen and the 3 inch inside diameter of the pressure cylinder is approximately 4. If a maximum air pressure of 100 psi is introduced into the pressure cylinder it will create a maximum deviator stress of 400 psi on the soil specimen. This corresponds to a total axial load of 600 pounds which should be adequate for most laboratory compacted specimens.

B. Maximum and minimum frequencies.

The maximum and minimum frequencies of the proposed periodic loading apparatus are mainly governed by the response of the solenoid valves and the timing unit. From a variety of commercially available timing units an appropriate selection
can easily achieve a loading frequency from a maximum of 300 cycles per minute to a minimum of 4 cycles per day.

C. Variation of principal stresses.

The proposed apparatus with the pressure diversion system already discussed in Chapter V will be able to simulate both positive and negative periodic deviator stresses by varying the intensity of the sustained deviator stress with time. It is believed that this could be a starting point in developing a random loading apparatus for the study of soil behavior under earthquake loading conditions. By further modifying the sequence of pressure diversion it is possible to vary the intensity of the confining stress simultaneously with the periodic deviator stress. In order to accomplish such an objective, the following modifications are necessary.

A fifth unit consisting of an air reservoir, a pressure regulator and a pressure gage should be added to the main air pressure line. This additional air reservoir unit will operate with unit 1 as shown in FIG. 17. Solenoid valve #3 will be introduced to substitute the shut-off valve shown in FIG. 16. The tubing from air reservoirs 1 and 5 will be connected to the two inlet openings of the solenoid valve #3. The outlet opening of the solenoid valve #3 will be connected to the triaxial cell. It would be further necessary to wire the new solenoid valve #3 in parallel with solenoid valve #1 through a time delay relay to the timer. The function of the time delay relay is to separate the electrical signal of the timer into two signals with a minimum time delay of
FIG. 17 SCHEMATIC DIAGRAM OF A MODIFIED PERIODIC LOADING APPARATUS FOR TRIAXIAL TESTING.
0.05 second. This arrangement can secure a time delay between the build up of the confining stress and the built up of deviator stress in order to maintain a predetermined constant principal stress ratio.

D. Static Tests.

The proposed equipment can be directly utilized to run controlled stress type static tests without major modifications.

Controlled strain type tests can be performed by introducing a motorized hydraulic jack under the triaxial cell. The motorized jack will be placed on the platform of the testing frame and the pressure cylinder will be removed. Either a proving ring or a force washer can be introduced between the piston of the triaxial cell and the reaction plate of the loading frame for monitoring the load intensity.
VII. RECOMMENDATIONS

The periodic loading apparatus proposed in this dissertation has been so designed to possess all of the previously mentioned special features. Unfortunately, it is not possible to foresee all the unexpected problems that may arise when this apparatus becomes operational. Adjustments in the design of the apparatus will be undoubtedly necessary. A series of pilot tests will be most desirable to attain this objective.
APPENDIX I. LIST OF COMMERCIALY AVAILABLE PARTS.

The following list consists of commercially available parts which are recommended for building the proposed triaxial periodic loading apparatus. It should be pointed out that this list does not represent the only brands of equipment that can be utilized for this purpose and furthermore does not necessarily imply that these are the only ones available.

The pressure cylinder and the supporting framework will be specially fabricated. Detail drawings for these parts have already been made and are available in the Civil Engineering Department.

<table>
<thead>
<tr>
<th>Item</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Triaxial Cell</td>
<td>Clockhouse Engineering Ltd.</td>
</tr>
<tr>
<td>Air Reservoirs</td>
<td>General Supply and Equipment Co.</td>
</tr>
<tr>
<td>Solenoid Valves</td>
<td>Catalog No. 8300A9, Form &quot;I&quot;, Automatic Switch Co., Florham Park, New Jersey.</td>
</tr>
<tr>
<td>Air Regulators</td>
<td>Model 10, Catalog No. 10163, Kendall, Stratos Division, Industrial Products Branch, Fairchild Stratos Corporation, West Babylon, New York.</td>
</tr>
<tr>
<td>Air Pressure Gages</td>
<td>Robertshaw Accragage, T21-367A-41/2&quot; 0-100 PSI 1/2&quot; NPT Back Connection, Fulton Sylphon Division, Robertshaw Controls Company, Knoxville, Tenn.</td>
</tr>
<tr>
<td>Component</td>
<td>Description</td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Ball Bushing of the Pressure Cylinder</td>
<td>Type XA-61014, Super Precision Ball Bushing, Thomson Industries, Inc. Manhasset, Long Island, New York.</td>
</tr>
<tr>
<td>Bellofram of the Pressure Cylinder</td>
<td>Part Identification 3-300-237-DCJ, Bellofram Corporation, Burlington, Massachusetts.</td>
</tr>
<tr>
<td>Force Washer</td>
<td>Model WR7S-0.5C, Lockheed Electronics Company, Los Angeles, California.</td>
</tr>
<tr>
<td>Linear Motion Transducer</td>
<td>Position/Model 159, Standard Travel range: 1 1/2&quot;, Resistance: 1K, Wire type: Platinum, Bourns Inc., Instrument Division, Riverside, California.</td>
</tr>
<tr>
<td>Gage Pressure Transducer</td>
<td>Pressure/Model 304, Range 0-100-PSI. Resistance: 1K, Wire type: Platinum Alloy, Bourns Inc., Instrument Division, Riverside, California.</td>
</tr>
<tr>
<td>Toggle Valve</td>
<td>Part No. 1GM4-S4-A, Whitey Research Tool Co., Oakland, California.</td>
</tr>
<tr>
<td>Main Air Pressure inlet valve</td>
<td>Part No. 600-3/8 QC-200-DESO, Swagelok, Crawford Fitting Company, Cleveland, Ohio.</td>
</tr>
<tr>
<td>Tube Fittings</td>
<td>Swagelok, Crawford Fitting Company, Cleveland, Ohio.</td>
</tr>
</tbody>
</table>
APPENDIX II. BIBLIOGRAPHY.

1. Department of the Army, Corps of Engineers, Sacramento District, "Accelerated Traffic Test at Stockton Airfield, Stockton, California, (Stockton Test No. 2)", May, 1948.


11. Hampton, D., and Yoder, E. J., "The Effect of Rate of Strain on Soil Strength", Purdue University Engineering Extension Department, Extension Series 95, 1958, pp. 116-129.


