SOIL BEHAVIOUR UNDER REPEATED VERTICAL AND HORIZONTAL STRESSES

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BY

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SCOPE AND CONTENTS

The purpose of this research is to simulate the state of stress on soil element in the field under the action of moving wheel loads. The behaviour of an over-consolidated soil subjected to the action of repeated vertical stresses with concurrent repeated horizontal stresses (cell pressure) is compared to the behaviour of soil under the action of repeated vertical stresses with constant horizontal stress. Attention is given to the axial strains and pore water pressures generated under different loading conditions.

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CHAPTER (I)

INTRODUCTION

The strength and deformation characteristics of naturally deposited soils and mechanically compacted soils subjected to gradually increasing applied loads have been studied intensively for more than four decades. Considerable progress has been made in evaluating the factors affecting these characteristics.

During the last two decades, studying the effects of repeated stresses on soils was one of the most important subjects in soil researches.

The importance of repeated loadings was realized when it was noticed that the repeated applications of wheel loads moving over highway and airfield pavements often affects the strength and deformation characteristics of the underlying soils in a detrimental manner. Much of the research on repeated loadings was carried out on compacted highway subgrade materials. An important concept was introduced; there exists a critical repeated vertical stress level below which the soil behaves predominantly elastic and above which the soil behaves predominantly plastic and would fail (Sangrey, 1969). The critical stress level was found to be lower than the maximum static load which caused shear failure of the soil. The value of that critical stress level varies between $0.37\sigma_s$ (J.R. Greenwood, 1970) and $0.5\sigma_s$ (Sangrey, 1969), where σ_s is the maximum compressive strength of the soil determined in standard undrained compression test. The value of the critical stress level is highly dependent on the type of soil and its properties.

Beside moving wheel loads on highways and airfields, there are other practical applications of repeated loadings such as: variations of water level due to tide, wave action against water front structures, wind action on a structure, moving loads across a factory floor or over a support of a bridge, earthquake effects on soils, etc.

In most of the tests performed in previous research, the soils were subjected to repeated vertical stress and constant horizontal stress. Little attention was given to the effect of varying the horizontal stress as well as the vertical stress even though the soil in the field is subjected to variations in both vertical and horizontal stresses due to the application of vertical loadings.

An element of soil under the action of a moving wheel load, is subjected to variation in vertical stresses, horizontal stresses and shear stresses. None of the various testing techniques presently available is capable of reproducing these stresses completely and there would appear to be two main problems to be solved before this is possible. Firstly, there is a practical difficulty in applying both normal and shear stresses directly to a sample simultaneously. Secondly, the difficulty in applying the tensile stresses in conjunction with the other stress variations.

In this research an attempt was made to simulate as closely as possible the stresses induced in the field under the application of moving wheel loads. The changes of vertical and horizontal stresses were reproduced in triaxial tests by pulsing the cell pressure and the deviator stress. The shear stresses were not studied because the triaxial test cannot reproduce shear stresses. Two types of tests were conducted for this purpose. In the first type, the soil was subjected to repeated vertical stress and constant horizontal stress, in the second type, the soil was subjected to repeated vertical stress and concurrent repeated horizontal stress. In both types of tests, the magnitude of the applied repeated vertical stress is the same.

Undisturbed samples of silty clay taken at a depth of 20 to 25 feet from a pumping station plant site, Welland, Ontario, were used for the testing program.

All testing was carried out on a triaxial testing machine, which is modified for repeated loadings. The duration of loading was 45 seconds and the interval between load applications was 15 seconds, giving a total time of 60 seconds for the load cycle.

Test results indicated that samples subjected to repeated vertical and repeated horizontal stresses failed under lower effective vertical stresses and lower strains than samples subjected to repeated vertical stress and constant horizontal stress, although the magnitude of the applied repeated vertical stresses was the same for the two tests.

CHAPTER (II)

LITERATURE REVIEW

In recent years, considerable attention has been given to soil behaviour under repeated stress conditions. Such studies are important in connection with highway pavement design, airport runways, structures subjected to wind loading, construction in areas within earthquake zones, etc.

The effects of repeated loadings on soil behaviour were first studied by Kersten (1943) who reported the results of both repeated and static laboratory plate bearing tests, on two compacted soils. Kersten's data showed that, for a given level of vertical stress, the initial penetration for the first cycle of the repeated loading test was essentially the same as the corresponding penetration obtained for static test. However, subsequent cycles of repeated loading produced increasingly larger penetrations which he stated exceeded those obtained for the static test at all corresponding levels of applied repeated vertical stresses. The magnitude of these levels was not clearly stated by Kersten.

The effects of high and low frequency loadings were studied by Tschebotarioff and McAlphin (1947). They used controlled strain and stress plunger type loading devices. Samples of sands, clays and sand-clay mixtures under all saturation conditions produced greater deformation when subjected to many thousands of repetitions of high and low frequency loadings than samples subjected to static loadings of equivalent magnitude.

A series of repeated triaxial tests has been conducted by Buchanan and Khuri (1954). Two groups of tests were conducted on lean clay soils. The first group of samples was subjected to a repeated vertical stress and a constant horizontal stress. The second group was subjected to a repeated vertical stress and a concurrent repeated horizontal stress. The results indicated that any repeated loading that exceeded the "elastic limit" caused large displacements. The plastic displacements increased with the number of repetitions, whereas, the elastic displacements remained fairly constant. Both elastic and plastic displacements increased with larger magnitudes of applied vertical stress. However, for levels of repeated vertical stress below the soils "elastic limit", no plastic displacements developed.

Following these studies, extensive laboratory investigations were conducted by Seed and Chan (1955) in which compacted soils were subjected to repeated applications of vertical stress in a triaxial cell. The horizontal stress remained constant. Test results indicated that the displacements for specimens of silty clay, subjected to repeated vertical stress applications, were considerably greater than those for similar specimens subjected to a sustained vertical stress of the same magnitude. They also found that partially saturated soil specimens may fail suddenly after having withstood a number of repeated vertical stress applications of the same magnitude. It is possible that this breakdown is due to the generation of pore water pressures associated with the soil structure collapse.

An apparatus was developed by Seed and Fead (1959) to study the behaviour of soil under repeated vertical loadings. Vertical loadings were applied to a compacted soil sample in a triaxial cell by a piston attached to a loading yoke. The load was applied to the yoke by an air pressure system, the flow of which was controlled by a solenoid valve. No drainage was allowed during the tests. In this apparatus, the duration of load was 0.1 second which simulates a wheel load moving at 30 m.p.h. This apparatus was designed to study the effect of vertical repeated loads and to study the comparative effects of different intensities of deviator stress or variations in frequency of stress applications.

The change in stress on an element of soil in the ground due to a moving wheel load as stated by Seed and Fead (1959) can be represented by the wave shape in Figure 1. The major disadvantage of this apparatus was that it did not represent this wave, but it used an idealized form of a square wave, Figure 1. Results indicated an increase in the soil displacements under a large number of repeated vertical stress applications.

The apparatus was further modified to apply both repeated vertical stress and a repeated horizontal stress concurrently. The repeated

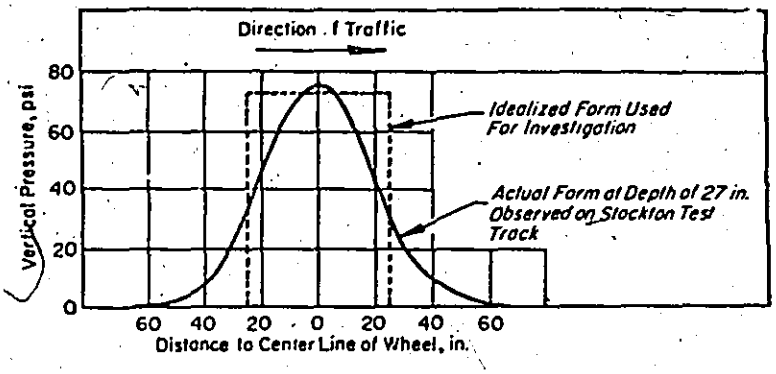
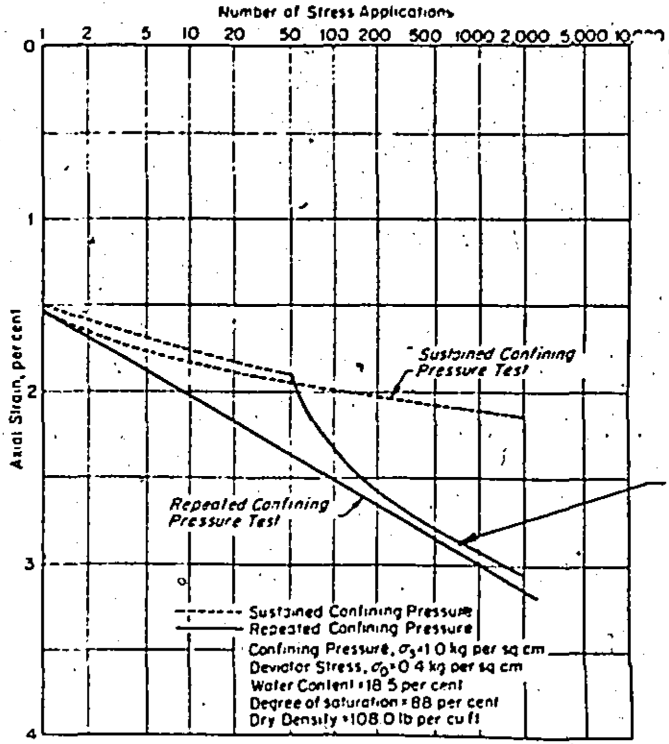


FIG. (1)' CHANGES IN VERTICAL STRESS ON SOIL ELEMENT DUE TO MOVING LOAD

After Seed and Fead, 1959

horizontal stress was applied to the triaxial cell by compressed air through a second solenoid-operated air control valve. In this way, it was possible to compare the displacements obtained for the same value of deviator stress, first when only the vertical stress was applied and second, when the vertical and horizontal stresses were applied. An important consideration in this type of test is the relative rates of increase of the vertical stress and the horizontal stress. These rates depend primarily on the response of the air control valves which were used for two separate purposes, applying the load to the yoke and increasing the chamber pressure. It is a requirement to keep the ratio between the vertical and horizontal stresses constant and, if the response of the control valves is at different rates, so that the deviator stress is built up more rapidly than the confining pressure, then the ratio of the major to the minor principal stresses will be greater than that which will occur in a practical situation, and larger deformation will occur. There was great difficulty with this aspect of the apparatus and it was not possible to keep this ratio constant. The test results indicated that for a procedure using both repeated vertical stress and repeated horizontal stress somewhat larger displacements resulted than when using repeated vertical stress while keeping the horizontal stress constant - even though the deviator stress applications in the two types of tests were identical. These tests were conducted on silty clay with saturation of 95 per cent. Figure 2, from this work shows these results.



Changes from Sustained to Repeated Confining Pressure

FIG. (2) COMPARISON OF SOIL DEFORMATIONS IN SUSTAINED AND REPEATED CONFINING PRESSURE TESTS

After Seed and Fead, 1959

Further research using only repeated vertical stress with the horizontal stress constant was conducted by Seed and Chan (1961) to study the effect of loading duration. The tests were done on both clay and sandy soils. They concluded that the effect of duration of stress application on the displacements varies widely depending on the interval between stress applications. For silty sand, increased durations of stress applications resulted in an increased displacement. For compacted clays, displacements were influenced by a variety of phenomena, which included creep effects, thixotropy, stiffening due to repeated stress applications, and probably, loss of resistance due to separation of clay particles during unloaded periods.

In 1962, Larew and Leonards developed the concept of critical stress level for soils subjected to repeated loading. Depending on the test conditions employed, the following criterion of failure for compacted fine grained soils, acted on by repeated loadings of constant magnitude, was established. A critical level of repeated deviator stress exists at which the slope of the curve for displacements vs. number of repetitions is constant after the first few load applications. For levels of deviator stress greater than this critical level, the displacements increase until failure occurs either by sliding along a shear plane or by excessive bulging. For levels of deviator stress less than this critical level, the displacements occurring approach a horizontal asymptote.

A special apparatus was constructed by G. D. Grainger and N. W. Lister (1962) to study the effect of both repeated deviator and repeated horizontal stresses on soils. This apparatus was bulky and complicated as each system needed a controlling component, and there was a difficulty in measuring the vertical loads to compute the deviator stress. Grainger and Lister ran preliminary tests to check the operation of the apparatus and to measure the elastic modulus E of the soil. Samples of London clay were subjected to a deviator stress of 3.9 lb./sq.inch (1 psi = 0.0703 kg/cm^2) and a horizontal stress of 2.0 lb./sq.inch; a pulse time of 0.4 seconds with a cycle time of 4.0 seconds were used. Figure 3,shows the changes in the elastic modulus E of the sample and Figure 4,shows the changes in the permanent displacements occurring during the test. It was realized that considerable stiffening of the sample occurred, so that after 3,000,000 load repetitions the modulus E was 3 to 4 times that at the start of the test.

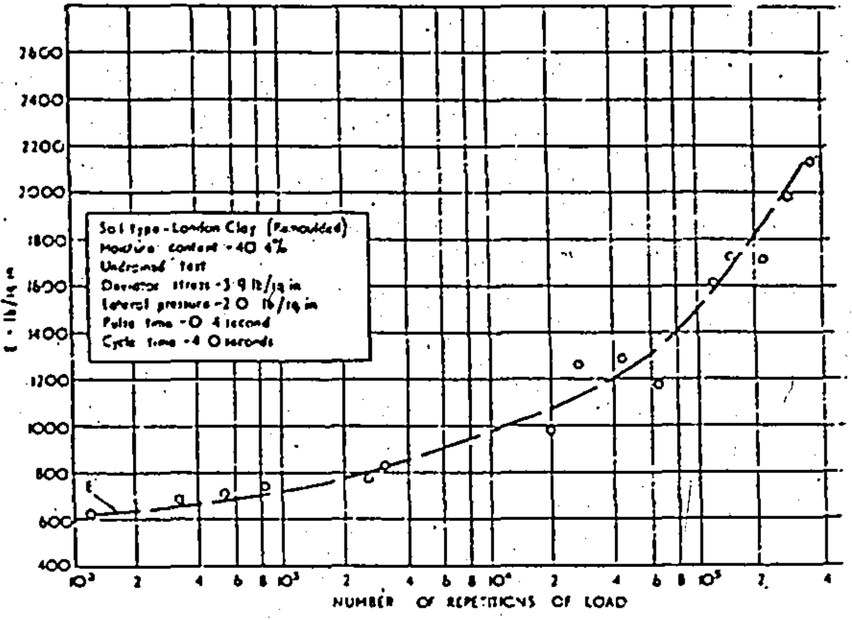


FIG. (3). CHANGES IN ELASTIC MODULUS, E, OF REMOULDED LONDON CLAY WITH REPEATED LOAD

After Grainger & Lister, 1962

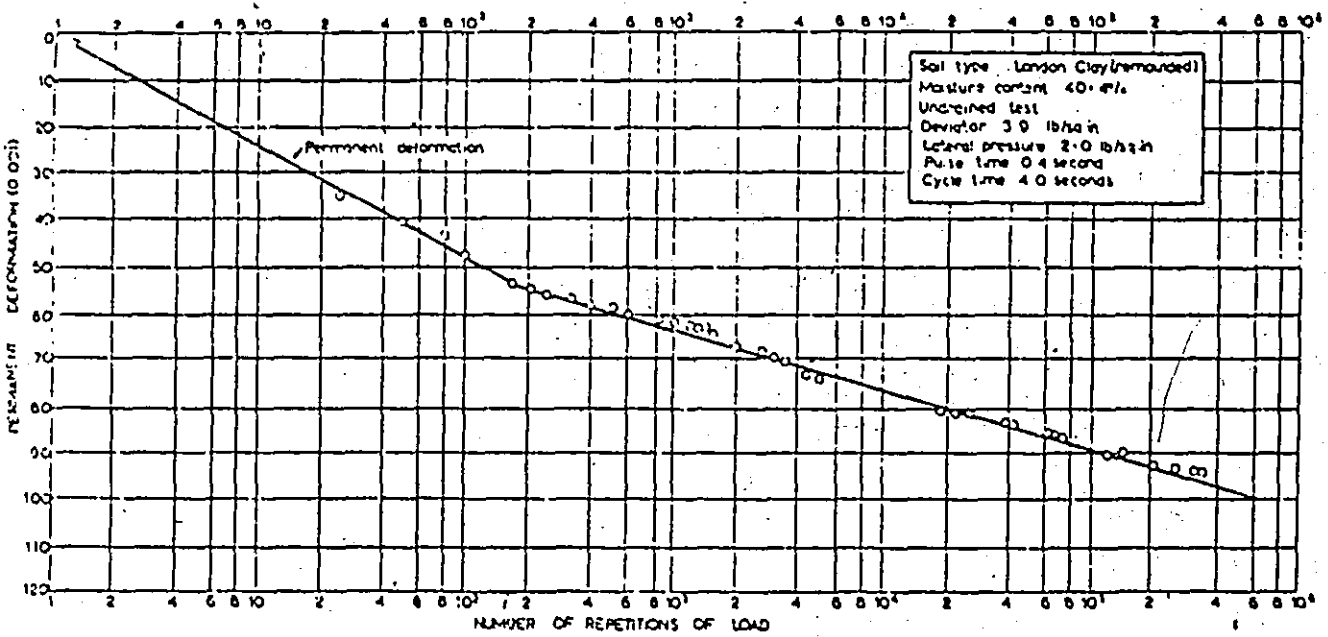


FIG. (4). CHANGES IN PERMANENT DEFORMATION OF REMOULDED LONDON CLAY DURING REPEATED LOADING TEST

After Grainger and Lister, 1962

Knight and Blight (1965) studied the effect of repeated vertical loadings on saturated normally consolidated and heavily overconsolidated soils. They concluded that for normally consolidated clays, there is a residual pore water pressure during periods of load removal, and there is a critical range of stress over which the effects of repeated loadings are significant.

For the purpose of investigating soil behaviour under earthquake loading conditions, Seed and Chan (1966) concluded that during earthquakes, the soil underlying building foundations and in earth embankments is subjected to a series of vibratory stress applications for a limited period of time. Records of ground motions during earthquakes indicate that during the main shock, the ground is subjected to a horizontal acceleration that may approach its peak intensity as many as 10 to 15 times in the period of approximately one-half minute. Including after shocks the total number of the larger acceleration pulses may thus be as great as 30 or 40. These pulses and the associated deformations that they may induce in soils will cause an increase in the soil stress and increase the tendency for shear deformations to occur. Although, the stress pulses induced by an earthquake will vary in magnitude, they can be presented, in effect, by a series of stress pulses of constant magnitude. To study the stability and deformations of soils during earthquakes requires an understanding of the deformation and strength characteristics under combined sustained and repeated stresses. Seed and Chan (1966) stated that for clay soils with high degrees of saturation, varying both the horizontal stress and the vertical stress concurrently will have negligible effects on soil strength.

Glynn, Kirwan and Wilson (1969) studied the behaviour of peat subjected to repeated loadings. Peat samples were tested in a controlled stress triaxial compression machine modified for repeated applications of deviator stress and confining pressure. This equipment was developed from the prototype constructed by Grainger and Lister (1962). Test results indicated that for low levels of applied deviator stresses the displacements are comparatively low, and for high levels of deviator stresses there is a significant increase in the peat displacements associated with a marked increase in pore water pressures, Figure 5.

Three sets of undrained repeated vertical loading tests on saturated clay were conducted by Sangrey, Henkel and Esrig (1969). In the first set, samples normally consolidated under an all around pressure were considered. In the second set, samples normally consolidated under anisotropic stress systems were studied, while in the third set, overconsolidated samples were used. The conclusion of that study was that, for anyparticular consolidation history, a critical level of repeated stress existed. Below that critical level a state of nonfailure

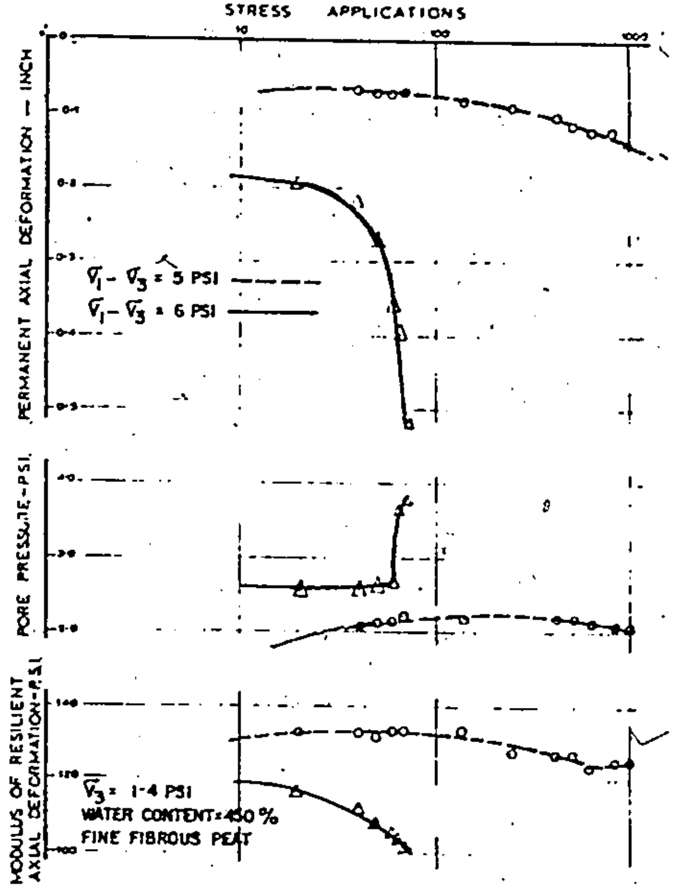


FIG. (5). TYPICAL TEST RESULTS

After Glynn, Kirwan
and Wilson, 1969

equilibrium was reached. Also, the relationship between the magnitude of the applied repeated stress and the increase of the pore water pressure was linear. Above the critical level of repeated stress failure occurred, and each application of loading produced cumulative increases in displacements. It was also observed that under nonfailure repeated loadings, the pore water pressure increased and at nonfailure equilibrium points the stress ratio was higher than in the single cycle test.

In 1970, J. R. Greenwood developed an apparatus to study the effect of repeated vertical stresses on normally consolidated saturated clay from Hamilton Bay. Laboratory prepared Kaolin samples were also used for comparison with the natural clay. A mechanical device was used to lower and raise the applied repeated vertical loads at durations and intervals of one minute. Pore water pressures were measured at the base of the cell using pressure transducers. Two types of tests were carried out: the first type was sustained loading (creep test); and the second type involved repeated vertical stress. In both types of tests, the horizontal stress was kept constant. In both types of tests, drainage was not allowed. A comparison was made between the two tests for different levels of applied vertical stresses. Greenwood concluded that there is an increase in both axial displacements and pore water pressures with time for normally consolidated clay subjected to repeated or sustained applications of deviator stress. Also, he predicted a critical repeated stress level of 0.37 σ_s (where σ_s is the maximum compressive strength of the soil resulting from triaxial compression undrained test) below which the soil behaves predominantly elastic, and above which the soil behaves predominantly plastic. Repeated loading at levels within the elastic region have no effect on the clay, and the displacements and pore water pressures depend only on the time under load. Repeated loading within the plastic region produced axial displacements and pore water pressures greater than those resulting from the sustained loadings of the same magnitude. Also, the critical stress level under repeated loading is lower than that under sustained loading.

In 1972, P. S. Pell and S. F. Brown made an extensive review of the state of knowledge at that time on characterisation of materials for flexible pavement design and discussed the various methods of laboratory tests available for this purpose.

Pell and Brown analyzed the in-situ stresses under wheel loads as follows:

When a rolling wheel load passes over a point in a road structure, the various layers are subjected to the stress variations shown in Figure 6. The main variation in fact is in the horizontal stress as shown in Figure 6, where tensile stress can develop at the bottom of stiff layers. Simulation of the in-situ stresses in the laboratory requires attention being given to stress history and condition of sample as well as to the stress pattern applied during a test. To

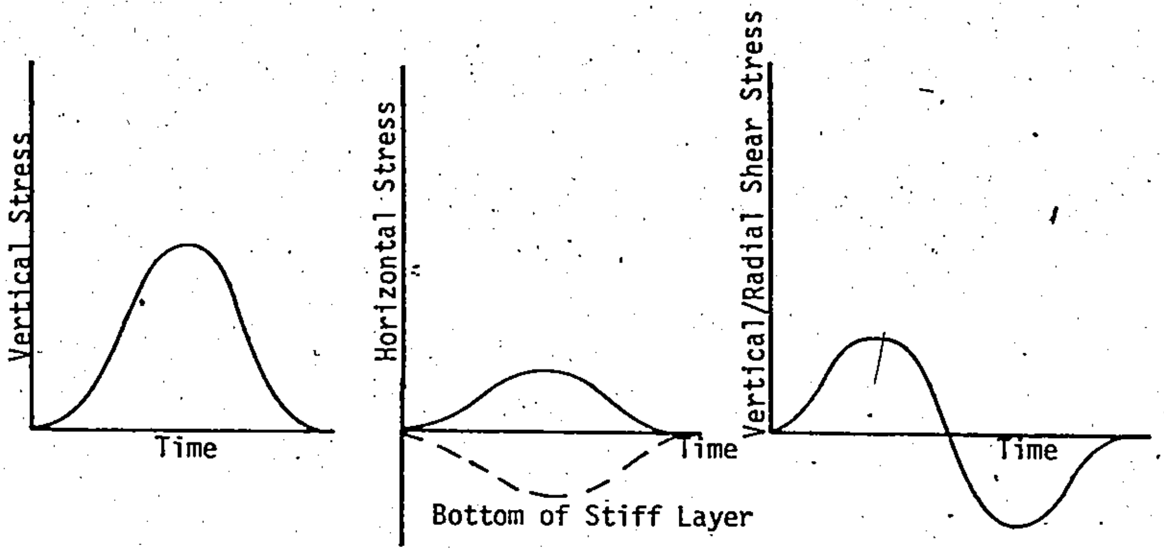
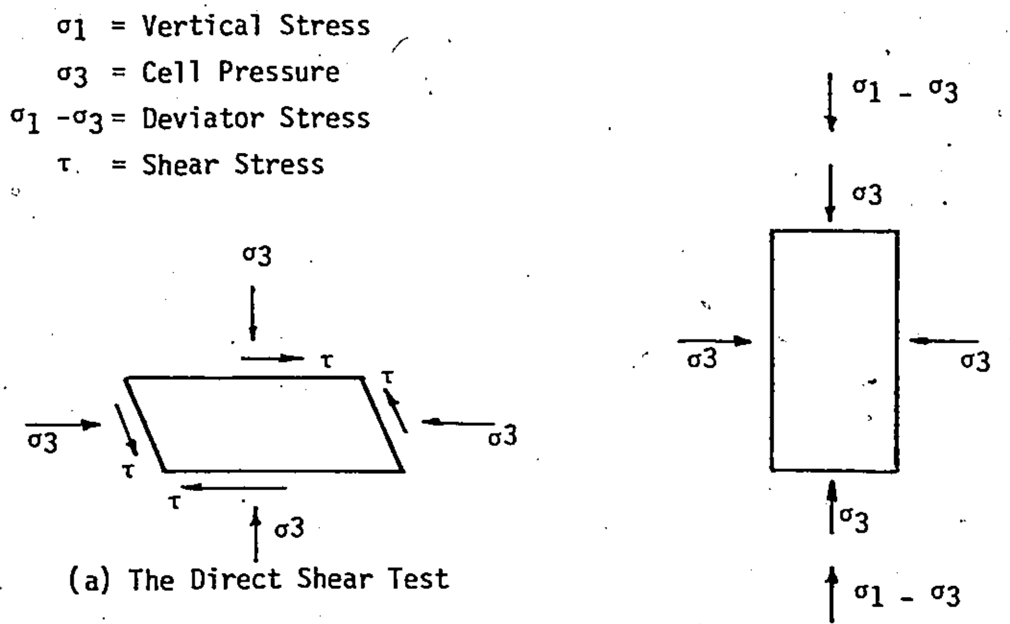


FIG. (6) . The Variation of Stresses on a Pavement Element Due to the Passage of a Rolling Wheel Load



(a) The Direct Shear Test

(b) The Triaxial Test

FIG. (7). THE REPEATED LOAD TRIAXIAL AND DIRECT SHEAR TEST represent the in-situ stresses in the laboratory, two main problems must be solved:

Firstly, there is a practical difficulty of applying both normal and shear stresses directly to a sample simultaneously. The repeated load triaxial test Figure 7a, is capable of pulsing both the normal stresses, but cannot reproduce the shear reversal shown on Figure 6 . Conversely, the direct shear apparatus Figure 7b, can apply shear stresses correctly, but has not so far been developed to the stage where the normal stress pattern can be applied. The second problem is that of applying the large tensile stresses, which occur near the bottom of stiff layers, in conjunction with the other stress variations.

From the review of the work carried out on repeated load triaxial testing in various laboratories in conjunction with in-situ stress investigations, Pell and Brown concluded that two factors are of particular interest when characterising soils and granular material for design purposes of pavements. Firstly, the resilient behaviour which may be simply stated as the relationship between applied stress and recoverable strain, and secondly the relationship between permanent strain and the number of load applications. Failure of materials usually depends on the second of these relations and though it is of obvious importance, complete failure of these materials is not usually a danger in pavement structures.

Resilient Behaviour

Resilient characteristics of pavement materials are normally specified in terms of a modulus of elasticity and Poisson's ratio, and that the modulus of elasticity is a function of both shear and normal stresses. For cohesive soils it is the shear stress which predominates while for granular materials the normal stress level largely defines the modulus.

Permanent Deformation

The relationship between permanent deformation and number of loading cycles for granular materials (from triaxial testing) is as shown in Figure 8a. The characteristic is a relatively sharp increase in permanent deformation during the early load applications followed by very little subsequent increase so that the material settles down to approximately elastic behaviour.

Figure 8b, shows typical relationships between permanent strain and number of stress applications for a saturated normally consolidated silty clay tested under repeated load triaxial conditions. The relationship differs from that for granular materials in that a definite failure point can be established when the rate of permanent deformation shows a sharp increase. The concept of "threshold stress" has been used to define the boundary between "stable behaviour" when no failure will occur and "unstable behaviour" when failure will eventually occur provided sufficient applications of load are applied.

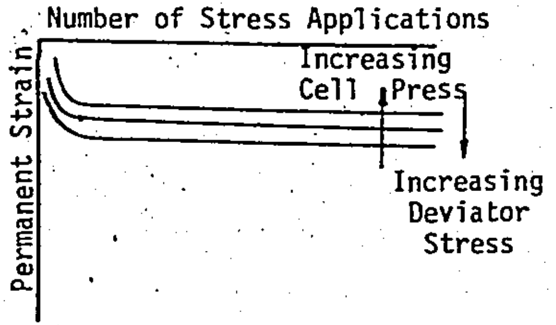


FIG. (8a). RELATIONSHIP BETWEEN PERMANENT STRAIN AND NUMBER OF STRESS APPLICATIONS FOR NON-COHESIVE SOILS

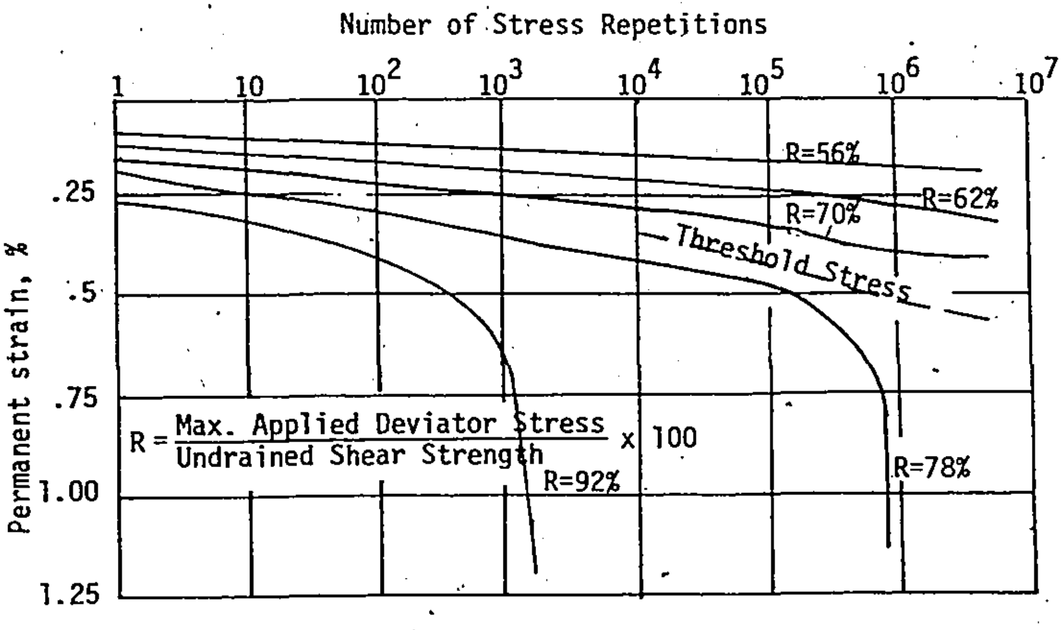


FIG. (8b). RELATIONSHIP BETWEEN PERMANENT STRAIN AND NUMBER OF STRESS APPLICATIONS FOR A NORMALLY CONSOLIDATED SATURATED SILTY CLAY

Both the resilient and plastic strain developed in cohesive soils under repeated loading depend on the stress history, density and moisture content of the soil.

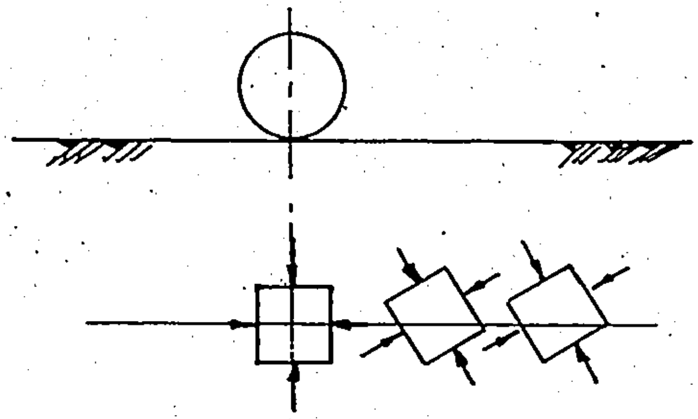
CHAPTER (III)

APPARATUS

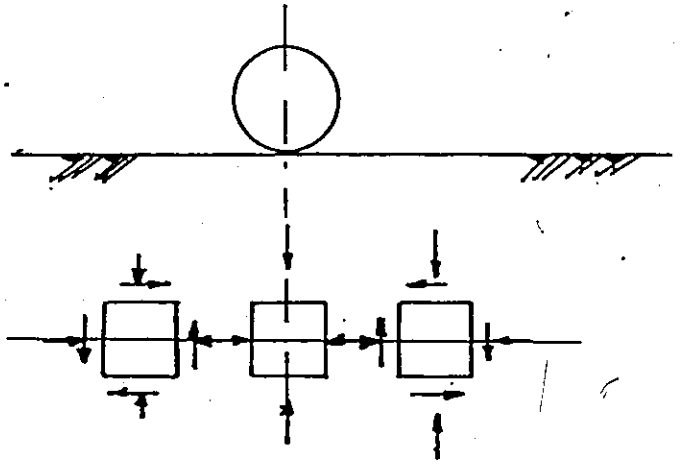
To simulate the stresses induced in the field under a rolling wheel load Figure 6, Chapter 2, an apparatus is required to apply both normal and shear stresses to the sample simultaneously. With the present laboratory techniques (direct shear test or triaxial test) it is difficult to reproduce the in-situ stresses.

For the laboratory part of this research, repeated loading triaxial apparatus was used in which the vertical and horizontal stresses were simulated. The shear stresses were not reproduced for the difficulty in applying shear stress by the triaxial apparatus.

Since the triaxial test cannot apply shear stresses directly to the sample the equivalent in-situ soil element must be subjected to normal stresses only and hence "rotates" as the wheel passes, Figure 9a. Since the deformation of the specimen is measured in the direction of the applied stress, the permanent deformation measured will not represent the vertical (or horizontal) permanent deformation of the soil, but will in fact over-estimate it. The soil sample should ideally be made analogous to the in-situ element shown in Figure 9b, which does not "rotate". In this case there will be a shear stress applied which reverses when the load moves over it and only when it is under the centre of the load does the stress conditions become the same as those in the triaxial test.



(a) Principal Stress - Element Rotates



(b) No Rotation - Shear Stress Reversal

FIG. (9). IN-SITU STRESSES BENEATH A ROLLING WHEEL

Design Criterion

The requirements of the constructed apparatus were to apply the repeated vertical stress without impact effects and to apply the repeated horizontal stress in phase with the repeated vertical stress. The apparatus consisted of three main parts:

1. Triaxial testing machine
2. Repeated vertical stress system
3. Repeated horizontal stress system

The apparatus is shown in Figure 10.

1. Triaxial Testing Machine

A Wykeham and Farrence triaxial compression testing machine was used for all tests because of its wide spread availability, simplicity and reliability. In all the tests, the back pressure and cell pressures were applied to the samples by means of a mercury pot and a spring compensating system.

Pressure Transducers:

Pore water pressures and cell pressures were measured using Statham Instruments Inc. Model PA-208-TC-25-350 pressure transducers. A typical transducer housing is shown in Figure 11. The excitation voltages were provided to the transducers from D. C. bridge amplifiers; the model

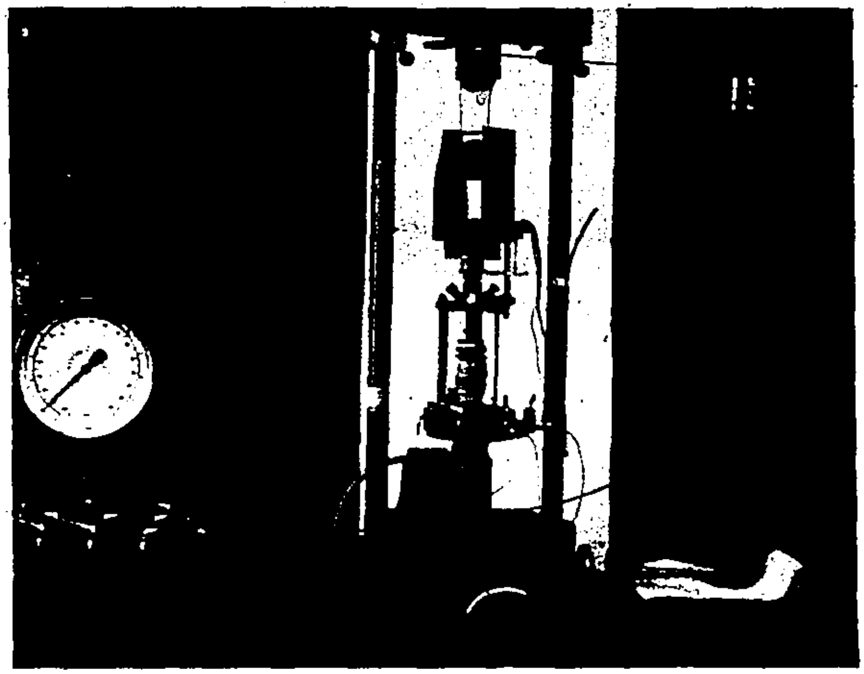


FIG. (10). PHOTOGRAPH OF THE REPEATED LOADING APPARATUS

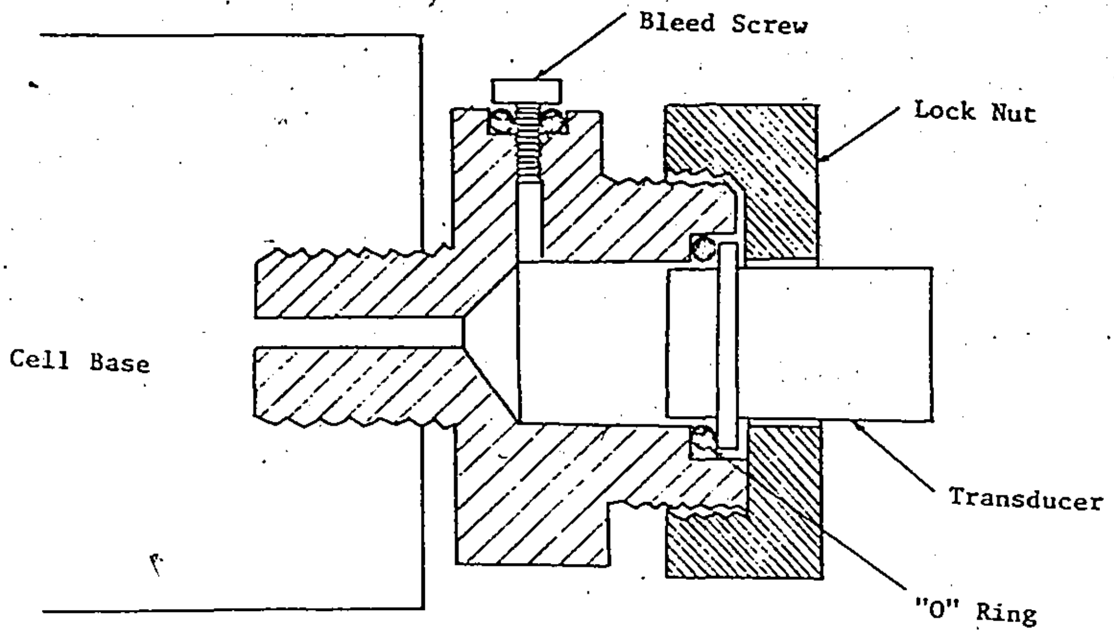


FIG. (11). TRANSDUCER HOUSING

number was F.E. 392-BBS built by Fylde Electronic Laboratories, England. The power supply was allowed to stabilize for one day before use. After a stabilizing time, the fluctuation in the excitation voltage observed were in the order of 0.01% of the correct value and were therefore considered insignificant. The signals from the transducers were passed through the bridge amplifiers to a Digital Voltmeter and were recorded on a Digital Recorder, both manufactured by Hewlett-Packard. Direct readings of the pressures in lb/sq inch were obtained by selecting the appropriate value of the excitation voltage for each transducer.

Using pressure transducers has the following advantages over null indicators: decreased possibility of error in the measured pressures; little time delay in measuring the pressures;and the pore water pressures can be recorded at any time during the test.

2. Repeated Vertical Loading System

The repeated vertical loads to be applied to the samples were lowered and raised using a mechanical device Figure 12 , driven by an electric motor through a "Zero-Max" variable speed gear box; this device had been used by J. R. Greenwood (1970). The mechanical device consists of a hanger and cable connected to a rotating cam wheel driven by the motor. The motor was adequate to lower and lift the loads without any reduction in speed. The impulsive force resulting from lowering the loads was very small and its effect was considered negligible.

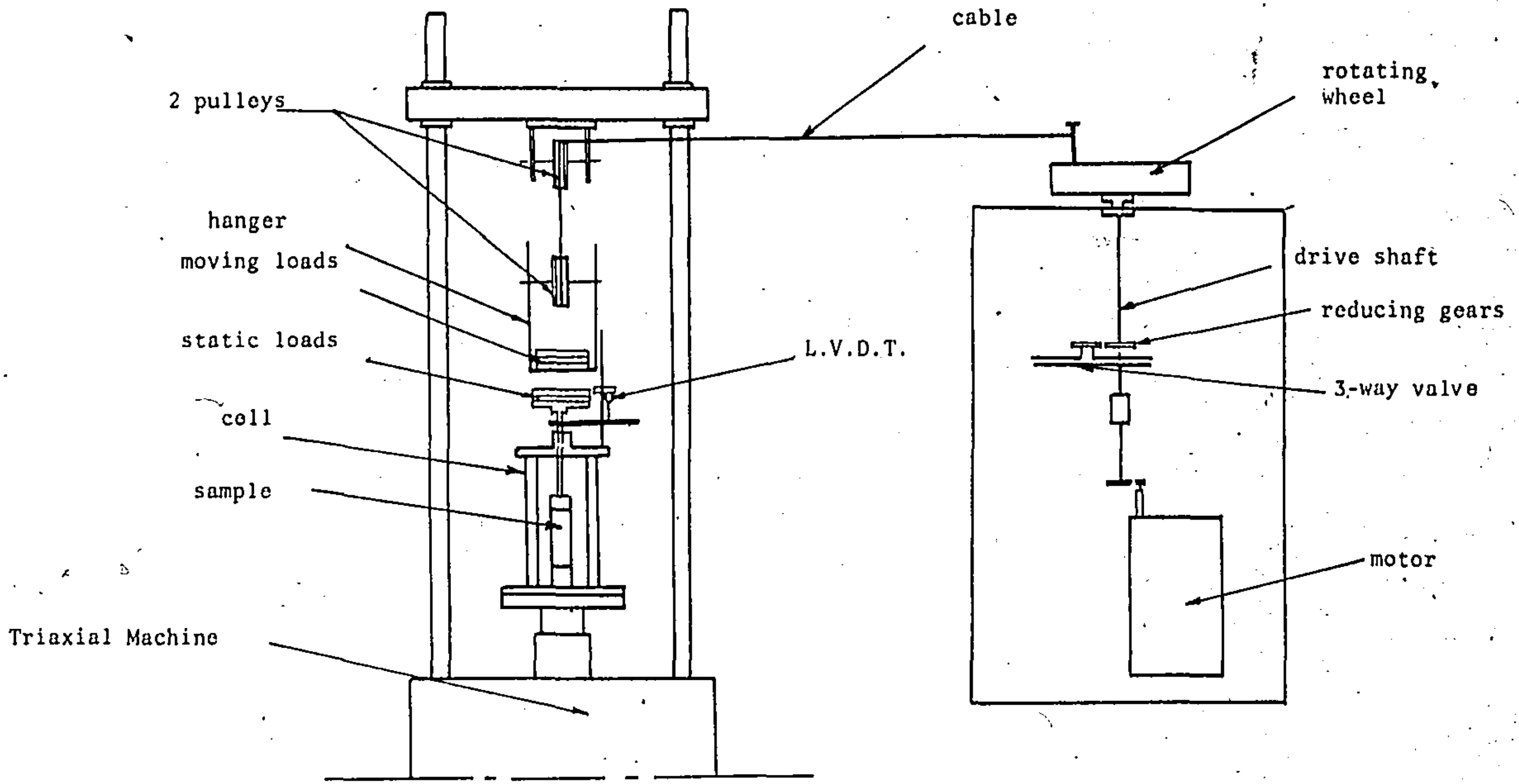


FIG. (12). REPEATED LOADING APPARATUS

3. Repeated Horizontal Stress System

The repeated horizontal stress cycles were applied using a three-way valve Figure 13 , connected to the mercury pot system. The three-way valve was connected through reducing gears on the motor shaft. The high pressure (required repeated horizontal stress) was connected to one of the side branches of the valve, while the low pressure (consolidation pressure) was connected to the other side branch. When the valve rotated the high and low pressures were repeatedly applied to the sample through the middle branch connected to the cell base. Connecting the valve in unit with the motor shaft had the advantage of applying the repeated horizontal stress with the same speed as the applied repeated vertical stress.

Synchronization

The three-way valve is designed to give a cycle of 75 per cent high pressure and 25 per cent low pressure Figure 14 . The low pressure is the same as the consolidation pressure. The same cycle for the repeated vertical stress can be achieved by adjusting the height of the base of the triaxial cell. For all tests the total time of the load cycle was 60 seconds. The duration of load applications was 45 seconds (time for load on), and the interval between load applications was 15 seconds (time for load off).

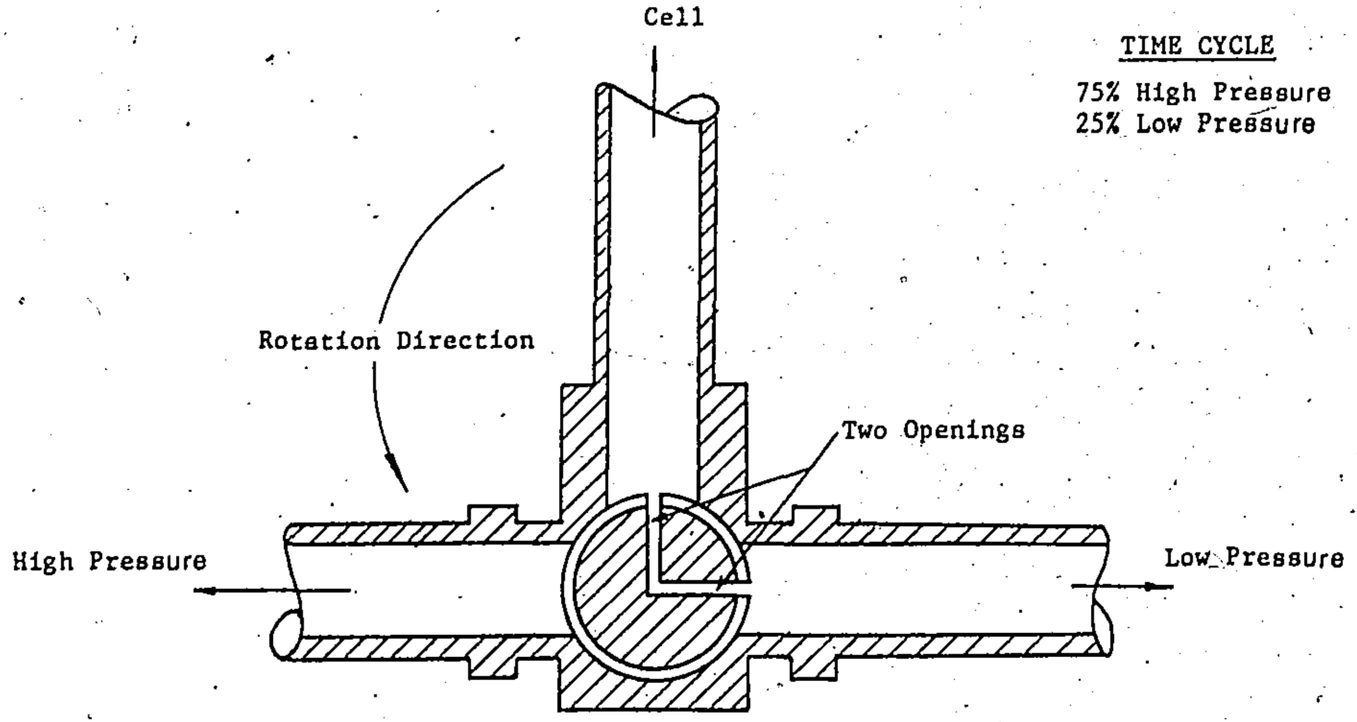
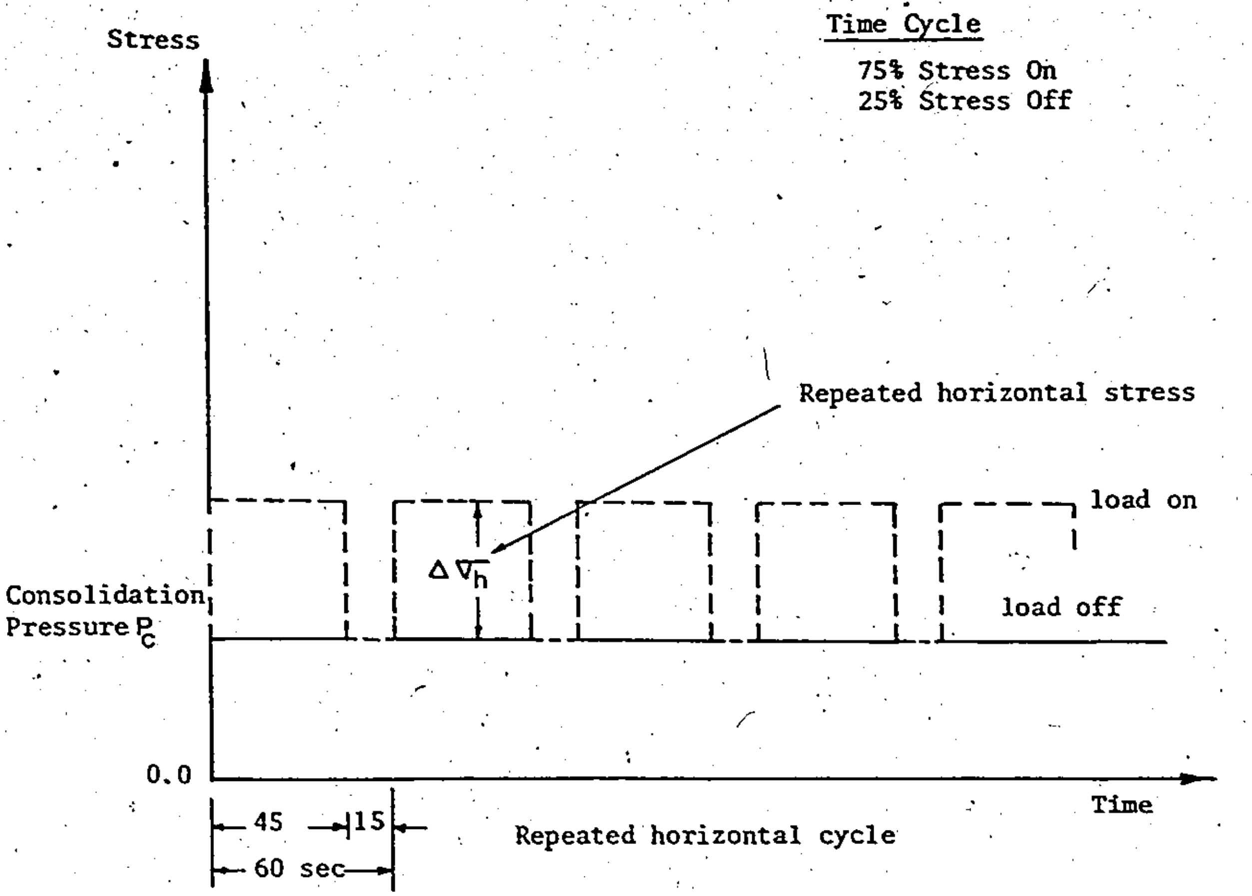
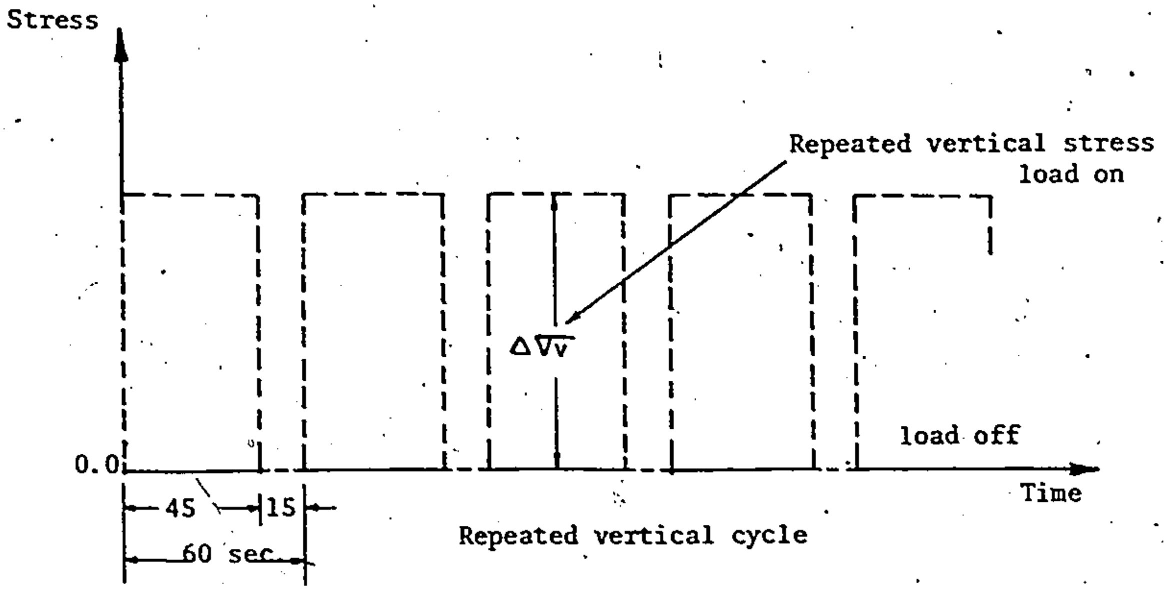


FIG. (13). THREE-WAY VALVE



Repeated horizontal cycle



Repeated vertical cycle

FIG. (14). REPEATED STRESS CYCLES
(Schematic Representation)

Starting Conditions

To apply the repeated vertical stress and the repeated horizontal stress concurrently, the speed of the motor shaft was set to one cycle per minute. Then the base of the cell was adjusted to give the required shape of cycle for the vertical load, i.e., by altering the length of the cable to the hanger. Finally, the gears connected to the three-way valve were adjusted to apply the pressure concurrent with the vertical load.

Axial Displacement Measurements

The axial displacements of the samples were measured using Hewlett Packard Model Number 24DCDT-05 Linear Variable Differential Transducers (L.V.D.T.). The transducers were excited by a power supply. Signals from the L.V.D.T. were recorded on the same Digital Voltmeter used for the pressure transducers. Direct readings in inches can be obtained by selecting the appropriate excitation voltage. The vertical displacements of the sample were measured by connecting the L.V.D.T. to the ram of the cell. In these tests the horizontal deformations of the samples were not measured.

CHAPTER (IV)

SAMPLE PREPARATION AND TEST PROCEDURE

Sample Preparation

The samples used in the research were prepared from large blocks of Welland clay dominated near Welland, Ontario, at a depth of 20 to 25 feet. The blocks of clay were wrapped in polythene and waxed. These blocks were kept in the humid room to maintain their natural water content. The properties of this clay are listed in Table 1. These blocks were cut into smaller blocks and each block was wrapped, waxed and kept in the humid room. When a sample was required, the protective wrappings were removed and the sample was trimmed on a soil lathe to a cylinder 1.4 inches in diameterand cut to a height of 2.8 inches. This process was done in the humid room to reduce any changes in the moisture content of the samples. Also, care was taken in handling and trimming to reduce any sample disturbance.

TABLE 1

PROPERTIES OF WELLAND CLAY

Silty Clay Soil Taken at a Depth of 20 to 25 feet from a Pumping Station Plant Site, Welland, Ontario

	L.L.	P.L.	P.I.
Atterberg Limits	36.9	21	15.9
Natural Water Content	29%		
Specific Gravity	Approx. 2.7		
Sensitivity	2.0 to 4.0		

Test Procedure

(a) Sample Assembly

The assembly procedure suggested by Bishop and Henkel (1957) was followed in setting up the samples. The diameter and length of the sample was checked, then the sample was placed on the de-aired pedestal of the triaxial cell with a saturated porous stone at the bottom and a saturated filter paper placed around the sample. A perspex top cap was positioned on top of the sample and a rubber membrane was placed around and secured with O-rings as shown in Figure 15. This assembly was done with the cell base submerged in water. The upper part of the cell was carefully placed over the base with the ram lifted to the upper limit of its travel. The cell was filled with de-aired water and the ram positioned in contact with the centre of the top cap. The cell was subjected to a pressure of 10 lb/sq. inch for 3 to 4 hours to give a chance of any air trapped between the sample and the membrane to pass to the cell water. The cell was then drained and a layer of silicone grease was smeared over the membrane. A second membrane was then applied and secured with O-rings. The transducers were set to zero. The cell was refilled with de-aired water and again the sample was allowed to stand under a small pressure to give any air trapped between the two membranes a chance to pass through the outer membrane into the cell water. The membranes used throughout the tests were Trojan prophylactics of 0.002 inch thickness. Tests by Lopes (1970) indicated that over time periods greater than one day, one membrane is permeable to water.

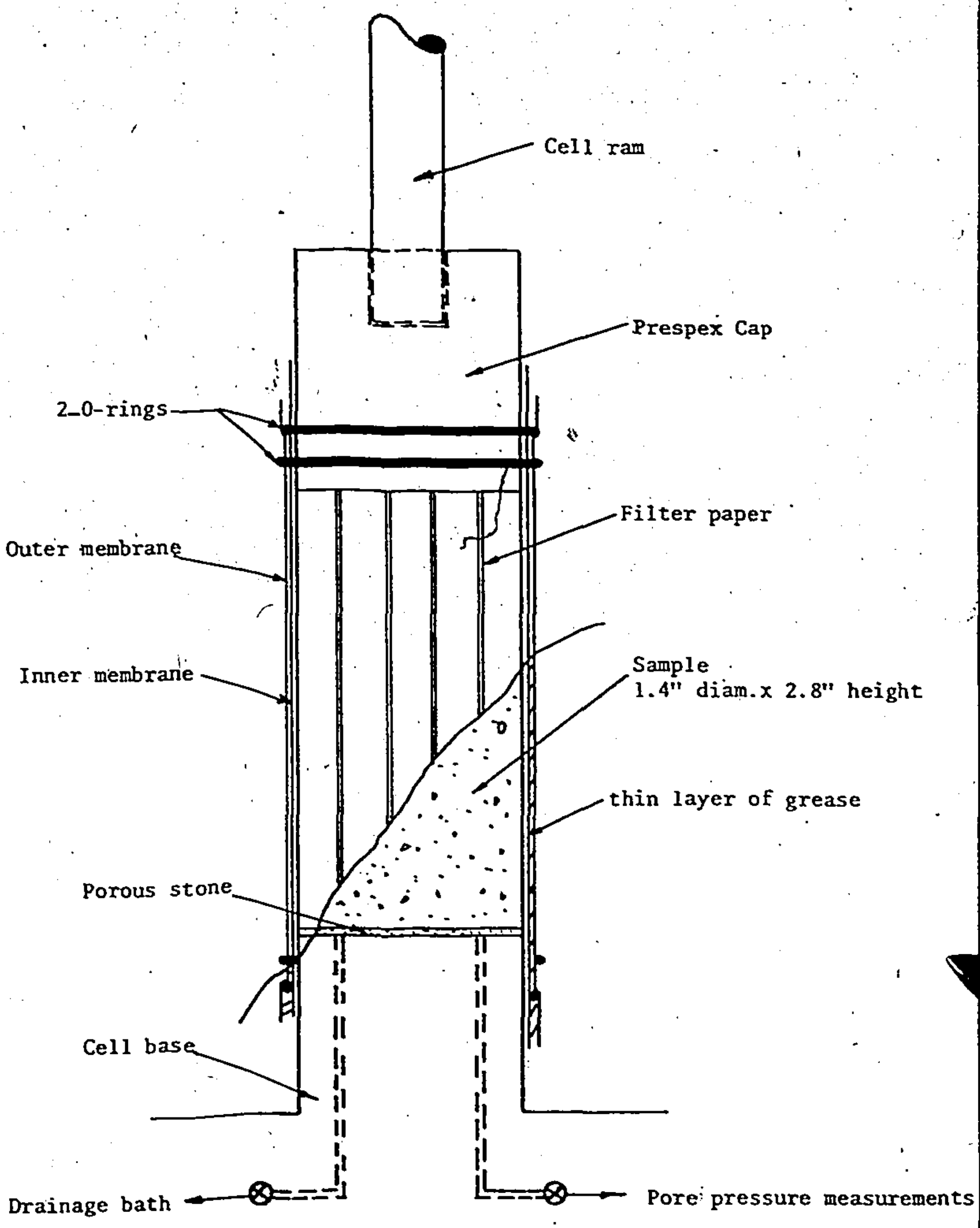


FIG. (15). SAMPLE READY FOR TESTING

However, the use of two membranes separated by a coating of silicone grease has been shown to virtually eliminate the passage of water for tests up to one week.

(b) Consolidation

Soil samples, which had a preconsolidation vertical stress of 14 lb/sq. inch were isotropically consolidated at a cell pressure of 13.3 lb/sq. inch, against a back pressure of 10.0 lb/sq inch, giving an effective consolidation pressure of 3.3 lb/sq inch. The back pressure was used to try to obtain complete saturation of the samples. A value of B = 1.0 was obtained from a B-test, indicating that the soil was fully saturated. A dead weight was applied to counterbalance the upward force on the ram resulting from the cell pressure. After applying the cell and back pressures, the drainage valve was opened and consolidation was completed after 5 days. The use of the filter paper speeded the consolidation process by allowing radial drainage.

(c) Compressive Strength Tests

Compressive strength tests were run to obtain the strength of the soil under gradually increased loadings as this data was required for estimating the values of the repeated stresses. The method described by Bishop and Henkel (1957) was applied to obtain the strength of the soil from the standard consolidated undrained test. The rate of testing was set to 2.33×10^{-4} in/min. based on a sample strain of 2 per cent.

This strain was considered to cover the range of strain conditions in the repeated loading tests. Pore water pressures were measured by the transducer, the axial load was measured by the proving ring, and the axial displacements were measured by the dial gauge. At the end of the test the sample was removed from the cell and weighed for moisture content determination.

(d) Repeated Loading Tests

Two types of repeated loading tests were conducted. The first type involved repeated vertical stress with the horizontal stress (cell pressure) kept constant. The second type was repeated vertical stress with concurrent repeated horizontal stress . The description of each type of tests is as follows:

(i) Repeated Vertical Stresses with the Horizontal Stresses Constant .

In these tests, the repeated vertical loadings were applied to the sample directly through the cell's ram using the device described in Chapter (III) for vertical loading applications. The horizontal stress (confining pressure) was kept constant during the tests. The speed of the wheel was set to give 1 rev/min., and the height of the triaxial base was adjusted to give a duration time of 45 seconds and an interval time of 15 seconds. The load hanger was positioned so that the load would land in a central position on the load platform. The static loads, which were used to counteract the upward ram force during consolidation were maintained on the ram. The selected value of the repeated vertical stress was calculated as a proportion of the maximum compressive strength of the soil, as obtained from the standard consolidated undrained test. The tests were continued up to 1000 cycles of loadings or until failure occurred. Measurements of the pore water pressures and the axial displacements were recorded throughout the tests.

(ii) Repeated Vertical Stresses with Concurrent Repeated Horizontal Stresses

In these tests, the repeated vertical stresses were applied as described before. The repeated horizontal stresses were applied using the three-way valve system described in Chapter (III). The tests were continued up to 1000 cycles or until failure occurred. Measurements of the pore water pressures, the axial displacements and the repeated horizontal stresses were recorded thoughout the tests.

For a group of samples, the above mentioned two types of repeated loading tests were performed in which the value of the repeated deviator stress was the same in both types of tests.

(e) Levels of Applied Repeated Stresses

Previous research on soil subjected to repeated vertical stresses, by Glynn, Kirwan and Wilson (1968), Sangrey (1969) and Greenwood (1970), indicated a critical level of repeated deviator stress below which the soil behaves predominantly elastic and above which the soil behaves predominantly plastic. The value of this critical level of stress varies between 0.37 σ_s (Greenwood) and 0.5 σ_s (Sangrey), were σ_s is the maximum compressive strength of the soil. This critical stress level is dependent on the type and properties of soil and on the test conditions.

The tests conducted in this research were divided into two stages based on the stress levels as follows:

(i) Subfailure Stage (Predominantly Elastic)

In this stage, the level of the deviator stress, i.e., the difference between the applied repeated vertical stress and repeated horizontal stress, was less than the assumed critical stress level. The value of the applied repeated vertical stress was 0.3 σ_s, where σ_s is the maximum compressive strength of the soil obtained from the standard consolidated undrained test. The value of the applied repeated horizontal stress was 0.15 σ_s, giving a ratio of the applied repeated horizontal stress to the applied repeated vertical stress as 0.5. This ratio will be termed K.

(ii) Failure Stage (Predominantly Plastic)

In this stage, the levels of both the applied repeated vertical and horizontal stresses were higher than the assumed critical stress level. The value of the applied repeated vertical stress was 0.6 σ_s, and the value of the applied repeated horizontal stress was 0.3 σ_s, giving a ratio of K = 0.5 between the applied repeated horizontal and vertical stresses.

CHAPTER (V)

EXPERIMENTAL RESULTS AND DISCUSSIONS

A - OUTLINE OF TESTS

A-1. Maximum Compressive Strength:

The compressive strength of the soil, based on the maximum deviator stress, was determined from the results of three standard triaxial consolidated undrained tests.

A-2. Repeated Loading Tests:

Sixteen repeated loading tests were carried out in four groups, based on the type and range of loading as follows:

First Group E_{1-4}:	Four samples; tested in the elastic range under the action of repeated vertical stresses and constant horizontal stress. (By elastic it is meant that the soil has essentially recoverable deformation.);
Second Group P_{5-8}:	Four samples; tested in the plastic range under the action of repeated vertical stresses and constant horizontal stress. (By plastic it is meant that the soil has essentialy non-recoverable deformation.);
Third Group E_{9-12}:	Four samples; tested in the elastic range under the action of repeated vertical stresses and concurrent repeated horizontal stresses (cell pressure).

Fourth Group P_{13-16}: Four samples; tested in the plastic range under the action of repeated vertical stresses and concurrent repeated horizontal stresses (cell pressure).

The results of each group of tests showed good agreement. In this thesis, results of one test from each group will be presented. The ranges of the results are shown on Figures 16 to 19 and the spread appears reasonable.

B - TEST RESULTS

B-1. Maximum Shear Strength of the Soil

In the standard triaxial consolidated undrained tests, the samples were isotropically consolidated under a cell pressure of 3.3 lb/sq. in. resulting in an estimated over-consolidation ratio of 4.00 (based on tests performed in Geotechnical Engineering 3A4). This consolidation ratio was selected, because most of the soils of Southern Ontario are glacial in origin and are slightly over-consolidated. The three samples were taken from the same block of soil. The natural moisture content of these samples before testing ranged between 28.5 per cent to 29 per cent. Results of these tests indicated that the maximum compressive strength of the soil under the consolidation conditions described, equals 9.25, 8.70 and 8.95 lb/sq. in. The average maximum compressive strength of the soil is 9.0 lb/sq. in., thus the maximum shear strength equals 4.5 lb/sq. in. The change in the final moisture content of the samples after testing was in the order of ± 0.2 per cent.

B-2. Repeated Loading Tests

For all types of tests, the samples were consolidated under a cell pressure of 3.3 lb/sq. in., with an estimated over-consolidation ratio of 4.0. The samples of each group of tests were taken from the same block of soil. The initial moisture content for all the samples tested was 29 per cent ± 0.5 per cent. All the samples were saturated and each sample was tested for saturation (B-test) before the loading test. A value of B = 1 was recorded for all the samples tested and indicated that the soil is saturated. After the loading tests, the moisture content of the soil had not changed significantly (± 0.5 per cent). The volume change for the soil during consolidation was not recorded.

Tests in the elastic range were carried out up to 1000 load repetitions. Tests in the plastic range were carried out until failure occurred. Table (2) shows the values of the applied repeated stresses for each type of test and loading stage.

TABLE (2)

VALUES OF REPEATED STRESSES FOR CONSOLIDATED UNDRAINED REPEATED LOADING TRIAXIAL TESTS

Stage of Loading	Repeated Vertical Stress With Constant Horizontal Stress (p.s.i.)	Repeated Vertical Stress With Repeated Horizontal Stress (p.s.i.)
Elastic Stage	Consolidation pressure $\sigma_c = 3.3$ Repeated vertical stress $\Delta\sigma_v = 2.7$ Repeated horizontal stress $\Delta\sigma_H = 0.0$ Total horizontal stress $\sigma_h = 3.3$ Total vertical stress $\sigma_v = 6.0$ Deviator stress $\sigma_v - \sigma_h = 2.7$ GROUP E_{1-4}	Consolidation pressure $\sigma_c = 3.3$ Repeated vertical stress $\Delta\sigma_v = 2.7$ Repeated horizontal stress $\Delta\sigma_H = 1.35$ Total horizontal stress $\sigma_h = 4.65$ Total vertical stress $\sigma_v = 6.0$ Deviator stress $\sigma_v - \sigma_h = 1.35$ GROUP E_{9-12}
Plastic Stage	Consolidation pressure $\sigma_c = 3.3$ Repeated vertical stress $\Delta\sigma_v = 5.4$ Repeated horizontal stress $\Delta\sigma_H = 0.0$ Total horizontal stress $\sigma_h = 3.3$ Total vertical stress $\sigma_v = 8.7$ Deviator stress $\sigma_v - \sigma_h = 5.4$ GROUP P_{5-8}	Consolidation pressure $\sigma_c = 3.3$ Repeated vertical stress $\Delta\sigma_v = 5.4$ Repeated horizontal stress $\Delta\sigma_H = 2.7$ Total horizontal stress $\sigma_h = 6.0$ Total vertical stress $\sigma_v = 8.7$ Deviator stress $\sigma_v - \sigma_h = 2.7$ GROUP P_{13-16}

PORE WATER PRESSURE VERSUS TIME RELATIONSHIP

1. Elastic Range

The relationships between pore water pressures and log time (log number of cycles) for the loads applied in the elastic range are shown in Figure 16. Curve E_4 represents pore water pressure generation for tests using repeated vertical stresses and constant horizontal stress (cell pressure), while Curve E_{12} represents pore water pressure generation for tests using repeated vertical stresses and concurrent repeated horizontal stress (cell pressure). Both types of tests were carried out in the elastic range.

For both types of tests, the pore water pressures increased for the first few cycles of loading, then it decreased towards the end of the tests. The decrease in the pore water pressures indicates soil dilatancy which is very common for over-consolidated soils.

The values of the net pore water pressures due to shear stresses for Sample E_4 are greater than those for Sample E_{12}, because the deviator stress for Sample E_4 is greater than the deviator stress for Sample E_{12}. The total value of the pore water pressure for Sample E_{12} is greater than the total value of pore water pressure for Sample E_4 because the repeated horizontal stress for Sample E_{12} was transferred to the pore water pressure. This can be explained by the following equations:

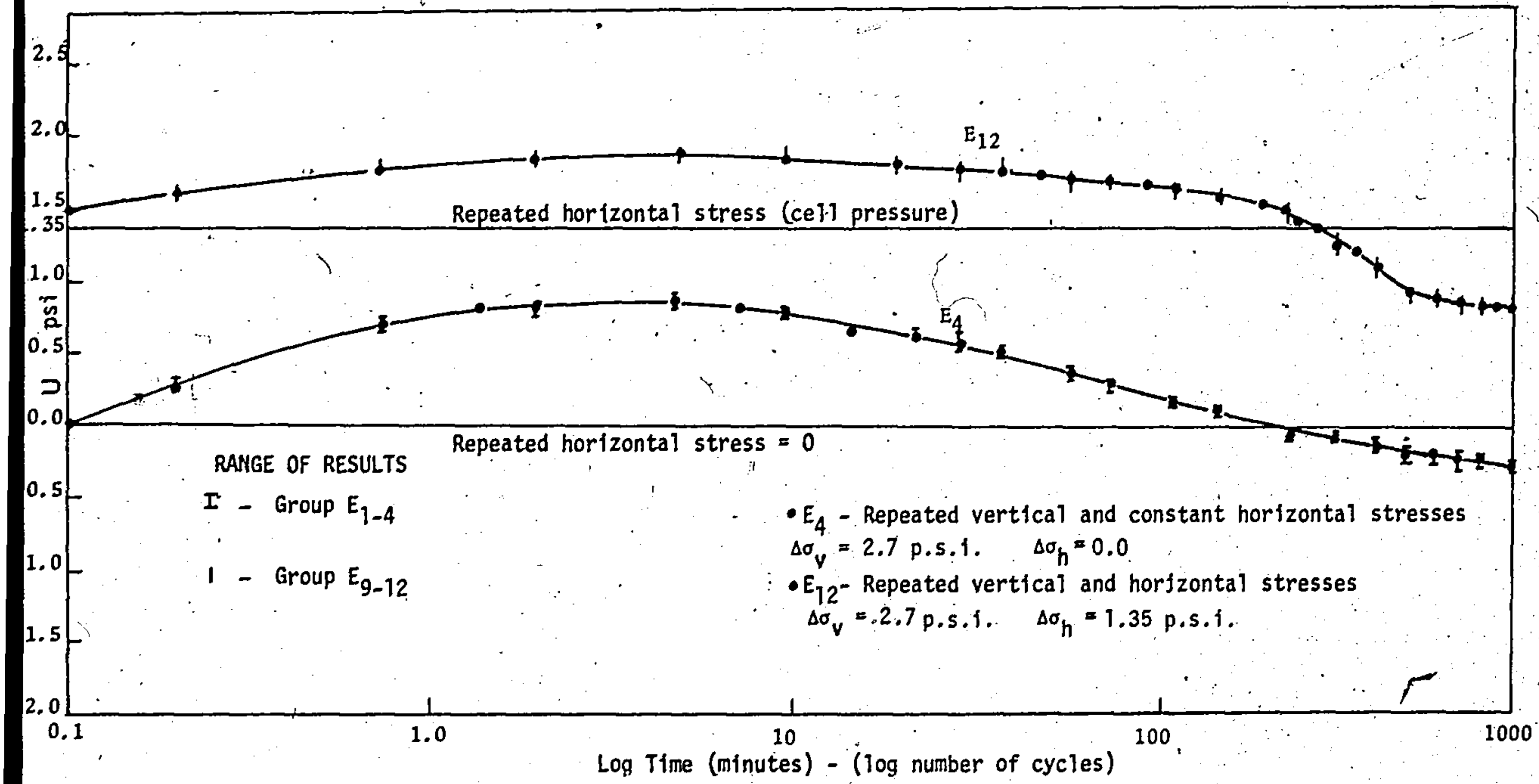


FIG. (16). PORE WATER PRESSURES U VERSUS LOG TIME FOR LOADS ON (ELASTIC STAGE)

$$\Delta U = B\left[\Delta\sigma_h + A\,(\Delta\sigma_v - \Delta\sigma_h)\right] \ldots\ldots\ldots (1)$$

where:

ΔU = change in pore pressure due to increased stresses

$\Delta\sigma_v$ & $\Delta\sigma_h$ = change in principal stresses caused by soil loading

$\Delta\sigma_v - \Delta\sigma_h$ = deviator stress

A & B = pore water pressure parameters

Case 1 when $\Delta\sigma_h = 0$

Therefore, $\Delta U_1 = B.A.\Delta\sigma_v \ldots\ldots\ldots\ldots\ldots\ldots (2)$

Case 2 when $\Delta\sigma_v > \Delta\sigma_h$

Therefore, $\Delta U_2 = B.\Delta\sigma_h + B.A(\Delta\sigma_v - \Delta\sigma_h) \ldots (3)$

Therefore, the difference between Case 1 and Case 2 is:

$\Delta U_2 - \Delta U_1 = B.\ \Delta\sigma_h\ (1-A) \ldots\ldots\ldots\ldots\ldots\ldots (4)$

Equation 4 shows that the difference in the pore water pressure depends upon the minor principal stress $\Delta\sigma_h$ and the pore water pressure parameters A and B. In case of saturated soil the parameter B = 1. The value of the parameter A depends upon the type of soil.

2. Plastic Range

The relationships between the pore water pressures and log time, for the loads applied in the plastic range are shown in Figure 17. Curve P_8 represents pore water pressure generation for tests using repeated vertical stresses and constant horizontal stress. Curve P_{16} represents pore water pressure generation for tests using repeated vertical stresses and concurrent repeated horizontal stresses. For both tests the pore water pressures increased with time until failure occurred, after one cycle for P_8 and 15 cycles for P_{16}. A sudden increase in the pore water pressure and the axial displacement indicates failure of samples. Sample P_8 failed after one cycle, under a deviator stress equal to 60 per cent of the maximum compressive strength of the soil (from the standard undrained test). It is believed that this failure occurred so rapidly due to the use of a high level of stress application. The levels of the applied repeated stresses were based on a maximum compressive strength of the soil equal to 9.0 p.s.i. obtained from the standard triaxial undrained tests described previously (Page 43). These standard tests were performed on samples from one block of soil, while the repeated tests P_8 were performed on another block. Extensive study on this soil (Reference #21) indicate that there is a large variation in the value of the shear strength for this soil, from one place to another. It is possible that the maximum compressive strength for the block of soil used for Group P_8 is less than 9.0 p.s.i. and that the levels of the applied repeated stresses are very high, which caused the soil to fail after one cycle of these stresses.

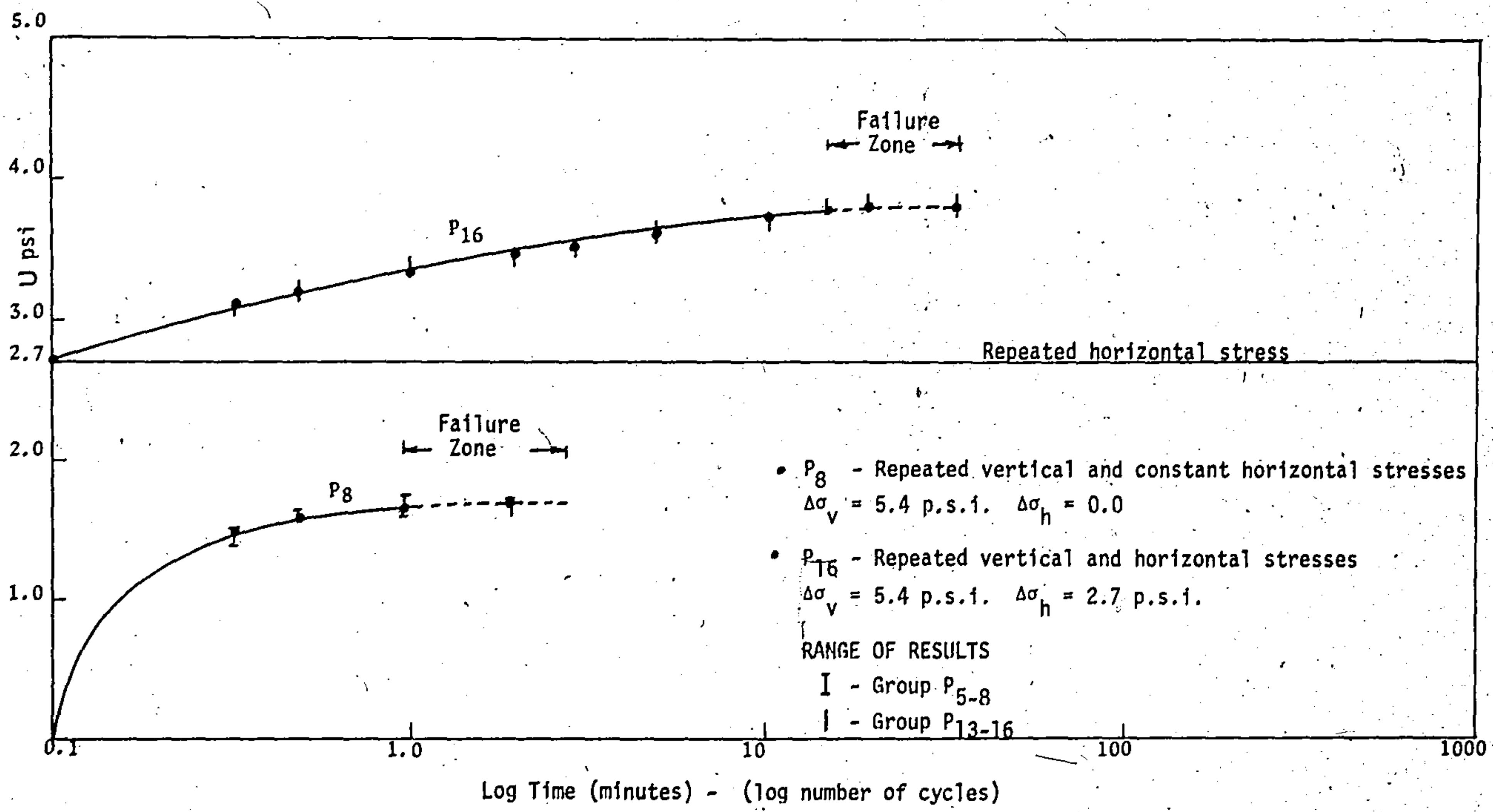


FIG. (17). PORE WATER PRESSURES U VERSUS LOG TIME FOR LOADS ON (PLASTIC STAGE)

For both elastic and plastic ranges the net pore water pressures were greater for samples tested under the action of repeated vertical stresses and constant horizontal stress than the pore water pressures for samples tested under the action of repeated vertical and repeated horizontal stresses. This is because the deviator stress in the first case was greater than that for the second case.

AXIAL STRAINS VERSUS TIME RELATIONSHIP

The relationships between axial strains and log time, for the loads applied, are shown in Figure 18, for tests carried out in the elastic range, and in Figure 19, for tests carried out in the plastic range. Figure 18, indicates a predominantly linear relationship between the strains and log time in the elastic range. Figure 19, indicates a definite tendency for increasing strain with log time. For both samples P_8 and P_{16}, the strains increased under each stress application until failure occurred. Sample P_{16} failed at a lower strain value and larger number of stress applications than Sample P_8 because the deviator stress on Sample P_8 was greater than that on Sample P_{16}.

A comparison between the elastic stage and the plastic stage based on the different types of loading is shown in Figure 20. The vertical axis represents the pore water pressures and the strains, while the horizontal axis represents log time. In the elastic stage,

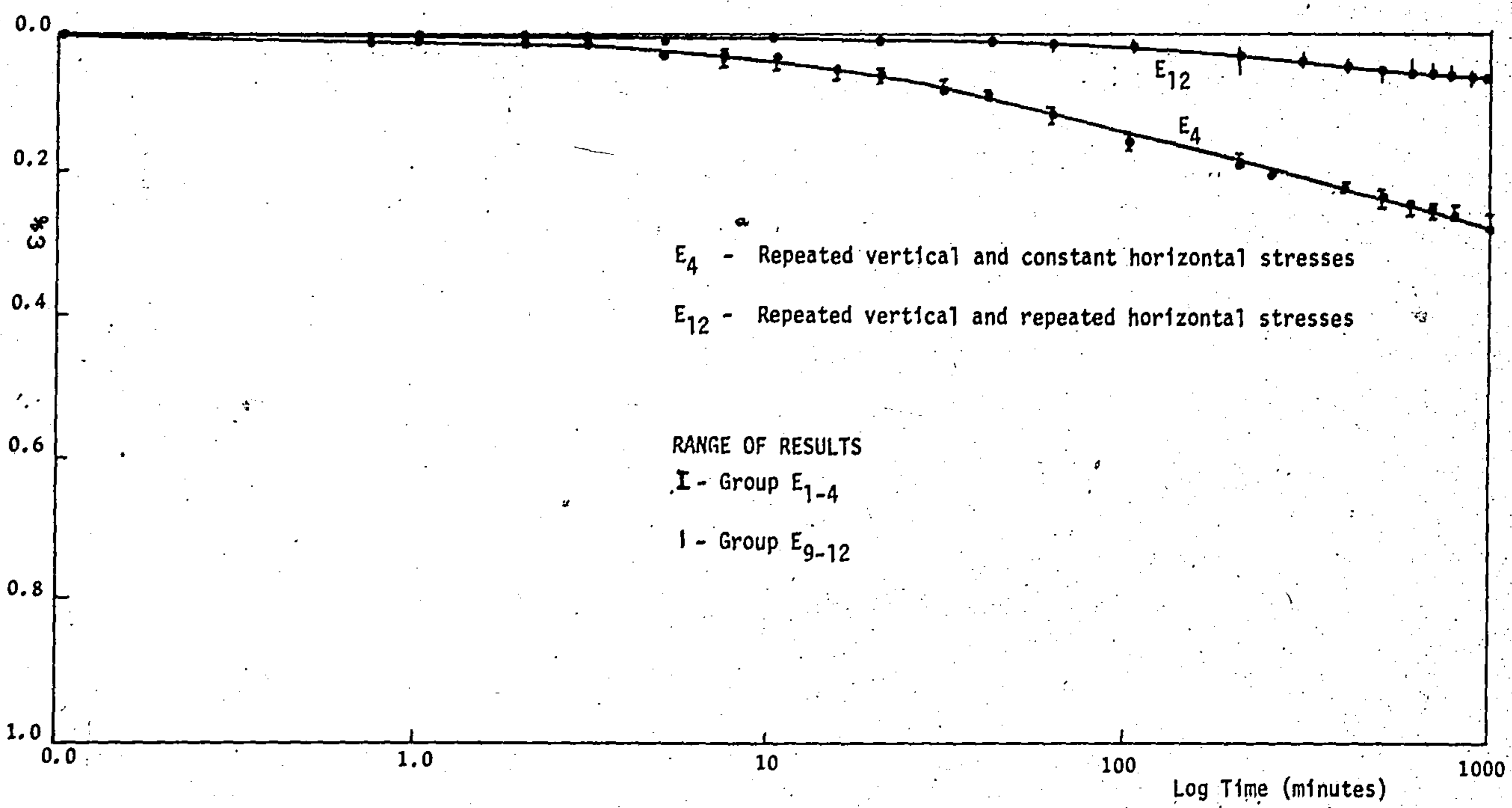


FIG. (18). AXIAL STRAINS ε% VERSUS LOG TIME FOR LOADS ON (ELASTIC STAGE)

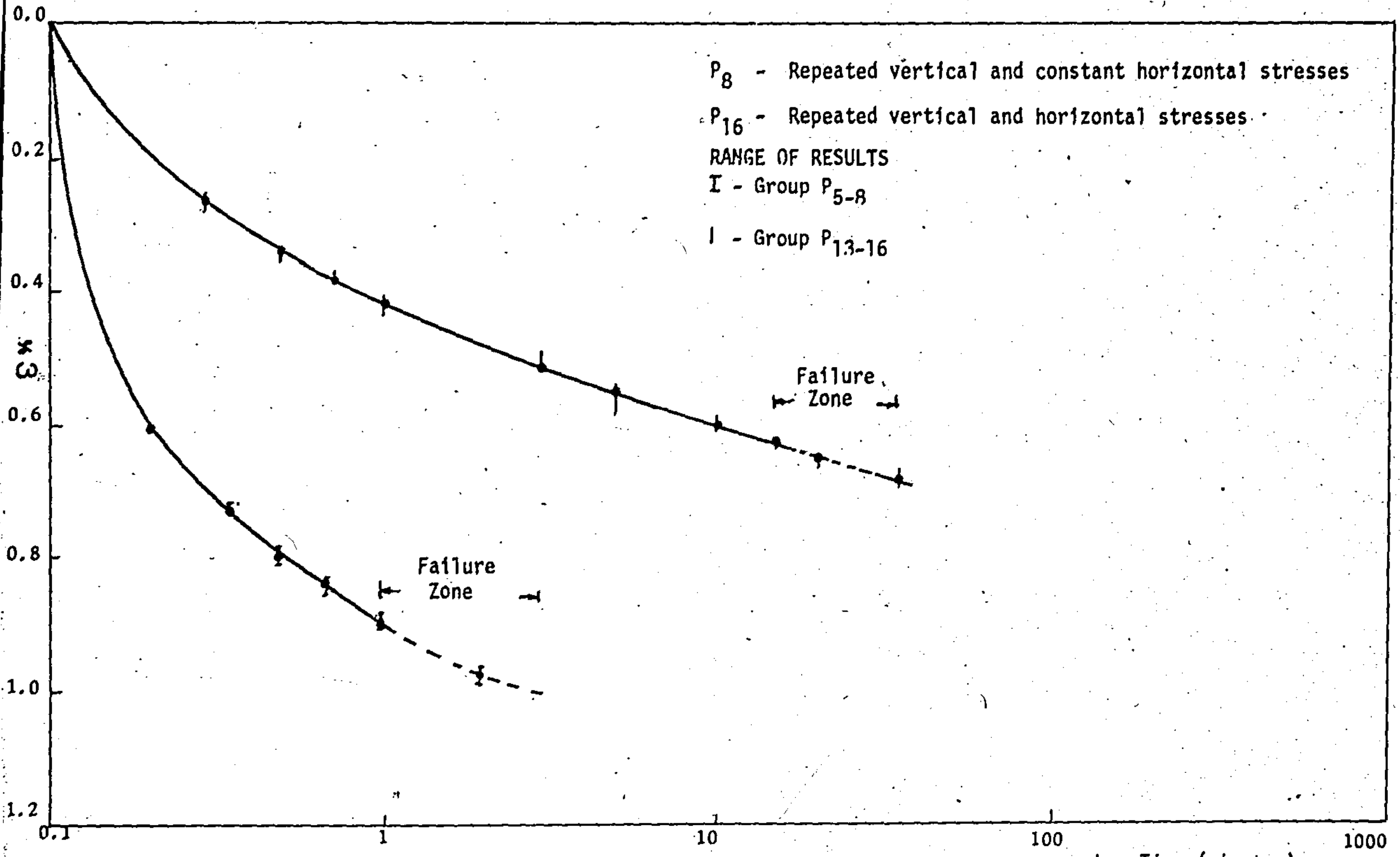


FIG. (19). AXIAL STRAINS ε % VERSUS LOG TIME FOR LOADS ON (PLASTIC STAGE) the soil is reasonably stable and can withstand 1000 load applications without significant deformations. The pore water pressures dropped down towards the end of Tests E_4 and E_{12} indicating dilatancy of the soil. Sample E_{12}, where both the vertical and horizontal stresses were varied showed more stiffening under increased number of load applications than Sample E_4 where the vertical stress was varied while the horizontal stress was kept constant. For higher levels of repeated stresses, the strain increased dramatically under each stress application until failure occurred.

For both the elastic and plastic stages, the strains which occurred for samples subjected to repeated vertical and repeated horizontal stresses were less than the strains which occurred for samples subjected to repeated vertical stress and constant horizontal stress.

Comparing the results of Sample E_4 (constant horizontal stress) and Sample P_{16} (repeated horizontal stress), where the deviator stress for both samples is the same. Sample P_{16} failed at lower number of stress applications and higher strain level than Sample E_4. This result could be due to two alternatives:

1. Higher strains occurred for Sample P_{16} than Sample E_4 as a result of the application of both the deviatoric stress and the repeated

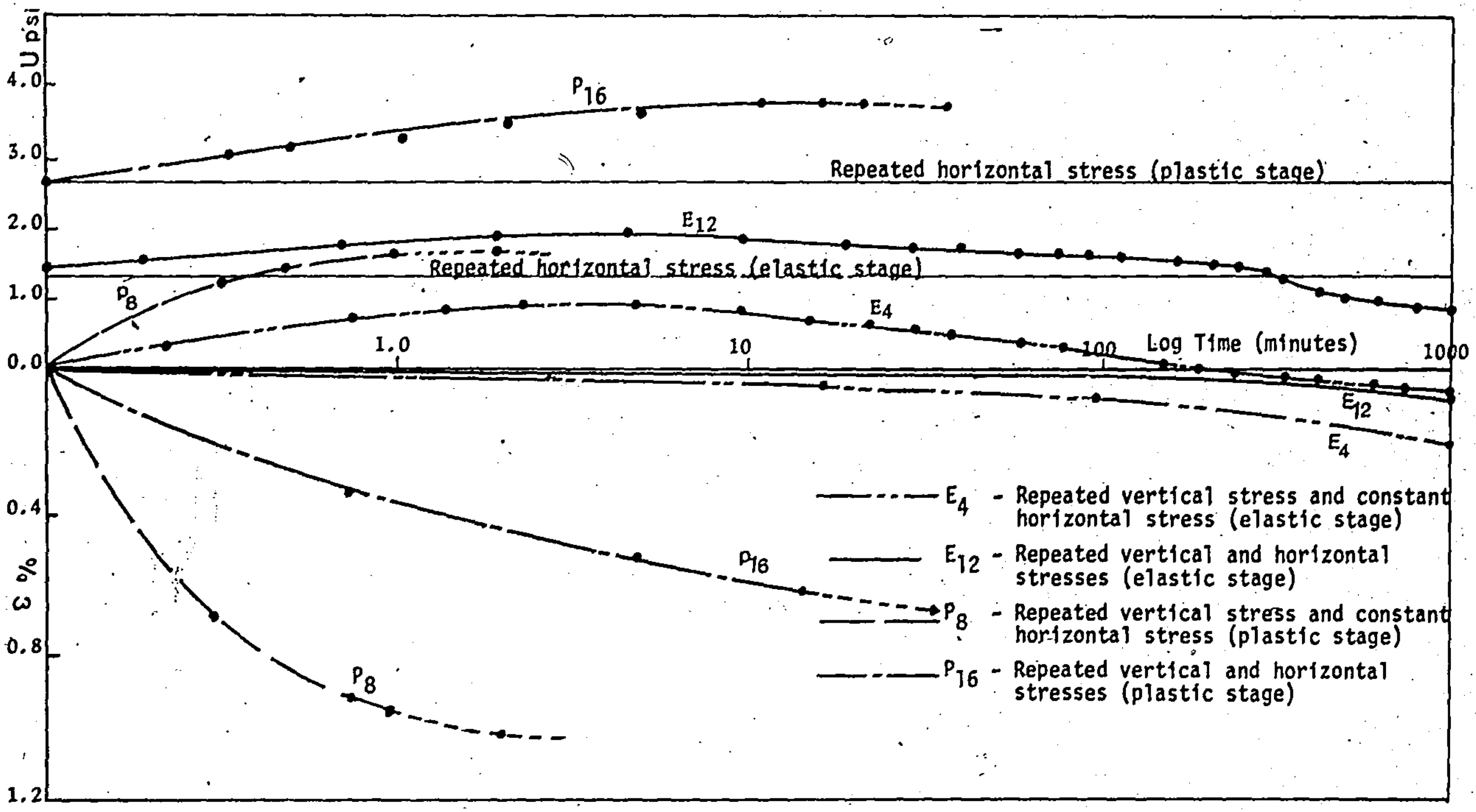


FIG. (20). PORE WATER PRESSURES, STRAINS VERSUS LOG TIME FOR BOTH ELASTIC AND PLASTIC STAGE, FOR LOADS ON horizontal stress. These results agree with the results of Seed and Fead (1959), where they found that for unsaturated soil, the vertical strains for samples subjected to repeated vertical and repeated horizontal stresses were greater than the vertical strains for samples subjected to repeated vertical stress and constant horizontal stress when they kept the value of the deviator stress constant for both types of tests.

On the other hand, these results contradict the results of Seed and Chan (1966), where they stated that for saturated clayey soils, varying both the horizontal stress (confining pressure) and the vertical stress concurrently will have negligible effects on soil strength.

2. For Sample P_{16}, the horizontal stress (cell pressure) was applied through a three-way valve. It is possible that there is a time delay in applying the horizontal stress due to the working mechanism of the three-way valve. Therefore, due to this time delay the sample at a certain time will be subjected to the repeated vertical stress only, resulting in larger strains.

PORE WATER PRESSURE VERSUS STRAIN RELATIONSHIPS

General Behaviour

For a sample tested in the elastic stage under the action of repeated vertical stress and constant horizontal stress (cell pressure), Test E_4, the pore pressure build-up and the axial strains under each load application are presented on Figure 21. The first application of stress produces immediate strain and excess pore water pressure. The strain and excess pore water pressure continues to increase until the stress is removed. On removal, there is a residual strain (ε_p) and a residual pore water pressure (U_p). With reapplications of stress, the residual strain and residual pore pressure continue to increase or decrease depending upon the levels of repeated stresses and types of consolidation. The total strain (ε) at any time with the load applied is comprised of a recoverable "elastic" component (ε_e) and a permanent "plastic" component (ε_p):

$$\varepsilon = \varepsilon_e + \varepsilon_p \text{.........}(5)$$

Similarly, the excess pore water pressure (U) with the load applied is comprised of a recoverable component (U_e) and a non-recoverable component (U_p):

$$U = U_e + U_p \text{..........}(6)$$

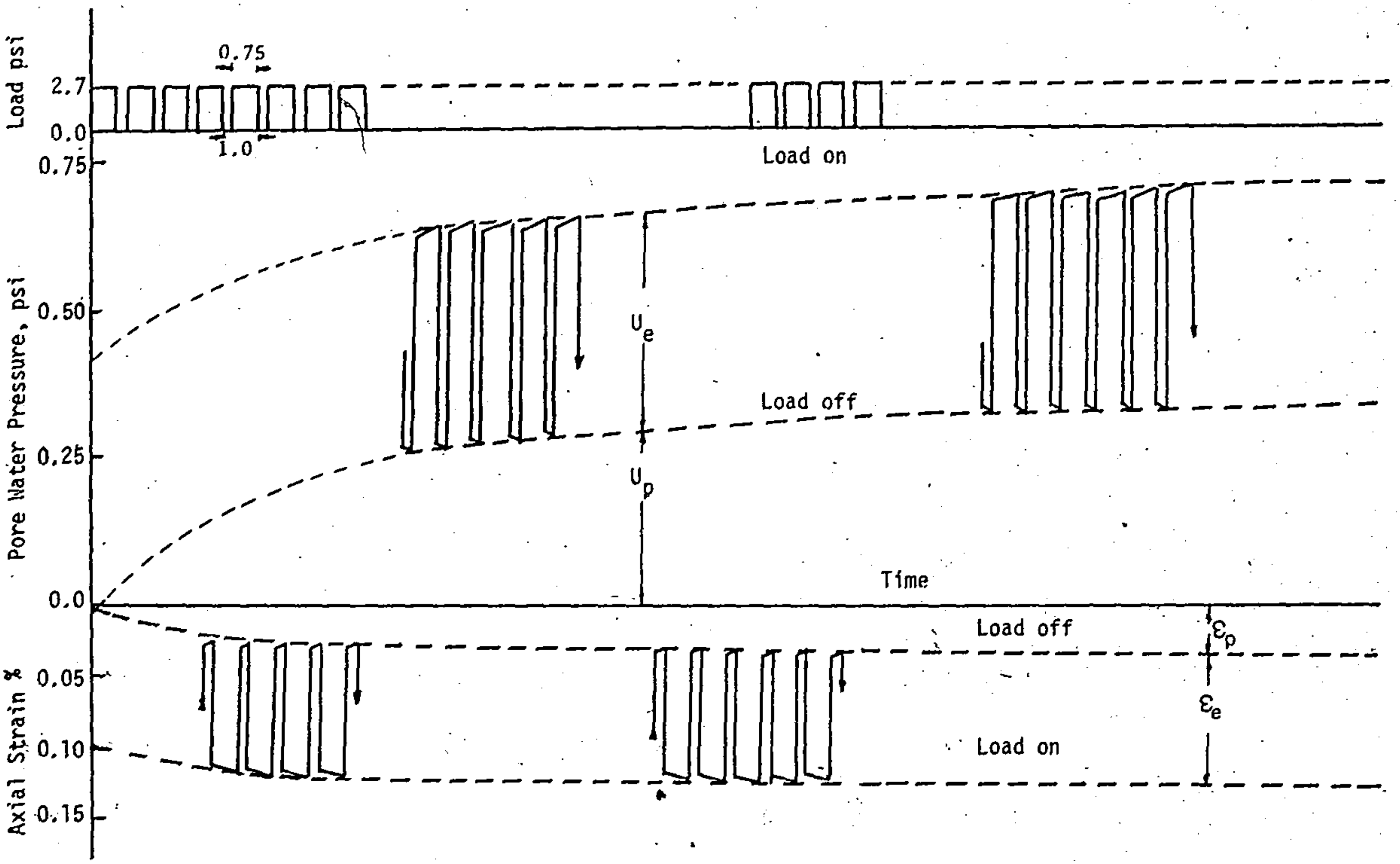


FIG. (21). (TEST E_4) CURVES OF LOAD, PORE WATER PRESSURE AND AXIAL STRAIN VERSUS TIME (ELASTIC STAGE)
(Schematic Representation)

Pore water pressures (U) are plotted against strain ($\varepsilon\%$) in Figure 22, for tests in the elastic stage and in Figure 23, for tests in the plastic stage. The lines on the graphs represent the behaviour of the soil after a certain number (n) of stress applications. The lines joining the "load off" to the "load on" points represent the recoverable components of the pore water pressure and the strain. Points of "load off" represent values of residual strain (ε_p) and values of residual pore water pressure (U_p). The residual pore water pressures Figure 22, for tests using repeated vertical and concurrent repeated horizontal stresses increase with the number of load applications as did the residual strain. Negative residual pore water pressures developed in tests using repeated vertical stresses and constant horizontal stress under subsequent load applications. There was an increase in the residual strain and a further increase in the residual negative pore pressures. For both types of loadings, linear relationships exist between the residual pore water pressures and the residual strains. Figure 23, for tests in the plastic stage, shows a decrease in the residual pore water pressures (U_p) and an increase in the residual strain (ε_p) as the sample approaches failure.

A pore water pressure (U) versus strain ($\varepsilon\%$) relationship, when the loads are applied, is shown in Figure 24, for tests in the elastic stage, and in Figure 25, for tests in the plastic stage.

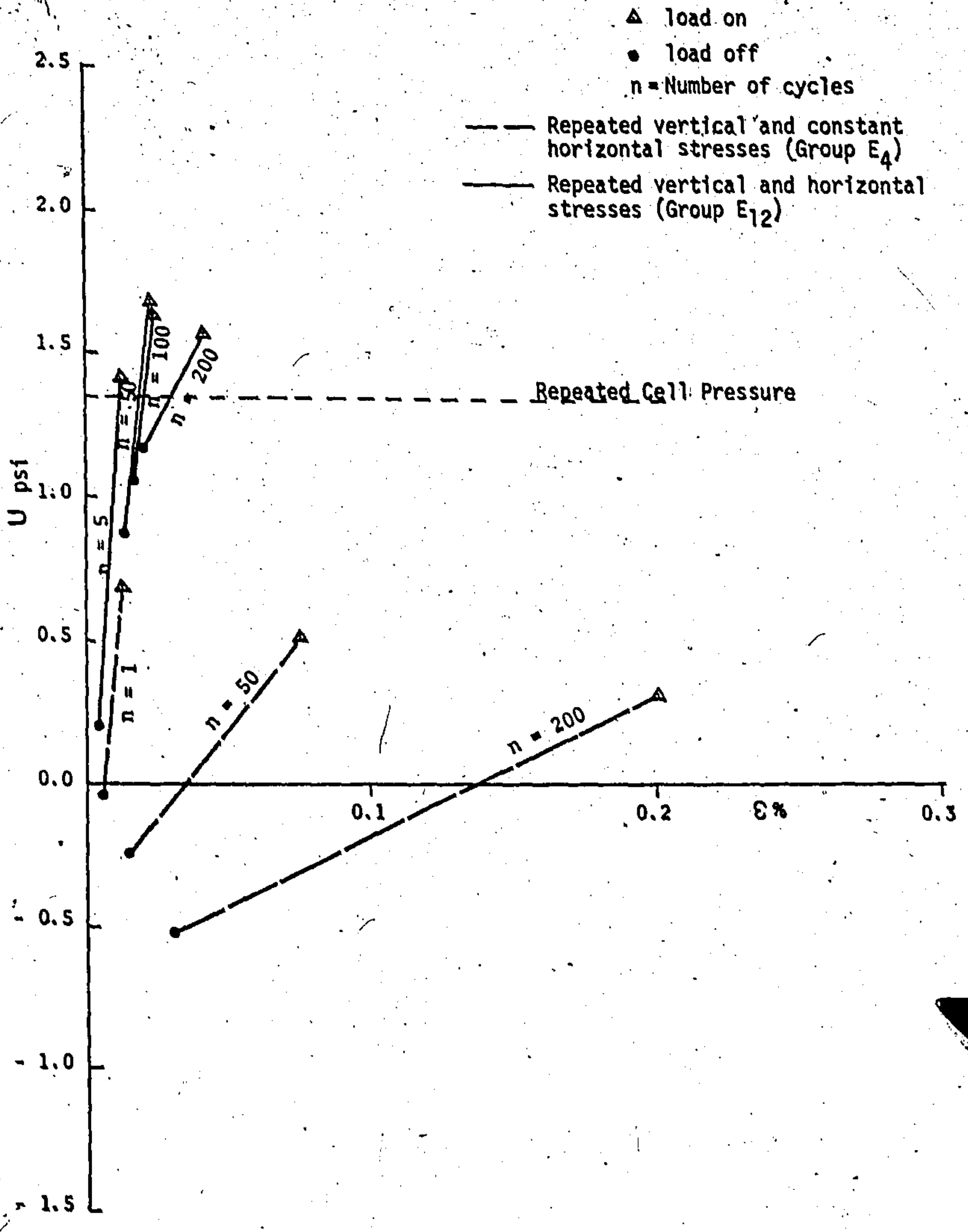


FIG. (22). PORE WATER PRESSURE (U) VERSUS AXIAL STRAIN (ε)% (ELASTIC STAGE)

(The horizontal scale (for ε) is four times the horizontal scale in Fig. 23)

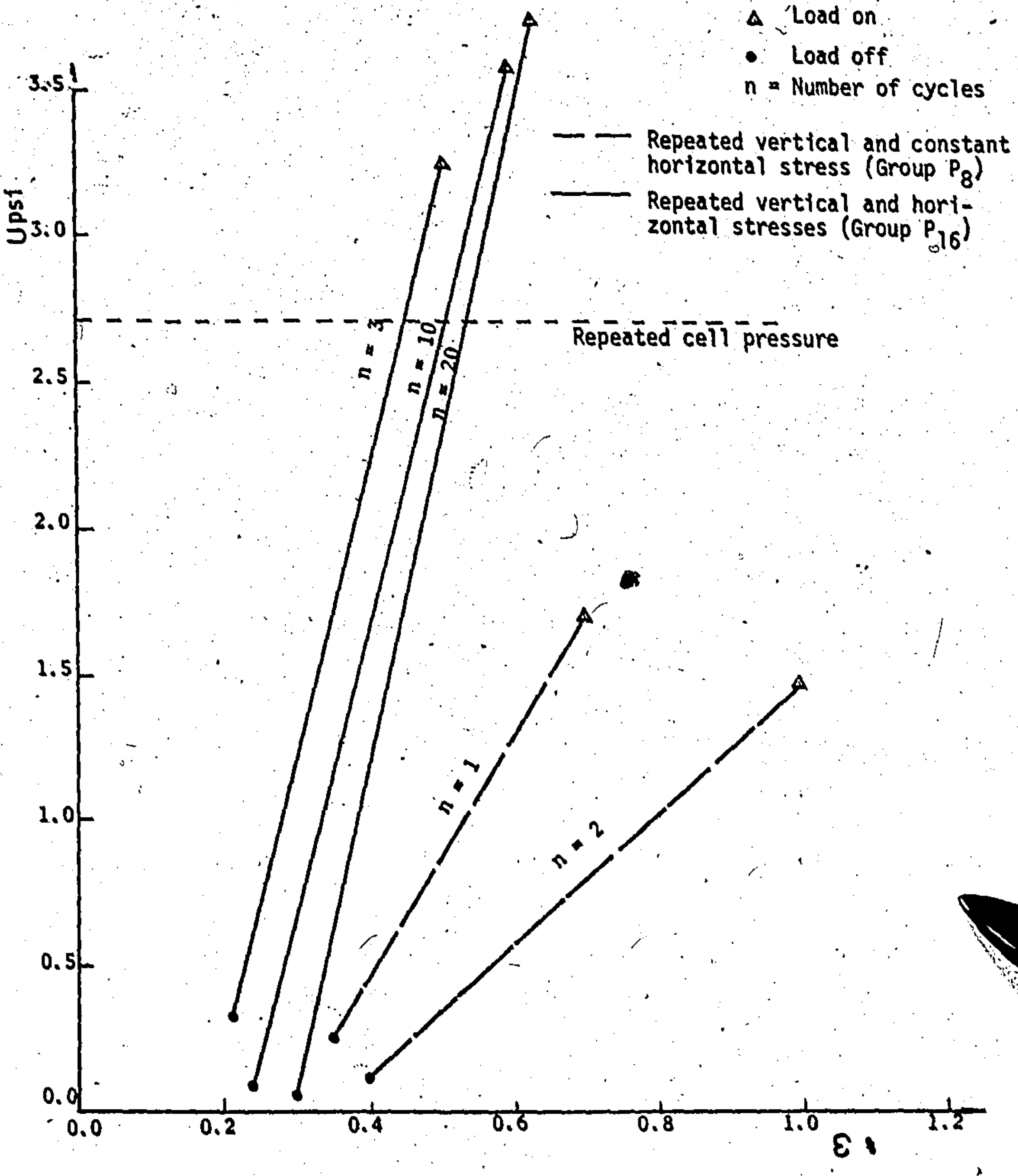


FIG. (23). PORE PRESSURE (U) VERSUS AXIAL STRAIN ϵ % (PLASTIC STAGE)

Both figures indicate greater values of pore water pressures and smaller values of strains for Tests E_{12} and P_{16} (tests using repeated vertical and repeated horizontal stresses) than those which occurred for Tests E_4 and P_8 (tests using repeated vertical stress with constant horizontal stress). Tests E_{12} and P_{16} produced more pore water pressures than Tests E_4 and P_8 as a result of the pulsed cell pressure which is transferred directly to the pore water pressure, which indicates that the soil is saturated and that the pore water pressure parameter $B = 1$ according to Equation (1). However, the net pore water pressures induced due to shear stress are greater for Tests E_4 and P_8 than those for Tests E_{12} and P_{16} due to the use of greater values of deviator stresses for Tests E_4 and P_8.

In the elastic stage, Figure 24, the strains developed for Test E_{12} are smaller than those for Test E_4 because the applied deviator stress for E_{12} was smaller than the applied deviator stress for E_4.

In the plastic stage, Figure 25, for both tests P_8 and P_{16}, the developed failure strains are very close. The level of the applied deviator stress for test P_8 are considered too high which caused the sample to fail after one cycle of load at a strain level higher than that occurred after about 15 cycles of load for Test P_{16}.

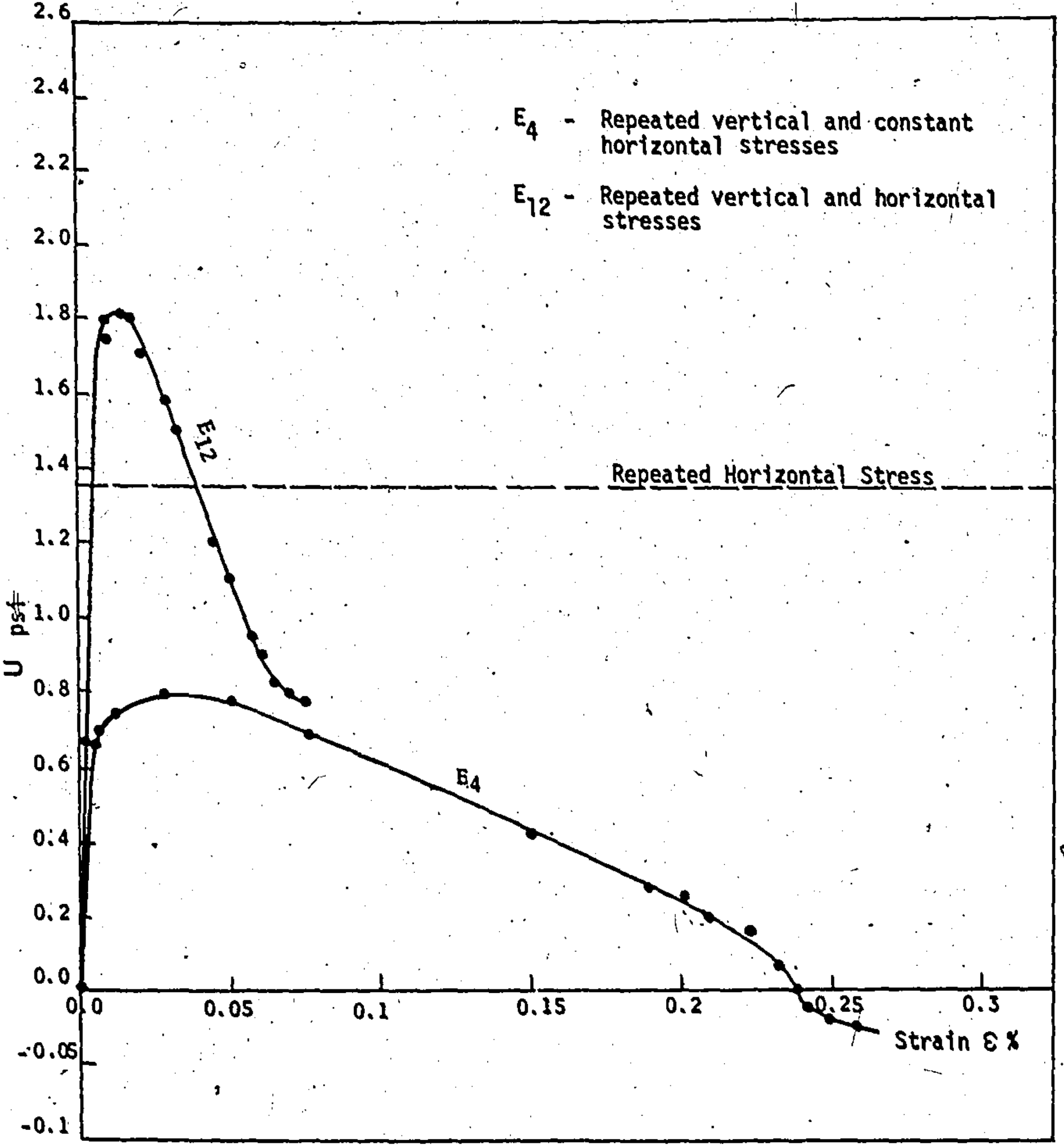


FIG. (24). PORE WATER PRESSURES U VERSUS STRAIN ε% FOR LOADS ON (ELASTIC STAGE)

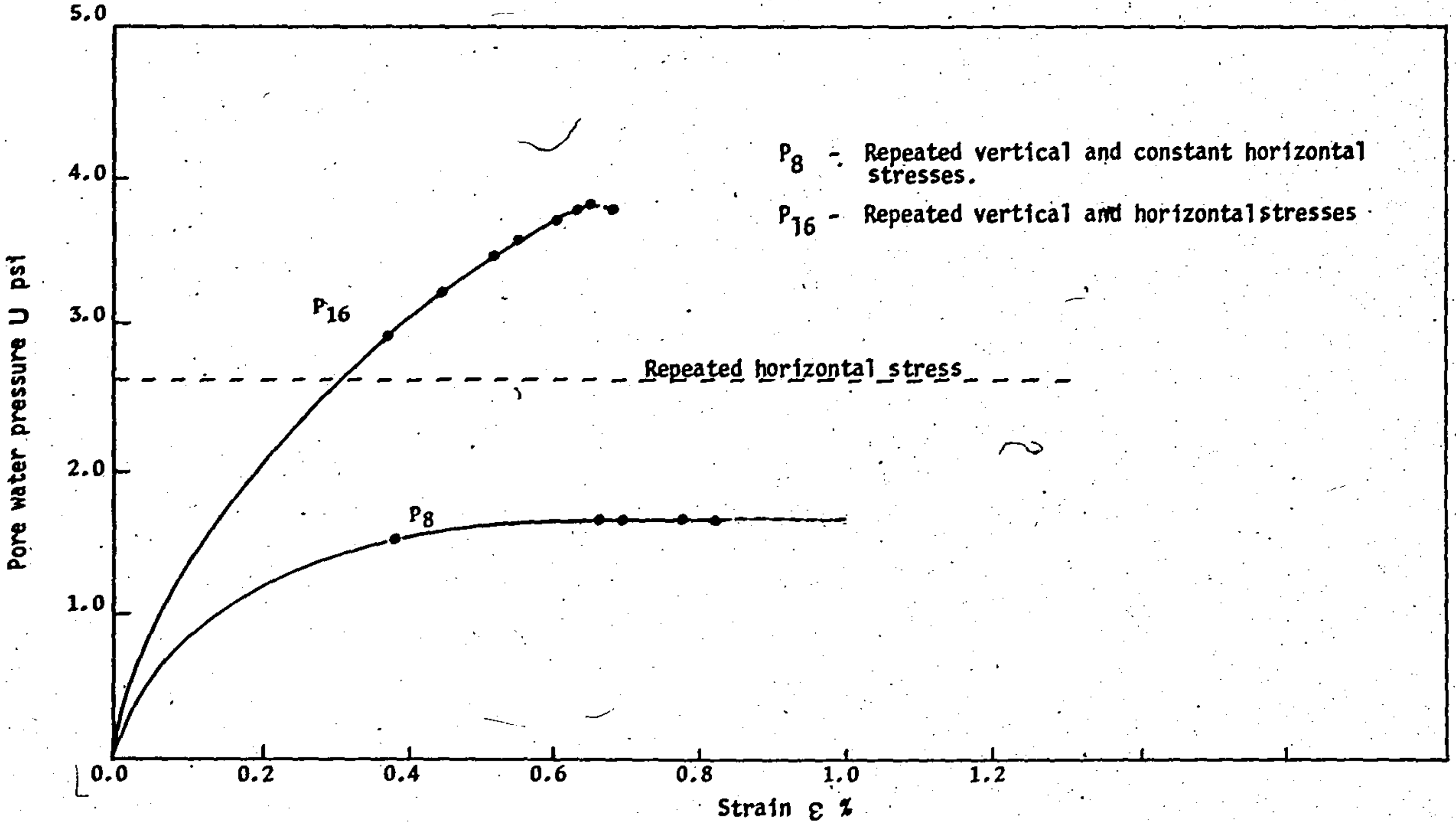


FIG. (25). PORE WATER PRESSURES U VERSUS STRAIN ε % FOR LOADS ON (PLASTIC STAGE)

Effective Stress Versus Strain Relationship

The relationship between the vertical effective stress ($\bar{\sigma}_1$) and the axial strain (ϵ%) is shown in Figures 26 and 27 for the elastic and plastic stages, respectively. For Tests E_4 and E_{12} in Figure 26, the effective stress $\bar{\sigma}_1$ started to decrease until it reached its minimum values at points 1 and 2. These points represent the maximum values of the positive pore water pressure which occurred during these tests (see Figure 16). With subsequent load applications, the effective vertical stress increased again with strain since the pore water pressure decreased as dilatancy of the soil occurred. The dilatancy was sufficient to develop pore water tensions and as a result the effective vertical stress increased until the end of the test at 1000 cycles. The photograph in Figure 28 shows Sample P_{16} after failure.

For levels of stresses higher than the estimated critical level (plastic stage), the effective vertical stress decreased until failure occurred, Figure 27. For Test P_8, the failure occurred after one cycle with a strain of 0.85 per cent and for Test P_{16} failure occurred after 15 cycles with a strain of 0.7 per cent. For Test P_8, the sample failed after one cycle of load only as a result of the use of a very high value of deviator stress, which also caused a higher effective vertical stress for P_8 than P_{16}.

Comparing the resulting effective vertical stress for Tests E_4 and P_{16} in Figures 29, where the value of the deviator stress is the same for both tests, the effective vertical stresses for both tests are approximately the same for the first 10 load applications, then the effective stress increased for Test E_4 as a result of the decrease in the pore water pressure. For Test P_{16} (repeated vertical stress and repeated cell pressure) the effective stress decreased as the pore water pressure increased until failure occurred after about 15 load applications. Also, the developed strains at failure for P_{16} where much higher than those for E_4.

The only difference in the loading conditions of these two samples is that P_{16} was subjected to repeated cell pressure as well as repeated deviator stress which could be the cause of the above different behaviour in the pore water pressures and the strains for both samples. Also, these differences in the behaviour of the two samples could be due to some problem with the repeated cell pressure system which may have caused a time delay in applying the repeated cell pressure concurrently with the repeated vertical stress.

The ratio between the effective vertical stress ($\bar{\sigma}_1$) and the effective horizontal stress ($\bar{\sigma}_3$) is also plotted versus strain (ϵ%) in Figures 30 and 31. For the elastic stage shown in Figure 30, the maximum stress ratio ($\bar{\sigma}_1/\bar{\sigma}_3$) indicates the start of soil dilatancy for Tests E_4 and E_{12}. Dilatancy has a significant influence on the effective stress ratio because the pore water pressure changes the values of both the effective vertical stress and the effective horizontal stress. For the plastic stage shown in Figure 31, the maximum stress ratios ($\bar{\sigma}_1/\bar{\sigma}_3$) for Tests P_8 and P_{16}, show that the samples failed under a few cycles of load.

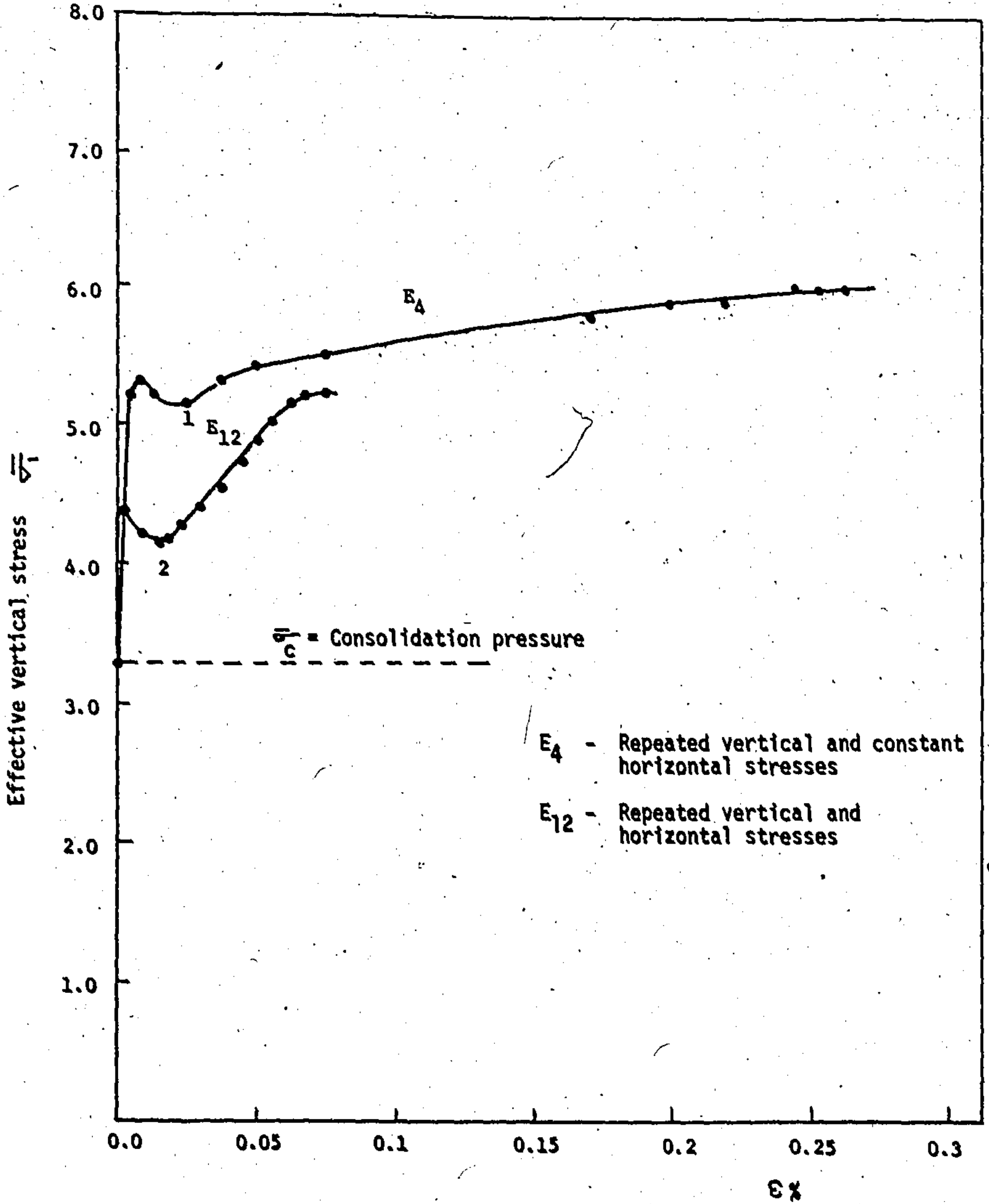


FIG. (26). EFFECTIVE VERTICAL STRESS $\bar{\sigma}_1$ VERSUS STRAIN ε% FOR LOADS ON (ELASTIC STAGE)

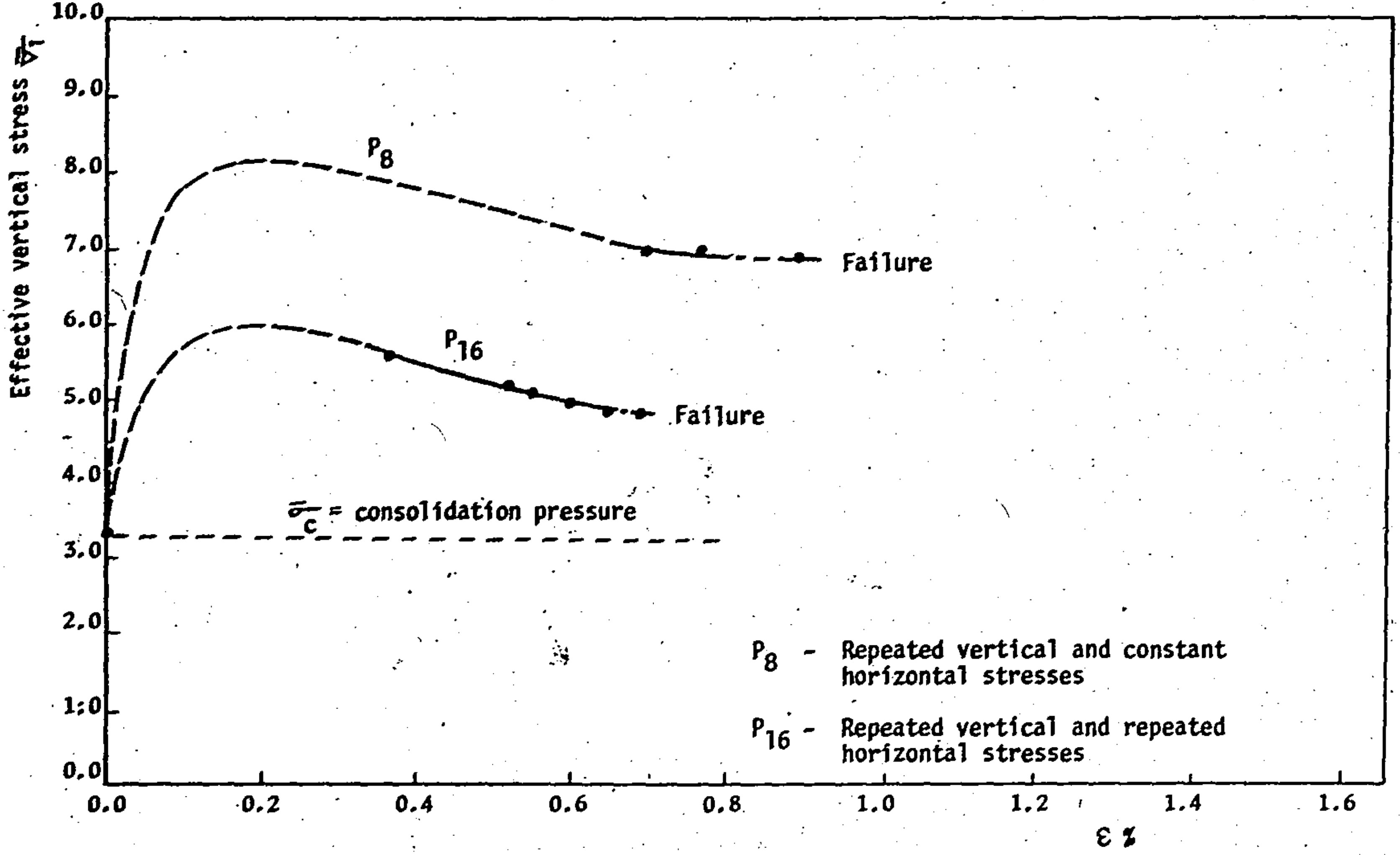


FIG. (27). EFFECTIVE VERTICAL STRESS $\overline{\sigma}_1$ VERSUS STRAIN ε % (PLASTIC STAGE)

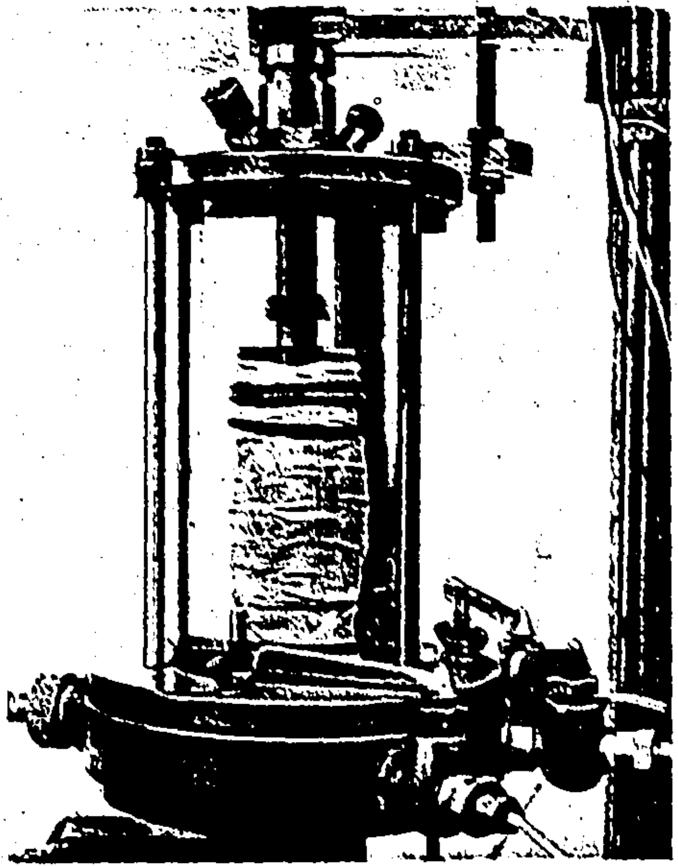


FIG. (28). SAMPLE FAILURE UNDER THE ACTION OF REPEATED VERTICAL AND HORIZONTAL STRESSES (P_{16})
(Chamber Water Drained to Facilitate Photography)

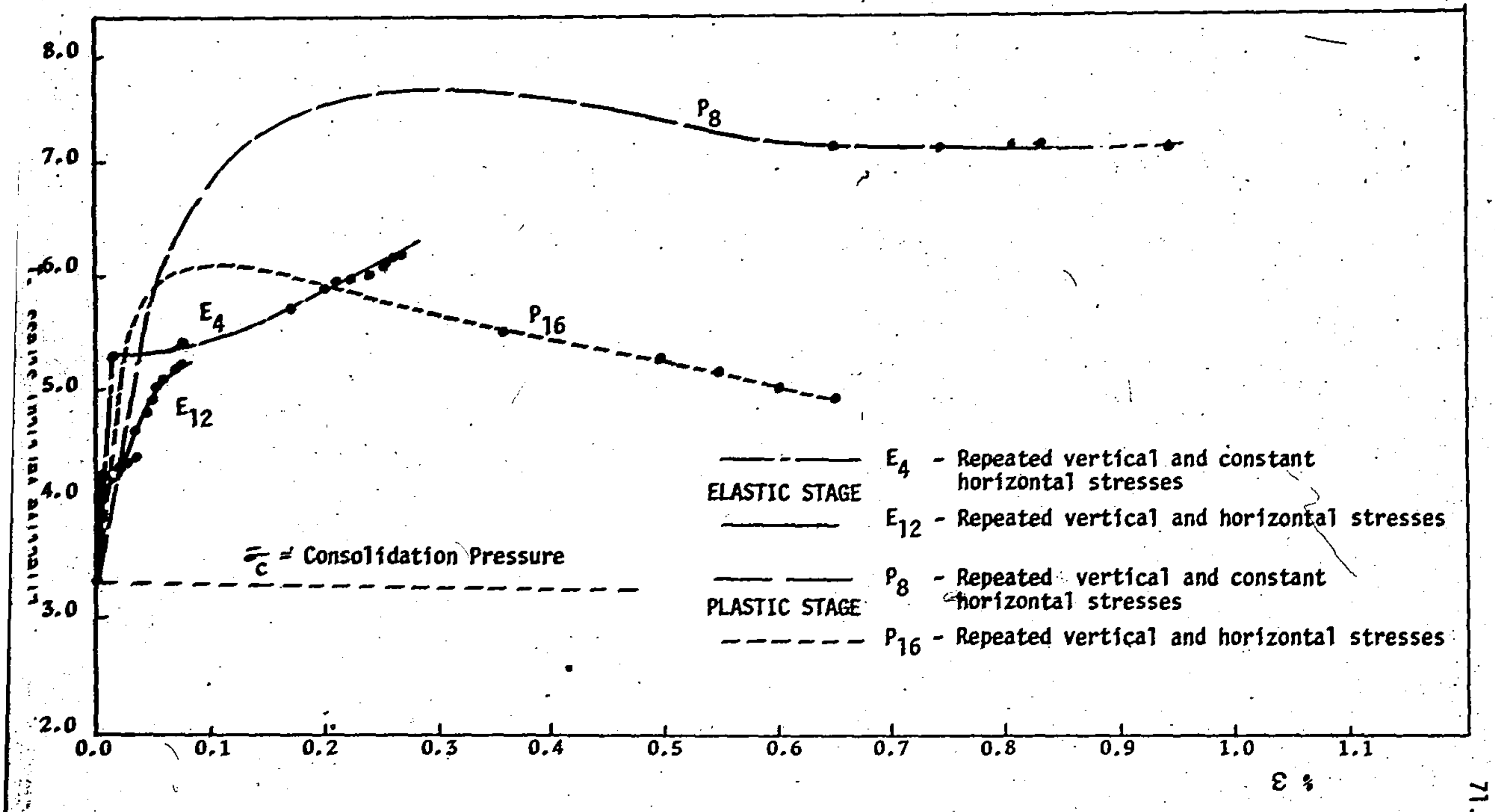


FIG. (29). EFFECTIVE VERTICAL STRESS $\bar{\sigma}_1$ VERSUS AXIAL STRAIN ε% FOR LOADS ON (ELASTIC AND PLASTIC STAGES)

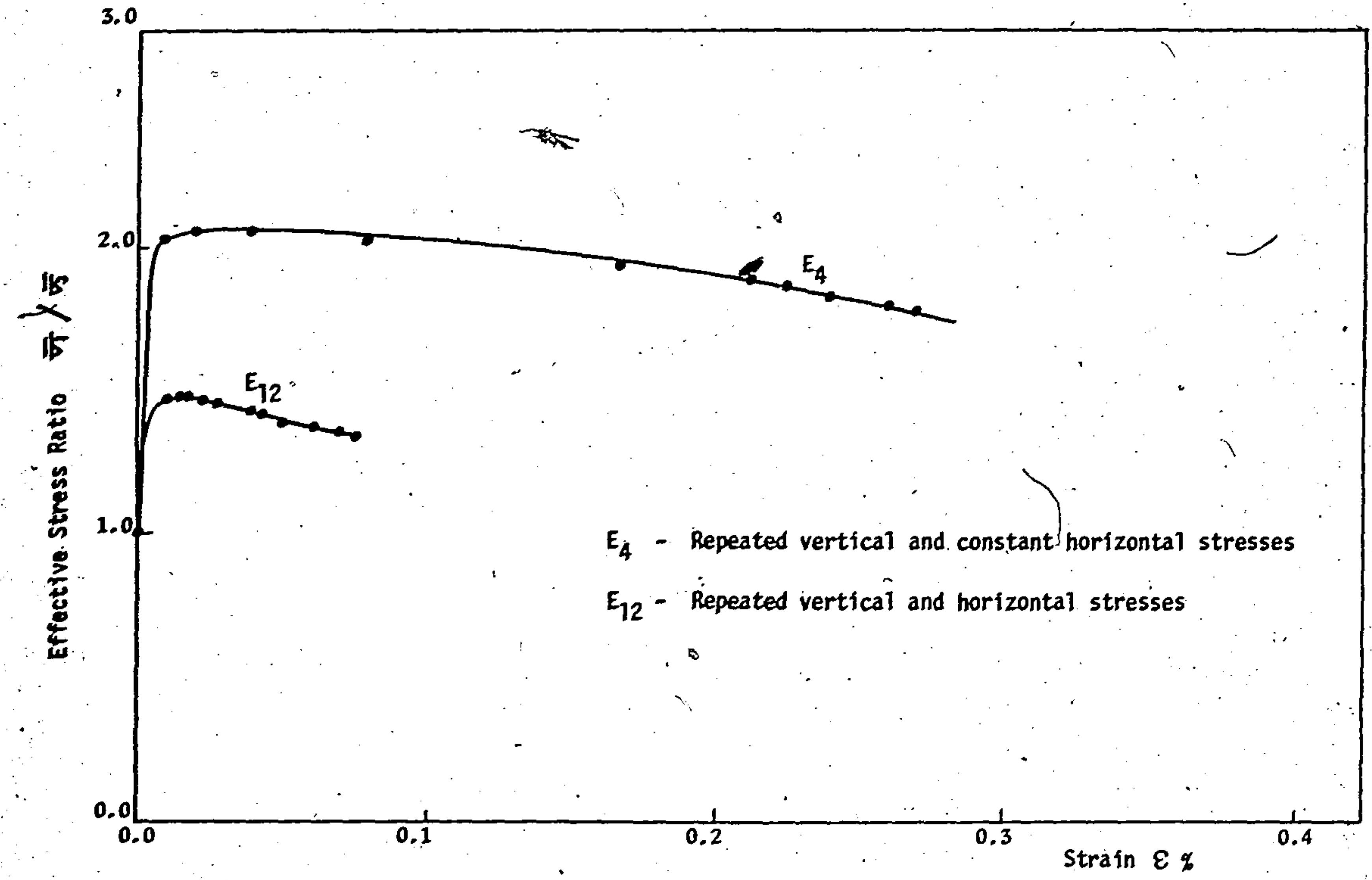


FIG. (30). EFFECTIVE STRESS RATIO $\bar{\sigma}_1/\bar{\sigma}_3$ VERSUS STRAIN ε % FOR LOADS ON (ELASTIC STAGE)

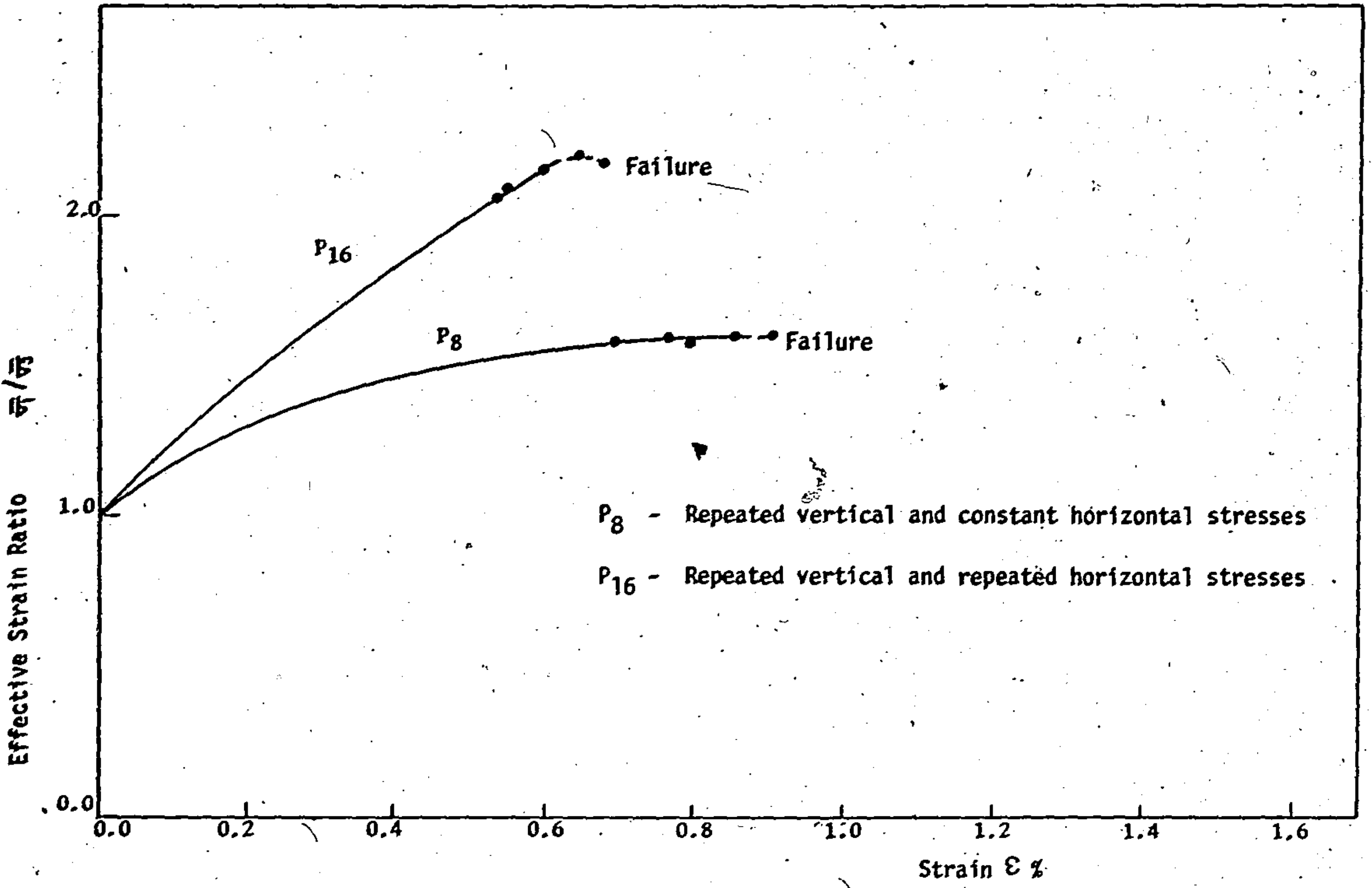


FIG. (31). EFFECTIVE STRESS RATIO $\bar{\sigma}_1/\bar{\sigma}_3$ VERSUS STRAIN ε % FOR LOADS ON (PLASTIC STAGE)

CHAPTER (VI)

CONCLUSIONS AND RECOMMENDATIONS

Highway Engineers have had many problems as a result of shear failures and/or rutting of subgrades supporting highway pavements. These soils are subjected to repeated loadings caused by the continuous passage of vehicles. Most of the current research dealing with repeated wheel loadings studied the behaviour of soils subjected to repeated vertical stresses and repeated cell pressure. In these studies the value of the deviatoric stress was not changed. In this thesis, the value of the deviator stress was changed.

Two cases of loading conditions were studied. The first case, was varying the vertical stress while the cell pressure was kept constant. In the second case, the vertical stress and the cell pressure (horizontal stress) were both varied concurrently. The value of the repeated vertical stress for both cases was the same. The second case of loading represents an idealized field conditions for the resulting stresses in the soil under a moving wheel load.

The results of the tests indicate that samples subjected to repeated vertical and repeated cell pressure produced more pore water pressure, lower values of effective stresses and axial strains than samples subjected to repeated vertical stress only. These results show that a design criterion based on varying the vertical stress only will over estimate the effective stresses and the axial settlement of the soil than predicted in the field.

The same two types of tests were performed taking into account that the value of deviator stress was kept the same. The results of these tests indicate that using repeated vertical stresses and repeated cell pressure produced higher values of axial strains and less effective stresses than those produced when using repeated vertical stress only. The results obtained for the first type of tests are believed to be due to the following reasons:

(1) Pulsing the cell pressure concurrently with the vertical stress;

(2) The possibility of time delay in applying the repeated cell pressure using the system discussed before; and

(3) The big variation in the values of the shear strength for the soil tested.

Recommendations

To represent the actual field conditions, further research can be done in which the soil is consolidated anisotropically and then subjected to varied vertical and horizontal stresses. K_0 is defined as the coefficient of earth pressure "at rest" which means no lateral strains. It might be of interest to investigate the value of K_0 for the soil where lateral strain cannot occur (case of an element at the edge of surface loading).

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