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COMPARISON OF SOIL SUCTION AND ONE-DIMENSIONAL CONSOLIDATION CHARACTERISTICS OF A HIGHLY PLASTIC CLAY

BY

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PREFACE

As fine-grained soils above the water table are dried through processes of evaporation or plant transpiration, pore water pressures become increasingly negative with respect to atmospheric conditions. Soils of high clay content exhibit large volume change with change in moisture stress. In sub-humid to semi-arid climates, negative pore water stresses cause effective stresses on the soil solid phase that may be much larger than the stresses imposed by engineering structures. Changes in these stresses arising from the soil climate are then of overriding importance in the long-term performance of foundations placed on such soils.

The purpose of this study was to compare the effects of one-dimensional consolidation caused by the application of load to the solid phase, with the shrinkage caused by a reduction of stress in the fluid phase. This report summarizes results presented in an M.Sc. thesis by the author, entitled "Comparison of Soil Suction and One-dimensional Consolidation Characteristics of a Highly Plastic Clay", presented to the Faculty of Graduate Studies, University of Alberta in May 1964. Much of the field and laboratory work associated with this study was carried out by the author while employed as a summer assistant with the Division (at the NRC Prairie Regional Station in Saskatoon) during the summers of 1962 and 1963, and forms part of a broad Divisional study of problems affecting building foundations on volume changing clay subsoils.

Ottawa
July 1967

R. F. Legget
Director

RÉSUMÉ

La Division des recherches en bâtiment du NRC poursuit depuis plusieurs années des recherches sur les caractéristiques de retrait et de gonflement des argiles fortement plastiques des Prairies. La difficulté qu'ont à surmonter les ingénieurs de génie civil provient de l'absence d'une méthode de calcul permettant d'estimer l'ampleur des déplacements verticaux d'un ouvrage léger. On a mené à bien une récapitulation bibliographique des travaux de recherches réalisés en Angleterre, en Afrique du Sud, en Australie, en Israël, et aux États-Unis, et une étude de deux méthodes de calcul proposées, l'une par le groupe Croney (1952), et l'autre par Jennings (1957).

L'auteur a mené à bien un programme d'essais pour la détermination des caractéristiques de succion de l'argile de la formation Régina, et pour établir une comparaison entre ces résultats et la courbe pression appliquée/teneur en humidité que donnent les essais habituels de consolidation. L'auteur montre que les courbes de pression-primitive/indice des vides, tant pour les essais de consolidation que pour ceux de succion aux environs du point de saturation, sont pratiquement similaires. L'allure des branches des courbes de pression/indice des vides concernant la recompression sont tout à fait différentes pour les deux techniques.

COMPARISON OF SOIL SUCTION AND ONE-DIMENSIONAL CONSOLIDATION CHARACTERISTICS OF A HIGHLY PLASTIC CLAY

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ABSTRACT

Investigation of the shrinking and swelling action of highly plastic clays on the Prairie Provinces has been carried out for several years by DBR/NRC. The problem facing engineers associated with the building industry is the lack of an analysis whereby the probable amount of vertical movement of a light structure can be predicted. A literature review of research work in England, South Africa, Australia, Israel and the United States was conducted and a study made of two analyses that have been developed; one by Croney et al (1952) and the other by Jennings (1957).

A testing program was conducted which involved the determination of moisture-suction characteristics of Regina Clay and a comparison of these results with the moisture-pressure relationships obtained by the conventional consolidation test. It was found that virgin pressure-void ratio curves are essentially the same for both consolidation and suction tests at close to full saturation. The curvatures of the recompression branches, however, of the pressure-void ratio curves for the two test techniques are quite different.

* * * * * * *

In recent years increasing interest has been shown in the behaviour of highly swelling soil. Vertical movements of engineering structures placed on the highly plastic lacustrine clays in Western Canada pose a serious problem (Baracos and Marantz, 1952; Baracos and Bozozuk, 1957; Hamilton, 1963). The basic problem confronting foundation designers appears to be the lack of a method of predicting the probable heave.

A considerable amount of research on this problem has been conducted in various countries of the world. A literature survey revealed two analyses that appear promising. One was developed in England (Croney et al 1952) and is based on the results from a suction test and a shrinkage test. The other, developed in South Africa (Jennings 1957), is based on the results of one-dimensional consolidation tests.

This paper discusses the stresses associated with the swelling problem in the field and an assimilation of these stresses in the laboratory. The major point of investigation comprises a comparison of the soil suction test and the one-dimensional consolidation test since it is these test results which have been used by other investigators to predict probable heave.

STRESSES ASSOCIATED WITH THE SWELLING PROBLEM

Upward vertical movements often occur in light structures as a result of the disturbance of the moisture regime existing prior to construction. The amount of movement depends upon the difference between the initial and final equilibrium water regimes. The moisture regimes are related to the relative importance of factors such as transpiration, evaporation, and infiltration. In areas where the climate is humid and the soil profile relatively wet, settlement of a structure may occur due to a cut-off in the amount of infiltration (Aitchison, 1961). In Western Canada where the climate is generally semi-arid, transpiration and evaporation give rise to a moisture-deficient soil profile. Evaporation and transpiration place a tensile stress on the water phase and thus increase the effective stress in the soil. Construction of a building, however, inhibits transpiration and evaporation and the net upward movement of water results in a moisture gain. The moisture gain decreases the pore water tension and results in a volume increase.

The distribution of stresses in the soil profile and the changes that can occur due to transpiration, evaporation, and infiltration have been clearly outlined by Jennings and Kerrich (1962) (Figure 1). Let us assume the case of a soil mass which is initially saturated, with a water table at a certain distance below the ground surface. For the condition of no water flow (Figure 1a), the pore water stress is negative, linear, and directly related to its height above the water table.

The term "soil suction" is widely used to designate the stress in the water phase and is defined as "the difference between the pressure of the pore water and atmospheric pressure and is a measure of the surface forces retaining water in the soil structure" (Croney et al, 1952).

Figure 1b shows the new equilibrium pore-water pressure conditions if a constant evaporation is imposed which is not large enough to cause the entry of air into the soil mass. The pore water pressure versus depth relationship is still linear, but lies to the left of the previous pore-water pressure line. The increase in effective stress causes consolidation and thus a settlement of the ground surface.

As further evaporation and transpiration by plants add to the tensile stress in the pore water, the effective stress is greatly increased and the high tensile stress may cause the soil to crack (Figure 1c). Placing a light structure on this soil mass increases the total stress. The prevention of evaporation and transpiration, however, and the infiltration of rain water results in a gradual decrease of pore-water tension, a reduction in the effective stress, and a volume increase. The volume change or the amount of heave depends upon the magnitude of the initial and final effective stress conditions in the soil mass.

TWO PROCEDURES FOR THE PREDICTION OF HEAVE

One analysis for the prediction of total heave was developed by Croney et al (1952) and is based on the results of a suction test and a shrinkage test. This analysis has been used for several years in Great Britain, India, and other countries to estimate the probable amount of heave beneath asphalt and concrete roadways and airport runways (Russam, 1962).

The initial soil conditions are measured in terms of a water content profile. The final conditions are in terms of an equilibrium water content profile based on an estimated pore-water stress profile which is below atmospheric pressure and a function of the distance above the water table. (The final equilibrium water conditions are estimated from the soil suction versus water content results.) The shrinkage test results are used to relate water contents to the specific bulk volume of the soil.

Another analysis was developed by Jennings (1957) and is based on the results of a "field or natural water content" consolidation test and a "free-swell" consolidation test. The "natural water content" consolidation test is used to represent field conditions where load is applied to the soil without any other external influence to change the moisture regime. The "free-swell" test is used to estimate the final equilibrium water content conditions under the applied load which acts as an impermeable covering over the soil. The amount of heave is predicted by determining the change in void ratio which occurs between the initial and final stress conditions in the field. Further research and modification of this procedure has been reported by Burland (1962).

THEORY

Since the two main procedures that have been used to predict heave are based on two different tests, it was decided to study the relationship between the tests on a typical volume-changing clay soil from Regina, Saskatchewan. There appears to be a definite lack of literature which deals specifically with this relationship. There is also the question of whether the suction test or the one-dimensional consolidation test more closely parallels the conditions to which a soil is subjected in the field such as transpiration, evaporation, infiltration, as well as changes in physical loading.

For clarity, the suction test theory is outlined in considerable detail since it is not found in present soil mechanics textbooks. The process of consolidation has been explained by Taylor (1948) and others by reference to a mechanical analogy using a piston and spring. A modification of their analogy is now proposed to represent the process of consolidation due to suction stresses in the pore water instead of loads applied directly to the solid phase. The modified piston and spring analogy is shown in Figure 2. Consider two frictionless, tightly fitting pistons, one placed in the chamber and the other in the cylinder as shown. The piston in the chamber has a hole in it which represents a pore at the surface of a soil mass. Initially, the stopcock at the bottom of the chamber is closed to prevent the escape of water and a load is placed on the pan connected to the bottom piston. The instant the stopcock is opened, water starts to move from the chamber into the cylinder and as both pistons sink, the load is taken up by the spring. The length of time required for the spring to take up the applied load depends upon the rate at which water escapes through the stopcock. When the piston stops moving, the load on the spring is equivalent to the stress in the water phase. It should be noted that the water meniscus that forms as part of the top piston has a radius of curvature which is a function of the tension applied to the water phase. The maximum tension that the water phase can develop is equal to the air entry value of the opening. Considering the case of a clay soil, the maximum air entry value may be in excess of one atmosphere, perhaps up to fifteen atmospheres or greater.

The changes in neutral and effective stresses during the "consolidation process" in a suction test are shown in Figure 3. Let us consider an undisturbed soil sample, the neutral and effective stresses of which are unknown. Initially, the sample is placed on the porous plate in the suction apparatus and allowed access to water until it comes to equilibrium under an applied suction. The total neutral and effective stresses are then known and are as shown in Figure 3a. Application of a new suction increment does not alter the stresses throughout the sample, except at the drainage surface where the neutral stress goes to $-P_2$ and the effective stress to $+P_2$ (Figure 3b). As consolidation proceeds, the effective stress increases and the tension in the pore water increases a corresponding amount (Figure 3c). When the pore-water tension throughout the sample is equal to P_2, the effective stress is also equal to P_2 and the consolidation is complete. Several points about the suction test are noteworthy: the total stress is atmospheric pressure throughout the consolidation process; after consolidation the water is in a state of tension; volume changes are always of a three-dimensional nature.

It should be noted that the laboratory testing program was carried out on pressure plate and pressure membrane apparatus rather than on a true suction apparatus. The theoretical difference between a true suction test and a pressure test is related to the change in pressure datum. Lowering the stress in the water and leaving the surrounding atmospheric pressure constant (as is done in a suction test) is the same as raising the surrounding air pressure in the cell and keeping the water stress at atmospheric (as is done in a pressure test).

Considering the pressure plate test, Figure 3 would remain essentially unchanged. In either test the important factors to remember in drawing stress diagrams are that stress is being applied to the water phase only and that the flow gradient must initially be at the "stopcock" or point of drainage. The above explanation refers only to a saturated soil mass.

SOIL AND TESTING PROGRAM

The soil used for this testing program was clay of high plasticity from the glacial Lake Regina sediment. It was obtained at elevation 1866.1 ft., i.e., 15.6 ft below the original ground surface of 1881.75 ft., from a test pit in the basement excavation for the new Saskatchewan Government Telephones Building on the northwest corner of College Avenue and Albert St., in Regina, Saskatchewan. A summary of the classification tests is shown in Table I.

A pressure plate extractor (Figure 4) and a pressure membrane extractor (Figure 5) were used to obtain results in a pressure range comparable to that of the standard consolidation test. The pressure plate extractor had an operating range of 0 to 1 kg per sq cm. The specimens are placed on a porous stone of high air-entry. Air pressure is applied from above; the water beneath the stone is at atmospheric pressure (Richards et al, 1943). The pressure membrane extractor extends the operating range by means of a cellulose membrane which has a very high air-entry value (Croney et al, 1958).

As part of this study, a new pressure plate apparatus was built which allows the measurement of the rate of consolidation (Figure 6). The permeability of the porous stone is more than 100 times greater than that of the soil and does not cause significant error in the determination of rate of consolidation.

The testing program involved the determination of the soil suction versus water content relationship, and a comparison of these results with those obtained from the standard one-dimensional consolidation test. Specific bulk volume was determined during the suction test as well as during evaporation after the samples were removed from the suction test apparatus. All testing was performed on soil which was initially remoulded at a water content near the liquid limit. The suction test samples were prepared by consolidating slurry in a one-dimensional consolidometer to various pressures after which they were rebounded to a token pressure. Varying the consolidation pressures gave rise to the various initial water contents. Thus the stress conditions associated with the preparation of the suction and one-dimensional consolidation test specimens were the same.

DISCUSSION OF TEST RESULTS

The results of tests carried out in the pressure plate and pressure membrane apparatus are referred to as soil suction values. These tests, however, do not reduce the pore-water stress below atmospheric but rather increase the surrounding air pressure and leave the pore-water stress at atmospheric pressure. The difference is essentially one of technique and does not appreciably alter the test results (Penner, 1959).

Figure 7 shows the relationship between water content and logarithm of soil suction for all suction tests performed on both the pressure plate and pressure membrane extractors. The one-dimensional consolidation results are shown in Figure 8 which is a plot of water content versus logarithm effective pressure. In comparing the test results, it should be first noted that the one-dimensional consolidation test induces anisotropic consolidation of the sample while the suction test causes isotropic consolidation. Comparisons of the two processes of consolidation (Aboshi and Monden, 1961; Bishop and Henkel, 1962) have shown that more water is forced out of the soil during isotropic consolidation. The difference in the amount of consolidation occurring is explained in terms of changes in the soil structure resulting from anisotropic and isotropic consolidation. The shear stresses between the soil particles is lower in isotropic consolidation and permits more consolidation of the soil mass. In the field, evaporation and transpiration are conducive to isotropic consolidation.

Comparison of the suction and one-dimensional consolidation test results shows their virgin compression branches to be very similar (Figure 9). When the consolidation curve was corrected for the compressibility of the filter paper and side friction in the consolidation ring, the curve appeared to fall directly on top of the suction curve for pressures up to 10 kg per sq cm.

There appears to be a difference in the recompression branches of the two curves (Figure 9). The suction test shows a smoother curve with no distinct break in curvature at the point where the preconsolidation pressure is exceeded. In addition, the suction results have lower water contents than the one-dimensional consolidation results on the recompression branch. The difference in the two curves is probably related either to the structural resistances and shearing stresses associated with isotropic and anisotropic consolidation or to the effect of side friction in the consolidation rings.

Jennings (1960) and Aitchison (1960) proposed that a point would be reached on the virgin compression branch where the suction and consolidation results separate. This point was believed to coincide with the commencement of air entry into the sample. Figure 10 shows the relationship between specific bulk volume and water content as samples of Regina clay were dried, first in the pressure plate extractor and later by evaporation. Specific bulk volume is herein defined as the volume in cubic centimeters occupied by one hundred grams of moist soil. Figure 11 shows the degree of saturation versus water content for the same samples. On the basis of the test results, it can be predicted that the curves should begin to diverge at a water content of approximately 25 per cent, with the one-dimensional consolidation curve going below the suction curve. The classification tests showed the plastic limit to be 25 per cent. The soil suction at this point would be approximately 16 kg per sq cm. The conventional effective stress equation for a two-phase system will not hold below this water content as the soil then constitutes a three-phase system.

In the analyses previously reviewed for the prediction of heave, the suction and the free swell test were used to estimate the final equilibrium conditions. Since the test results appear to be essentially the same, either analysis should give the same equilibrium conditions up to the air entry value of the soil. The main discrepancy would occur in the recompression range of the curves.

The rate of consolidation for Regina clay in the suction tests and in the one-dimensional consolidation test are next compared. Figure 12 shows the coefficient of consolidation versus soil suction and effective pressure for the suction and one-dimensional consolidation tests. In all cases, the load increment ratio was approximately 1. Since several of the factors affecting the coefficient of consolidation are equal in both tests, it is advantageous for the sake of clarity to plot pressure versus time to 50 per cent consolidation for a corrected length of drainage path. Figure 13 shows the plot of time to 50 per cent consolidation versus effective pressure for a corrected drainage length of 1 cm. The results show that at very low effective pressures (approximately 0.1 kg per sq cm) the time to 50 per cent consolidation for both types of tests is similar. At higher effective pressures the suction test requires much longer time for 50 per cent consolidation.

CONCLUSIONS

The following conclusions have been reached in this investigation:

1. The virgin compression branch of the suction and the one-dimensional consolidation test results are essentially the same in the pressure range tested.

2. The recompression branch of the suction test shows no distinct break in curvature at the preconsolidation pressure. At a given stress within the recompression range the equilibrium moisture content in the suction test is lower than in the conventional consolidation test. This difference is believed to be a result of structural resistance to recompression due to shearing stresses and/or side friction in the consolidation ring.

3. When Regina clay is dried from a slurried condition, the soil remains saturated to a water content near the plastic limit which corresponds to a soil suction of approximately 16 kg per sq cm. At moisture contents lower than the plastic limit, air invasion takes place resulting in partial saturation. At this and lower moisture contents the suction and the one-dimensional tests are not comparable.

4. The rate of consolidation appears to be different in the suction test than in the one-dimensional consolidation test. At low levels of effective stress (i.e. below 0.15 kg per sq cm) the rate in the former is greater than in the latter. At higher stress levels the reverse is true with the difference in rate increasing at higher effective stress levels. The plot of consolidation time to 50 per cent consolidation versus effective pressure shows the time to be longer in the suction test with a greater difference with increasing pressure. The low effective pressure range should, therefore, be further investigated.

ACKNOWLEDGMENTS

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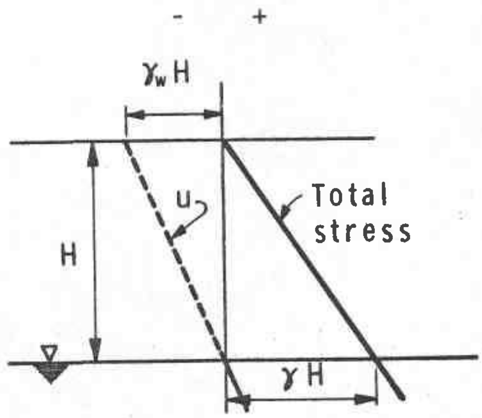
TABLE I

SUMMARY OF CLASSIFICATION TESTS ON REGINA CLAY

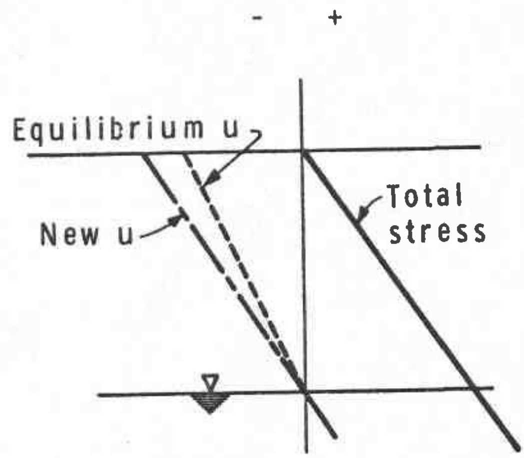
TEST		RESULT
Specific Gravity		2.83
Atterberg Limits		
	Liquid Limit	75.5 %
	Plastic Limit	24.9 %
	Shrinkage Limit	13.1 %
	Plasticity Index	50.6 %
Grain-size Distribution*		
	Sand Sizes	8 %
	Silt Sizes	41 %
	Clay Sizes	51 %
Mineralogical Composition of Material less than 2 microns**		
	Montmorillonite	77 %
	Illite	15 %
	Kaolinite	8 %
Exchange Capacity*** (milliequivalents per 100 grams dry weight of soil).		31.7 me/100 gm
Exchangeable Cations		
	Magnesium	15.3 me/100 gm
	Calcium	54.4 me/100 gm
	Potassium	0.59 me/100 gm
	Sodium	1.77 me/100 gm

* M.I.T. Grain-size Scale
** X-ray Analysis performed by Alberta Research Council
*** Exchange capacity analyses performed by the Soil Science Department, University of Alberta

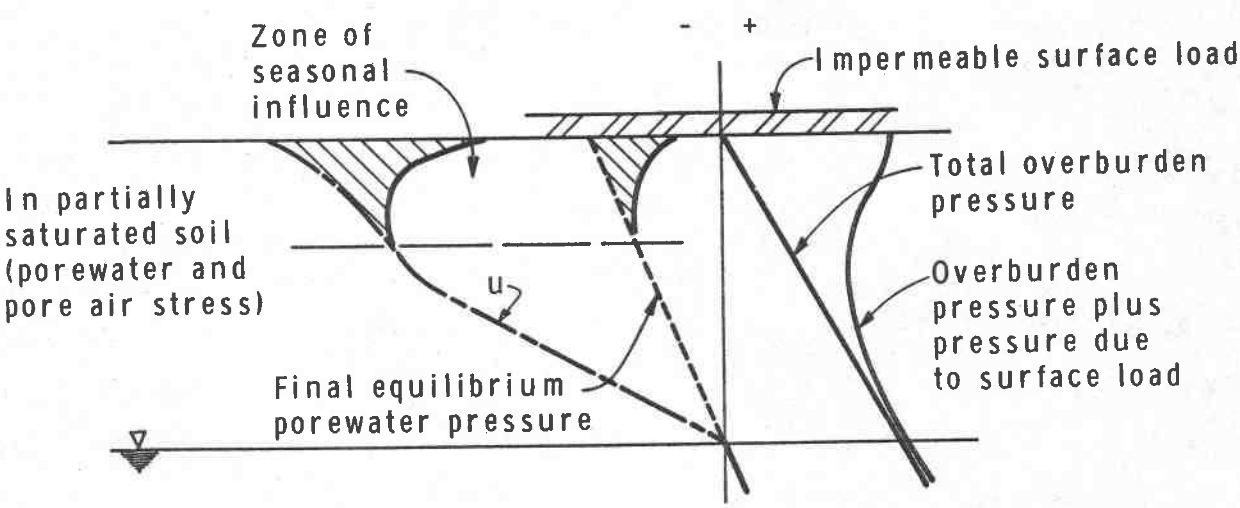
NOTE: Specific gravity, Atterberg limits, and grain size are the average of three sets of tests; X-ray analysis and exchange capacity were performed on one average sample.



(a) No evaporation from surface



(b) With evaporation small enough that no air entry or cracking of the soil occurs



(c) Evaporation large enough to cause air entry and cracking of the soil

FIGURE 1

STRESSES ACCOMPANYING THE DRYING AND COVERING OF A SOIL MASS. (After Jennings and Kerrich, 1962)

BR 3834-1

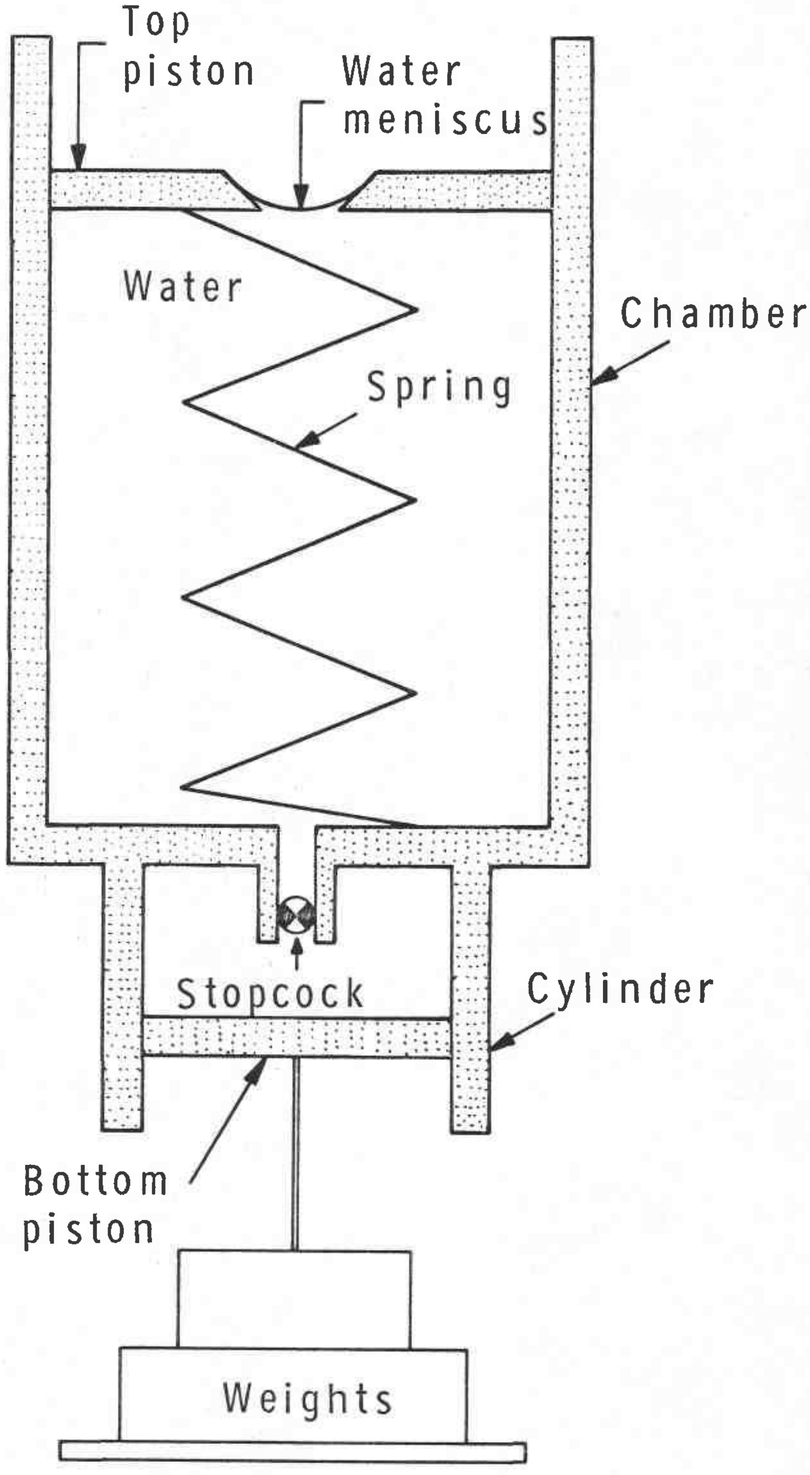
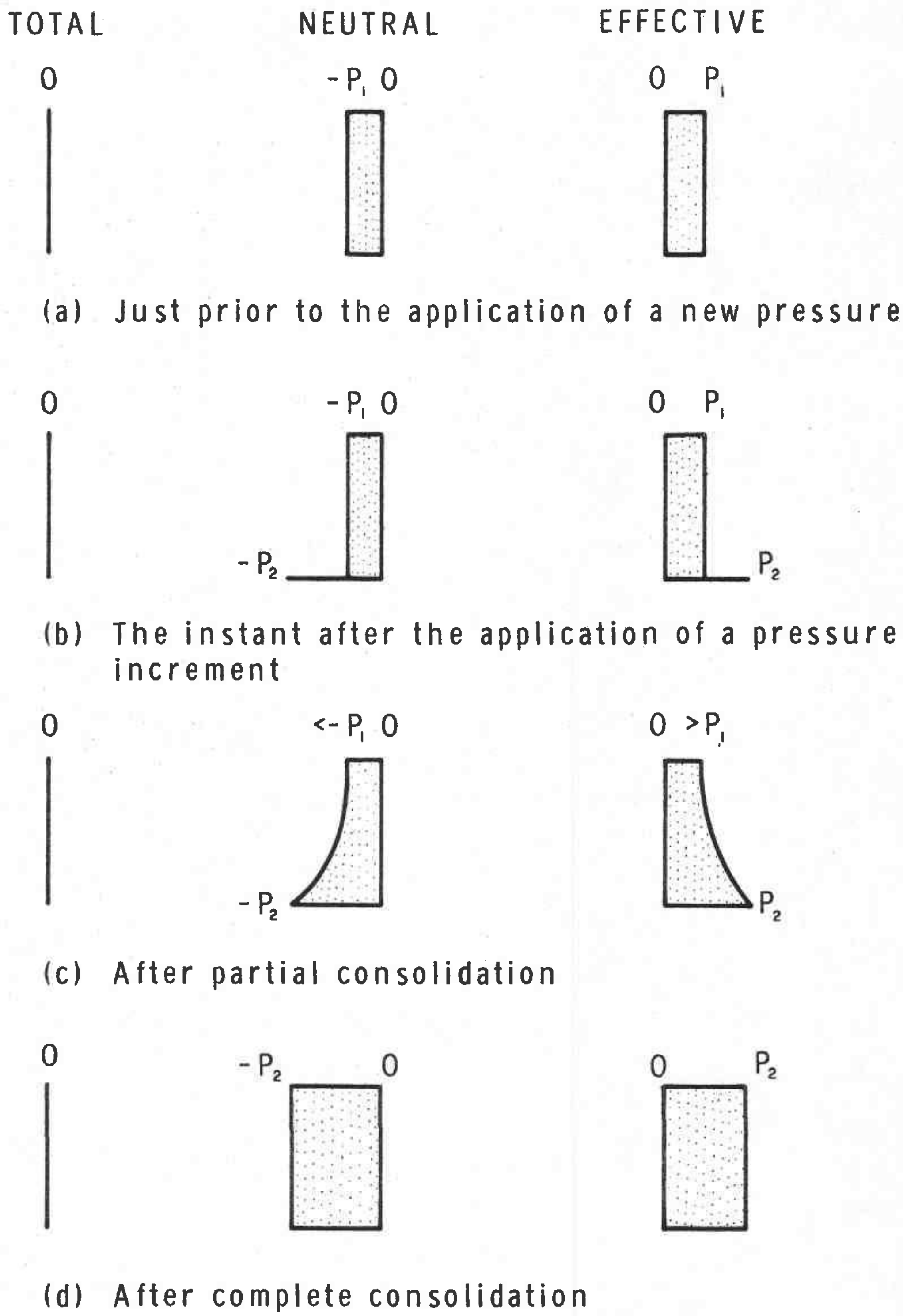


FIGURE 2

SUCTION TEST - PISTON AND SPRING ANALOGY

BR 3834-2

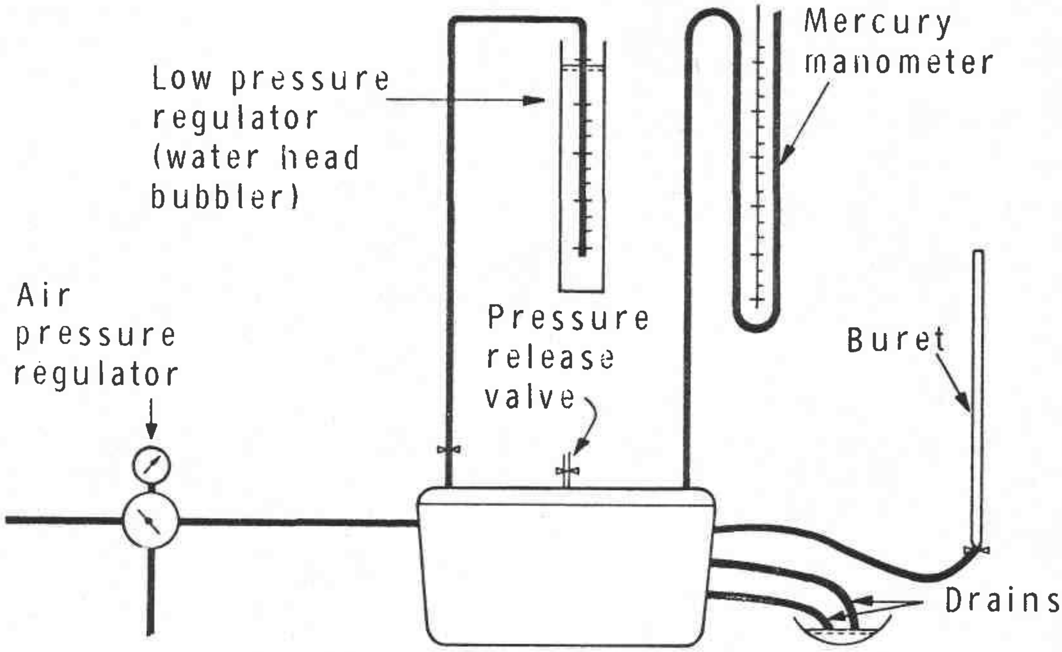


Note: Drainage at bottom of sample only

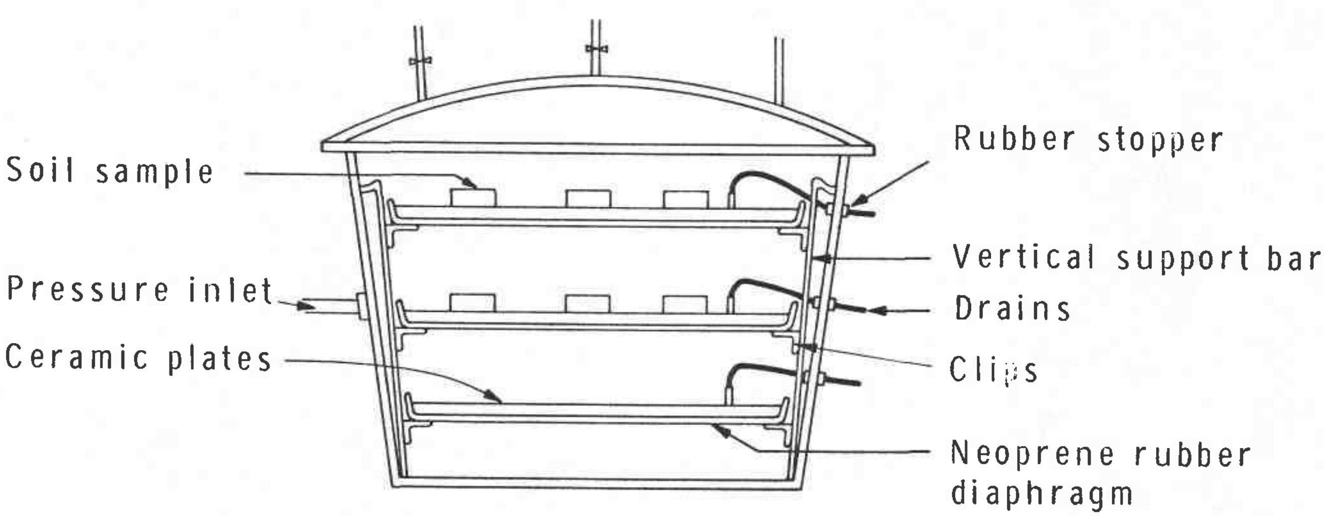
FIGURE 3

STRESS CHANGES DURING THE CONSOLIDATION PROCESS IN A SUCTION TEST

BR 3834-3



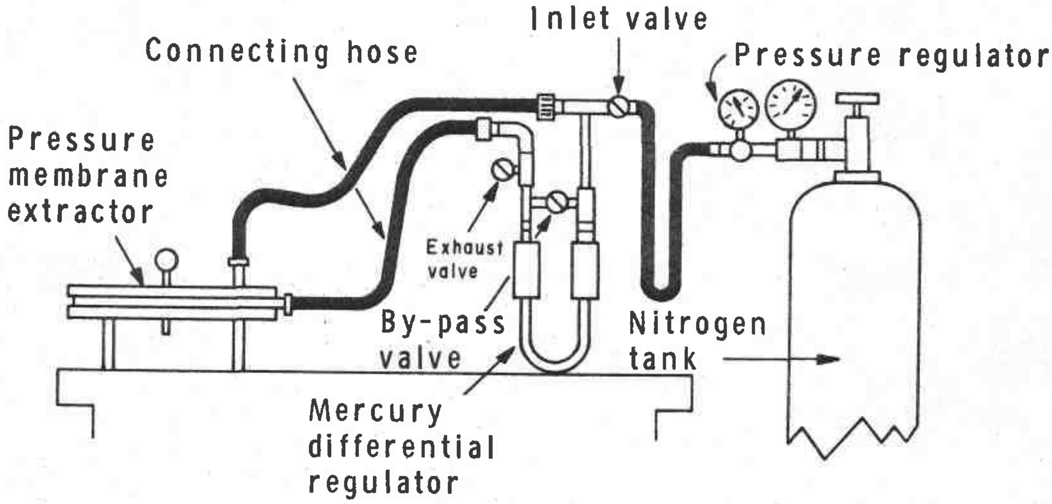
(a) ASSEMBLY OF PRESSURE PLATE EXTRACTOR



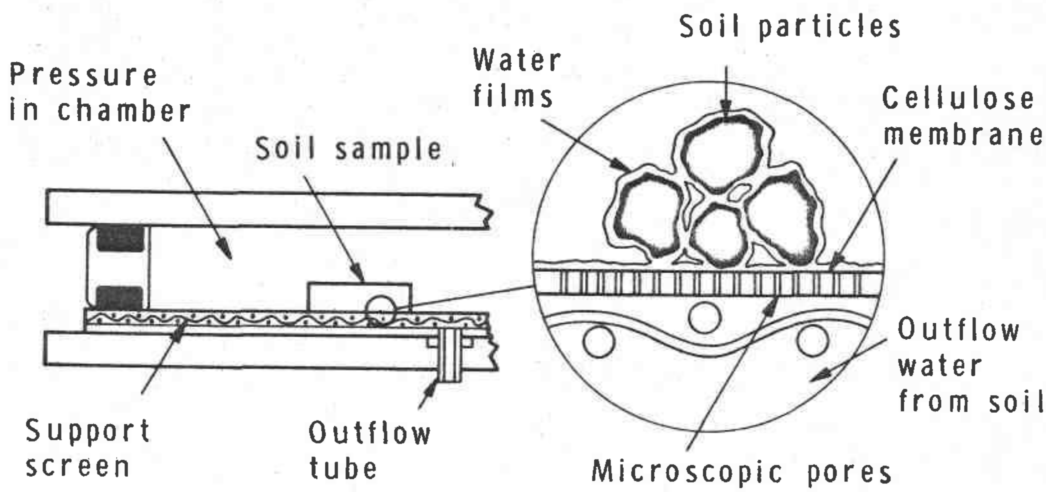
(b) PRESSURE PLATE EXTRACTOR

FIGURE 4

BR 3834-4



(a) ASSEMBLY OF PRESSURE MEMBRANE EXTRACTOR

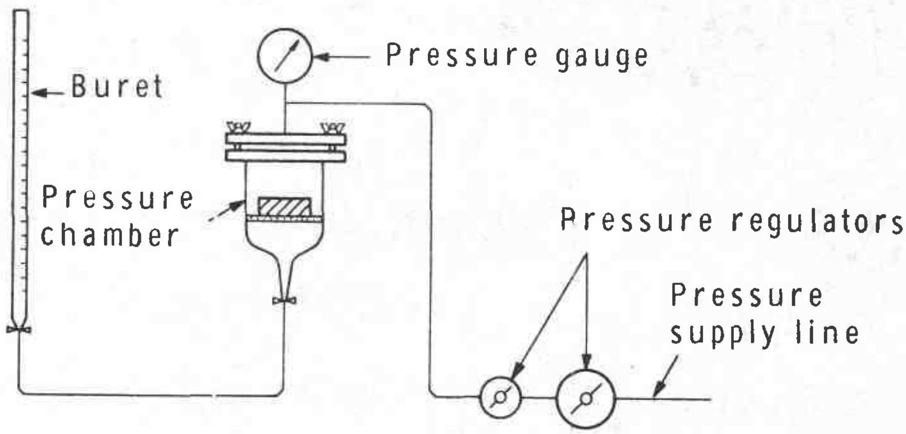


(b) SECTION VIEW OF EXTRACTION PROCESS

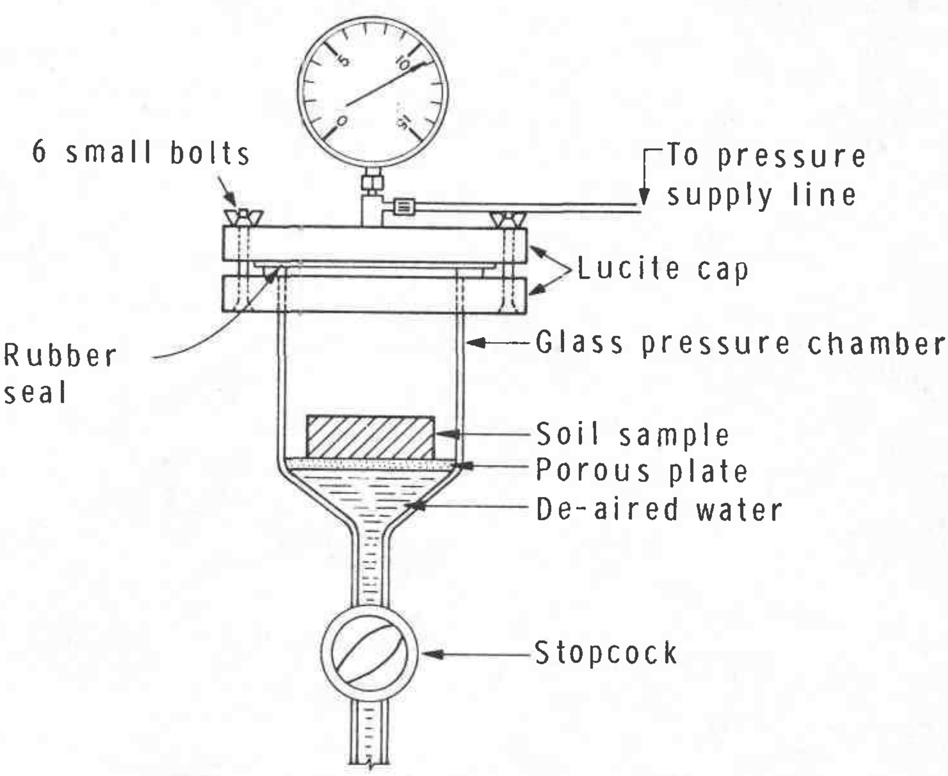
FIGURE 5

PRESSURE MEMBRANE EXTRACTOR

BR 3834-5



(a) ASSEMBLY OF NEW POROUS PLATE APPARATUS



(b) NEW PRESSURE PLATE APPARATUS

FIGURE 6

BR 3834-6

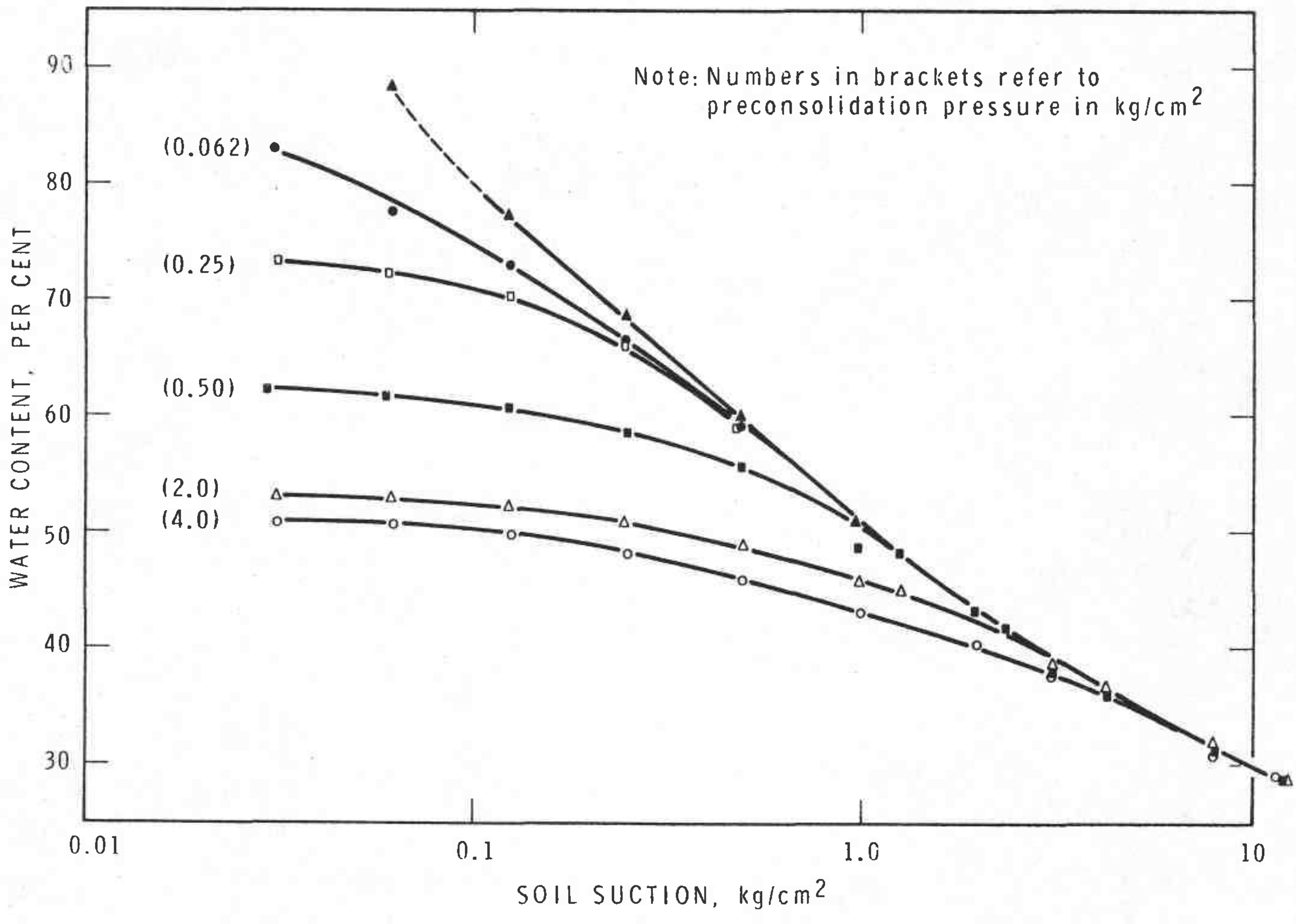


FIGURE 7

SOIL SUCTION VERSUS WATER CONTENT FOR REMOLDED REGINA CLAY

BR 3834-7

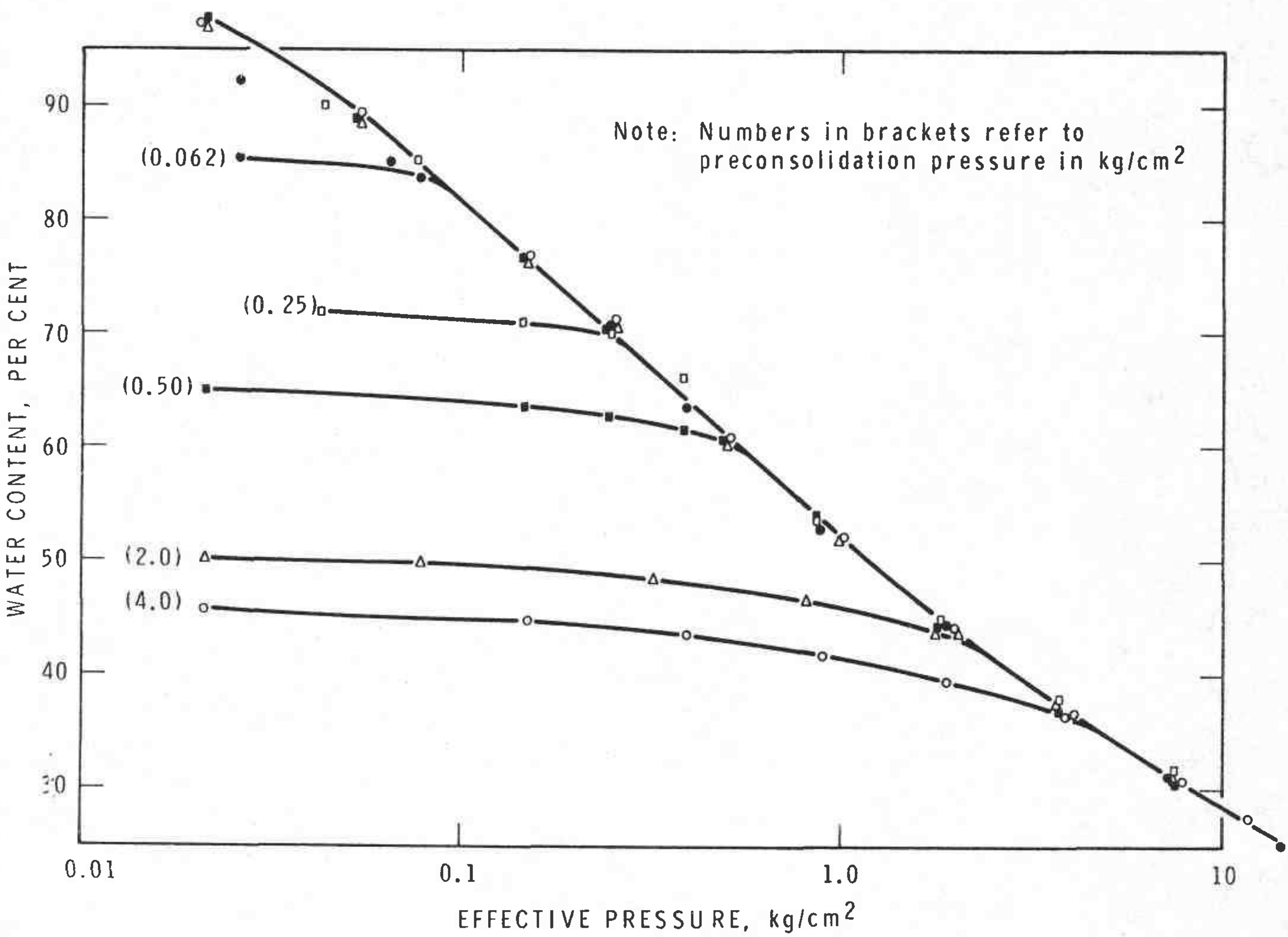


FIGURE 8

EFFECTIVE PRESSURE VERSUS WATER CONTENT FOR REMOLDED REGINA CLAY DERIVED FROM ONE-DIMENSIONAL CONSOLIDATION TESTS

BR 3834 - 8

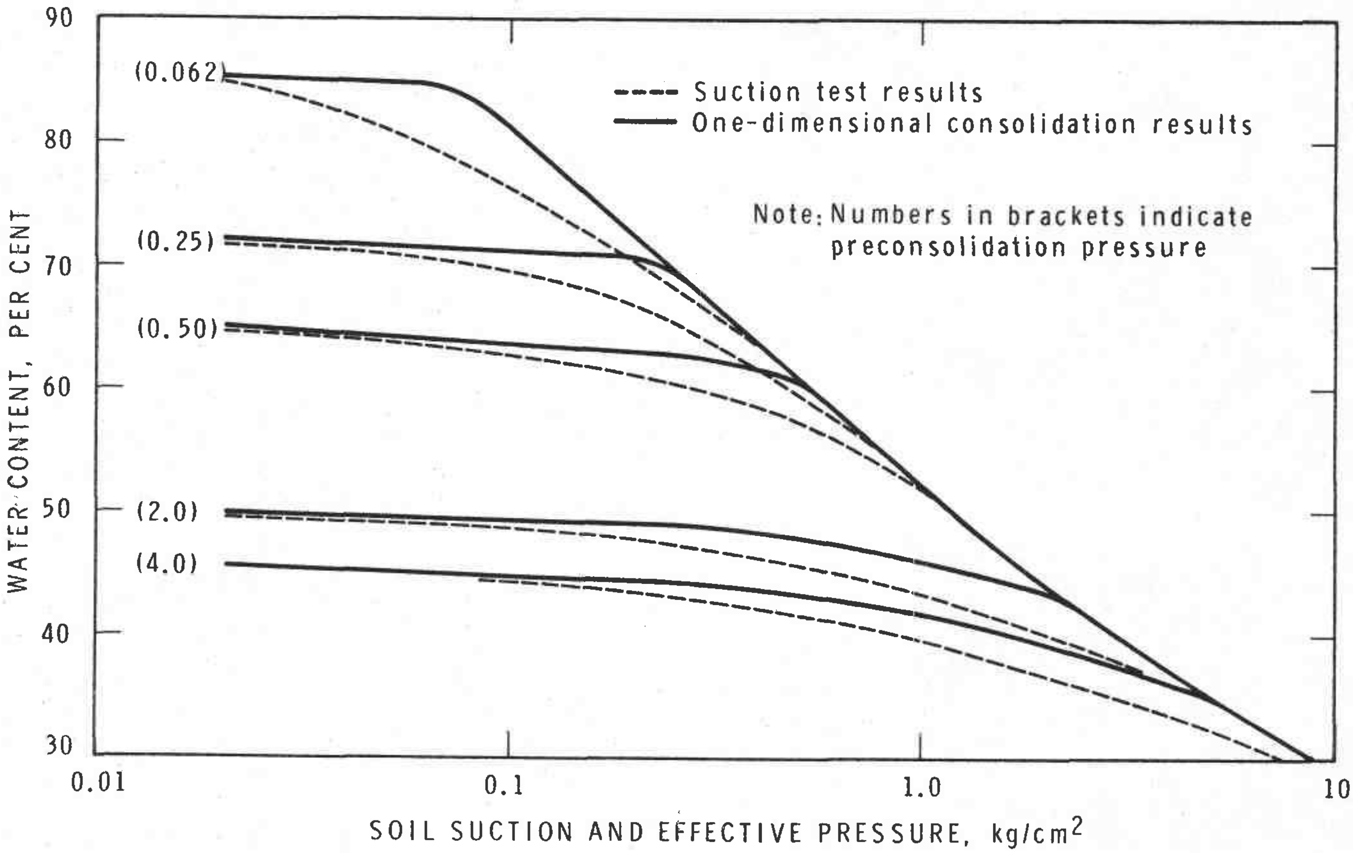


FIGURE 9

COMPARISON OF RECOMPRESSION BRANCHES FOR SUCTION AND ONE-DIMENSIONAL CONSOLIDATION TESTS FOR REGINA CLAY

BR 3834 - 9

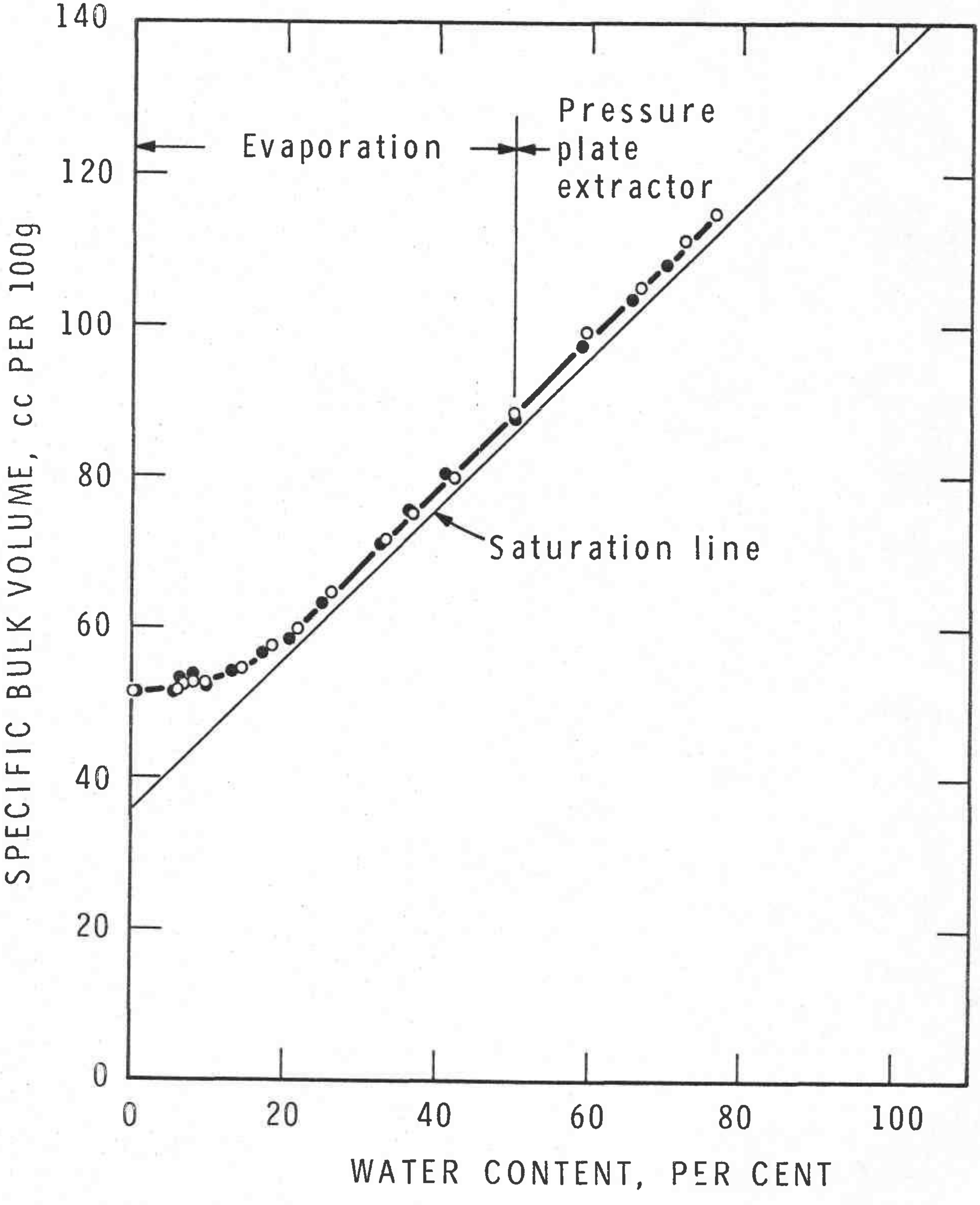


FIGURE 10

SPECIFIC BULK VOLUME - WATER CONTENT FOR REGINA CLAY

BR 3834-10

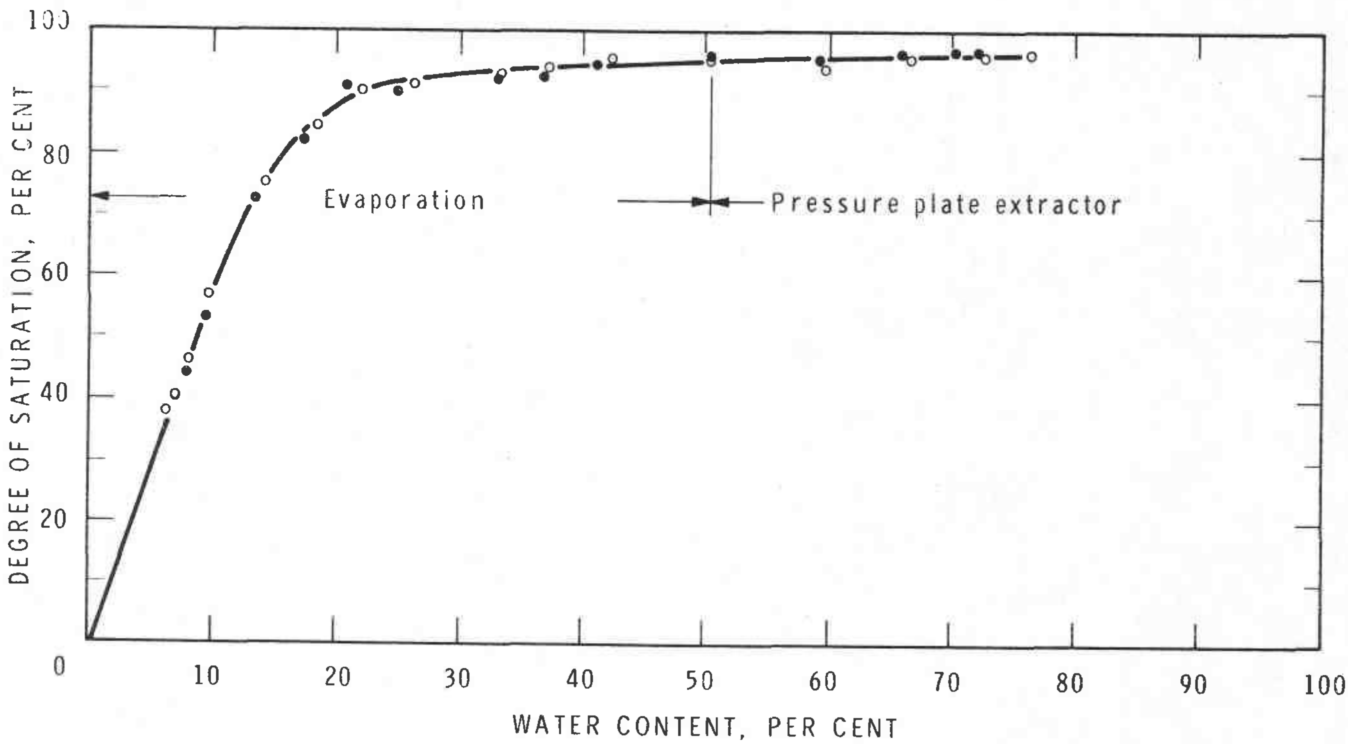


FIGURE 11

DEGREE OF SATURATION - WATER CONTENT RELATIONSHIP OF REGINA CLAY

BR 3834-11

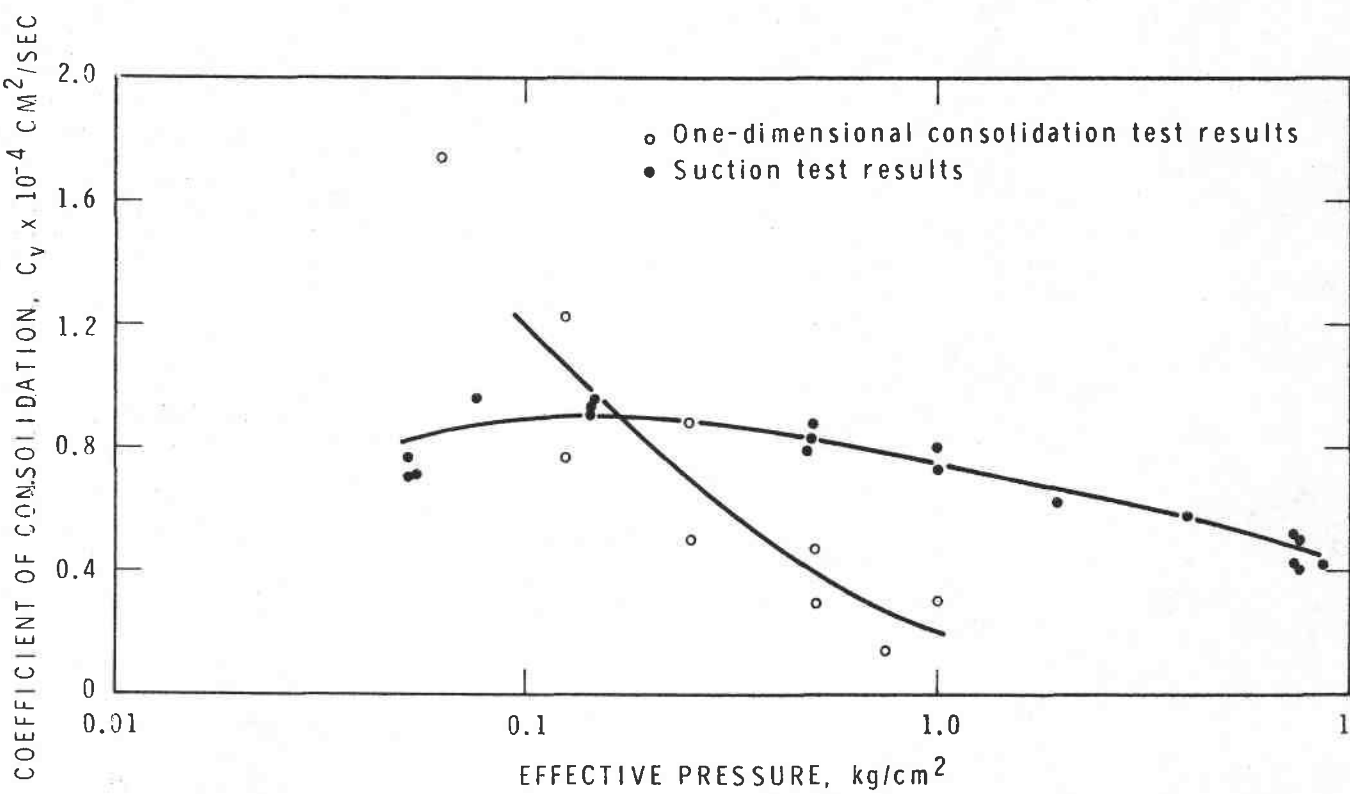


FIGURE 12

COEFFICIENT OF CONSOLIDATION IN THE ONE-DIMENSIONAL CONSOLIDATION AND SUCTION TESTS VERSUS EFFECTIVE PRESSURE

BR 3834-12

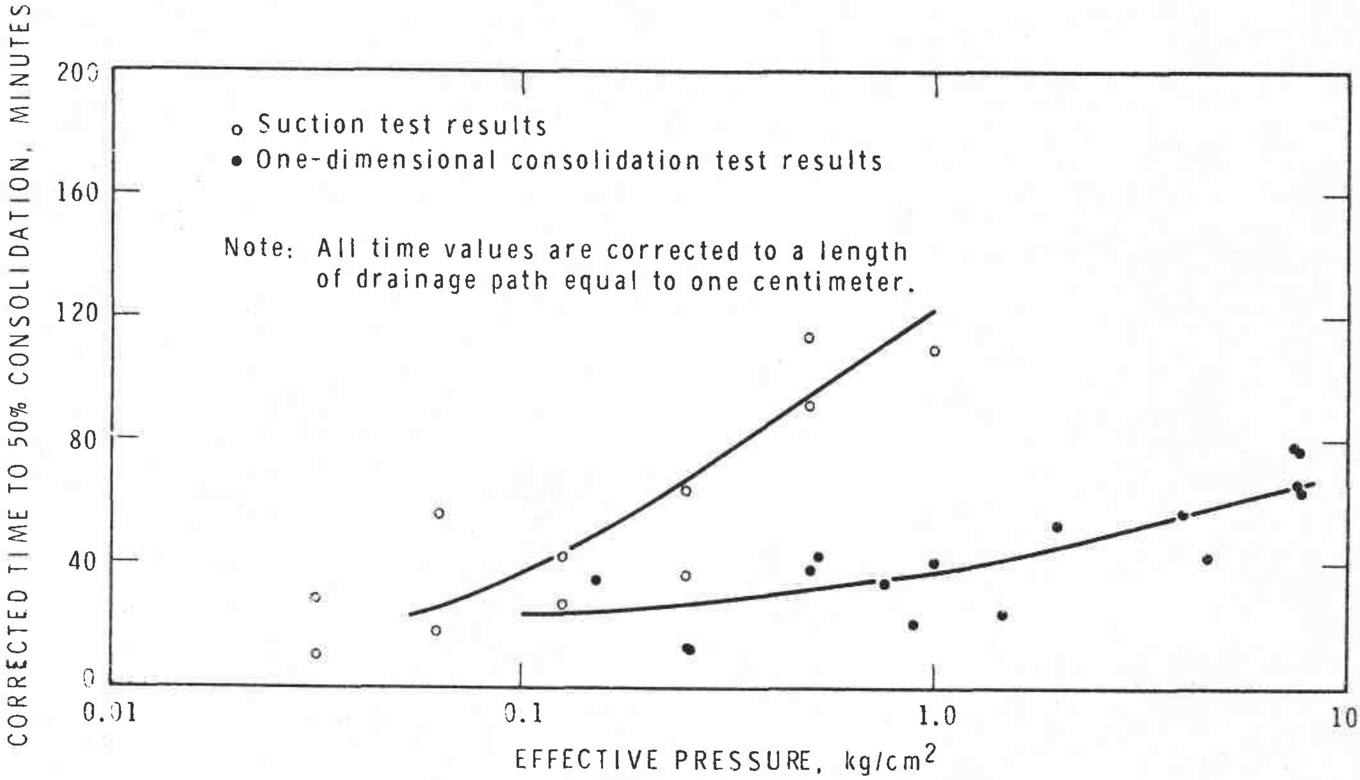


FIGURE 13

CORRECTED TIME TO 50% CONSOLIDATION IN THE ONE-DIMENSIONAL CONSOLIDATION AND SUCTION TESTS VERSUS EFFECTIVE PRESSURE

BR 3834-13