A Consideration of the Major Drawback in Null Type Measurement of Negative Pore Water Pressure

by

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Introduction

In partially saturated soils the pressure in the pore water, u_w, is lower than that in pore air, u_a. When pore air pressure is zero (gauge) the pore water pressure is negative, i.e. water is in a state of tension. There are numerous techniques available for measurement of negative pore water pressure. These have been reviewed by Satija (1978). The axis translation technique proposed by Hilf in 1956, continues to be particularly suitable for measuring pore water pressures during shear in a triaxial apparatus. This technique employs a high air entry value ceramic disc in between the soil sample and the measuring system. This technique is described briefly in the Appendix. Measurement with such a technique may be viewed as a null-type measurement. The water phase in the soil, the water in the ceramic disc and the water in the pore water pressure measurement line constitute a closed system.

Doubts about null-type measurements have been raised by Fredlund (1973). He states that air diffuses through the high air entry ceramic disc and comes out of solution below the ceramic disc which forces water upwards through the disc back into the soil and 'slowly the measured pressure changes from the original water pressure to the applied air pressure. In other words, the difference between the air and water pressure should tend toward a constant value but instead it continuously decreases due to a limitation in the measuring system. This behaviour is commonly observed when attempting to perform null type measurements of $(u_a - u_w)$.'

As early as 1961, Bishop and Donald while discussing the difficulties associated with measurement of volume of water flowing out of partially saturated soil samples during consolidated drained (CD) tests also raised this issue of diffusion of air. They stated that although the saturated ceramic disc resists the passage of free air at $(u_a - u_w)$ values which were less than the air entry value of the disc, air diffuses through the water in the ceramic disc and then comes out of solution below the ceramic disc under the influence of reduced pressure. These bubbles of air then cause problems in accurate measurement of the volume of water drained from the sample and also hinder the passage of water from the base back into the sample during a drained test. To overcome this difficulty they resorted to the use of a bubble pump for removal of free air from the system.

In fact literature on partially saturated soils now takes it almost for

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granted that whenever a pore water pressure measuring system malfunctions it is on account of diffusion of air into the system, Williams (1966), Bishop (1969), Dunlop et. al. (1978) etc.

It is of interest to investigate the validity of this view both theoretically by a study of the physics of the diffusion process as well as by controlled experimental work and assess whether in fact diffusion of air is as big a menace as it is believed to be. Such a study is presented in this paper.

Theoretical Study

Williams (1966) has described in detail the process of air diffusion in pore water. His analysis is summarized below :

Consider a partially saturated sample as shown in Fig. 1. Air-water interfaces of radius r_1 are visualized as being formed at sample boundaries. Air also exists as bubbles in pore water with different radii. Three bubbles *A*, *B* and *C* are shown in Fig. 1. Bubble *A* has a radius equal to r_1, bubble *B*, has a radius less than r_1 and equal to r_o, and bubble *C*, has a radius greater than r_1 and equal to r_2. If the pressure in the pore

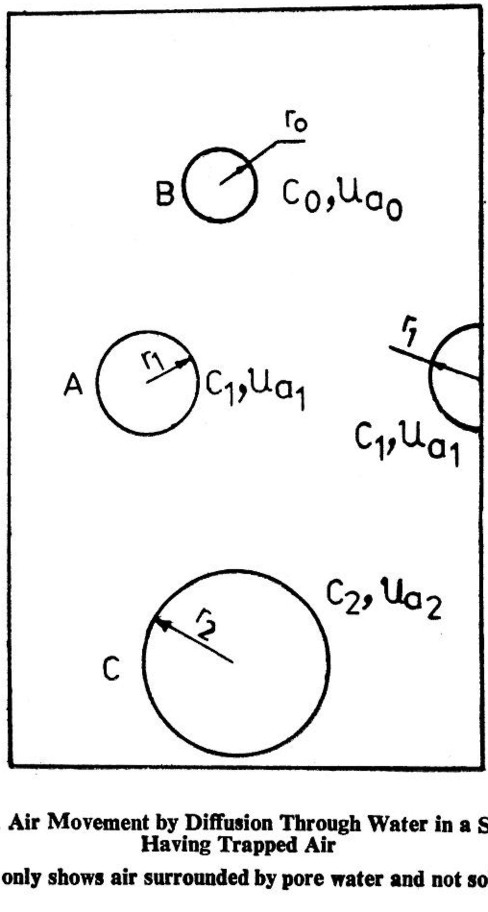

FIGURE 1. Air Movement by Diffusion Through Water in a Soil Sample Having Trapped Air

(The drawing only shows air surrounded by pore water and not solid particles)

water is constant, then the pressure in the air at sample boundary and in Bubble *A* is equal to u_{a_1} which, as per the capillary equation is equal to

$$u_{a_1} = u_w + \frac{2T}{r_1} \qquad \ldots(1)$$

Where *T* is the surface tension of water.

The pressure in the air in bubble *B* is u_{a_o} which is greater than u_{a_1} since r_o is smaller than r_1 and the pressure in the air in bubble *C*, u_{a_2} is less than u_{a_1} since r_2 is greater than r_1.

Air pressure governs the solubility of air in water as per Henry's law : greater the air pressure, the greater is the concentration of air that can be dissolved in the surrounding water. The concentration of dissolved air is, as such, highest around bubble *B*, and is designated as C_o, it is less around the interface at sample boundary and around *A* where it is designated as C_1, and it is minimum around bubble *C* where it has a value of C_2.

Different concentrations of dissolved air at different locations in the sample constitute a situation which is not one of equilibrium. Air as such will move through pore water from zones of high concentration to zones of low concentration by diffusion as per Fick's law : The rate of mass transfer $\frac{dm}{dt}$ is given by the product of the coefficient of diffusion, *D*, and the concentration gradient $\frac{dC}{dx}$ i.e.

$$\frac{dm}{dt} = -D\frac{dC}{dx} \qquad \ldots(2)$$

When $\frac{dC}{dx}$ is zero, the diffusion process ceases.

Consider the bubble *B*: dissolved air surrounding it has the highest concentration, this dissolved air will therefore move away from the zone around *B*. As it moves away, more air from the bubble can dissolve into the surrounding water, thus reducing the bubble size and increasing the pressure of air in it which in turn induces more air to go into solution. The process continues until bubble *B* vanishes.

Bubble *C*, on the other hand, is in a different situation. On account of the low concentration of dissolved air around it air diffuses towards bubble *C*. As it approaches bubble *C* it comes out of solution since the water surrounding bubble *C* becomes oversaturated with air. The size of bubble *C* thus increases which has the effect of reducing pressure u_{a_2}, which in turn further induces movement of air towards bubble *C* and bubble *C* continues to increase in size. Its growth is arrested by its extension into small pores where the air water interfaces again have a small radius.

It is evident, therefore, that diffusion of air occurs only due to difference in concentration of dissolved air in pore water and by this process small bubbles vanish but large bubbles tend to grow larger. This process of accumulation of air by air coming out of solution in a particular zone due to the presence initially of a large bubble will be referred to hereafter as mechanism I.

Liebermann (1957) identifies another mechanism, referred to hereafter as mechanism II, whereby air comes out of solution. He states that the notion of air bubbles persisting for long periods in pure unsaturated (i.e. unsaturated with air) water is incorrect. His studies show that a bubble's size diminishes rapidly even in deaired water with contaminants. Insoluble nuclei of contaminants, however, house submicroscopic bubbles which serve as bubble regenerators when the water pressure is reduced. The reduction in water pressure serves to produce a zone around the nuclei where water becomes oversaturated by air and air comes out of solution.

This mechanism II thus seems to cause air to come out of solution when water pressure is reduced. Mechanism I, it will be recalled, induces air to come out of solution by inducing an existing large bubble to grow. No other relevant mechanism which induces air to come out of solution is discussed in the literature.

Experimental Work

In Soil Mechanics studies for understanding the behaviour of partially saturated soil, one often resorts to triaxial tests. Prior to shear, one needs to measure the negative pore water pressure existing in the sample i.e. a null measurement of existing pore water pressure. One may also wish to alter this negative pore water pressure. It can be increassed by a process termed as desaturation (M.I.T., 1963) which consists of simultaneously increasing the cell pressure σ_c. and the pore air pressure u_a by the same amounts which causes an equal increase in u_w; this induced u_w is then allowed to dissipate by letting water drain off from the sample and as u_w reduces to zero, (u_a-u_w) increases. Samples can be sheared either under drained conditions (CD) i.e. the cell pressure, the pore air pressure and the pore water pressure are all kept constant during shear, and in order to ensure this the volume of pore water and pore air are allowed to change; or under undrained conditions i.e. the volume of both pore air and pore water are not allowed to alter, the cell pressure is kept constant but u_a and u_w are allowed to change; or under constant water content conditions $\overline{CW}$ i.e. the cell pressure and the pore air pressure are kept constant but the pore water pressure changes during shear, the volume of pore water is not allowed to alter but pore air volume is allowed to change.

Whether air coming out of solution below the ceramic disc will produce difficulty in the measurement of pore water pressure or not needs to be considered for the five above mentioned situations encountered during triaxial testing i.e. (1) null measurement, (2) desaturation, (3) drained shear, (4) undrained shear, and (5) shear at constant water content. Presented below are test results for four of these five situations (excluding shear under undrained condition). Also presented for each of the four cases is a discussion of whether mechanisms I or II described in the previous section are likely to operate or not.

The experimental investigation was conducted on compacted samples of Dhanauri clay whose classification details are presented in Table 1. Soil samples were statically compacted using either low energy to achieve low density samples, designated B or high energy to achieve higher density

TABLE 1

Soil Classification Characteristics

Liquid Limit	48.5%
Plastic Limit	25.0%
Plasticity Index	23.5%
Percent Sand Size	5.0
Percent Silt Size	70.0
Percent Clay Size	25.0
Activity	0.94
Specific Gravity of Solids	2.75
Base Exchange Capacity	8.7 me/100 gms of dry soil
Classification by Unified Classification System	CL-CH

samples, designated A, at the same compaction moisture content some what dry of optimum for both energies. Samples were tested either in their post compaction state after subjecting them to different $(\sigma_c - u_a)$ or they were first subjected to desaturation to raise their $(u_a - u_w)$ and then sheared after applying different $(\sigma_c - u_a)$ Both drained (CD) tests and constant water content $(\overline{CW})$ tests were conducted. Thus sample designated $A\ \overline{CW}$ 2-4 is the sample which was prepared at high density, was sheared under $\overline{CW}$ condition with a pre-shear $(u_a - u_w)$ of 2 kg/cm^2 achieved by desaturation, and $(\sigma_c - u_a)$ of 4 kg/cm^2.

1. Null Measurement

In null type tests, flow of water is not permitted and the water phase is controlled as a closed system. As such, pressure in water below and above the ceramic disc is equal at equilibrium. Since air pressure is applied at the top of the sample through the top cap, air will get dissolved in the pore water according to Henry's law and thus the concentration of dissolved air in pore water will depend upon the applied pore air pressure. Below the ceramic stone, the water initially exists in a deaired state. The saturated ceramic disc does not permit the passage of free air. Air in solution is likely to pass through the disc by diffusion to equilibriate concentration of dissolved air above and below the ceramic disc as per Fick's law.

In preparing the equipment for measuring negative pore water pressure the ceramic disc and the pore water pressure measurement line are carefully deaired by permeating deaired water under pressure through the ceramic disc and the lines. The possibility of a large air bubble remaining below the ceramic disc is therefore negligible. In view of this, air coming out of solution below the ceramic disc by mechanism I is not likely.

Since in the axis translation technique the pressure in water above and below the ceramic disc are rapidly brought into the positive range and at equilibrium are equal, mechanism II cannot operate either and thus the question of insoluble nuclei having submicroscopic bubbles increasing in size also does not arise. Dissolved air will diffuse through the ceramic disc but there is no mechanism to induce air to come out of solution below the ceramic disc. This corroborates well with the experimental observations reported herein which show that after having attained an equilibrium value of (u_a-u_w), the (u_a-u_w) remains constant with time even for periods as long as a week. The results are presented in Figs. 2 and 3.

2. Desaturation

Under this situation, as described earlier, pressure in the cell and the pore air of the sample is increased which induces an increase in the pore water pressure. The pore water pressure is then allowed to dissipate by permitting flow of water from the sample through the ceramic disc to the drainage line. The pressure in the water in the drainage line below the ceramic disc is maintained at atmospheric pressure and is less than the pressure in the pore water above the ceramic disc. Due to the low pressure below the ceramic disc, mechanism *II* may become operative and bubbles of air may be formed out of submicroscopic insoluble nuclei. Once a bubble appears below the ceramic disc, mechanism I may also operate due to the difference in concentrations of dissolved air in the pore water of soil sample and that surrounding the air bubble under the ceramic disc. During desaturation process in tests conducted in the laboratory to attain values of (u_a-u_w) of 2 and 3 kg/cm^2, no air was observed to collect below the ceramic disc. For samples in which a value of (u_a-u_w) of 4 kg/cm^2 was attained during desaturation, air did come out of solution below the ceramic disc in four out of eight tests. A bubble pump of the type described in M.I.T. (1963) was used to flush the air bubbles from below the ceramic disc and the volume of air flushed out is presented in Table 2.

3. Drained Shear

In a drained test, the pore water pressure is kept constant during the shearing process. The rate of deformation used is such that any tendency for the development of pore water pressure induces water to flow from or into the soil. Thus the pressures below and above the ceramic disc are nearly the same and remain constant with time. As discussed for the null measurement situation there is no mechanism likely to induce the air to come out of solution below the ceramic disc as indeed were the observations during *CD* tests (See Table 2).

4. Shear at Constant Water Content

During shear, flow of water from or into the soil sample in $\overline{CW}$ test is not permitted. Pressure in water below and above the ceramic disc remains the same. As discussed for the null measurement situation, if proper care has been taken to deair the ceramic disc and pore water pressure measurement line prior to the test there is little possibility of air coming out of solution below the ceramic disc by mechanism I. During the shearing process, the pore water pressure keeps on varying and may increase or decrease from its pre-shear value. In the event it decreases significantly it is possible that mechanism II may become operative and air be released from water below the ceramic disc. In the laboratory investigation conducted no air was observed to accumulate below the ceramic disc in $\overline{CW}$ test (see Table 2) basically because these tests were conducted at an elevated pressure in the pore water achieved by utilizing the axis translation technique. During shear the pore water pressure in fact increased for most tests, only for tests with (u_a-u_w) equal to the 'as-compacted' value did it

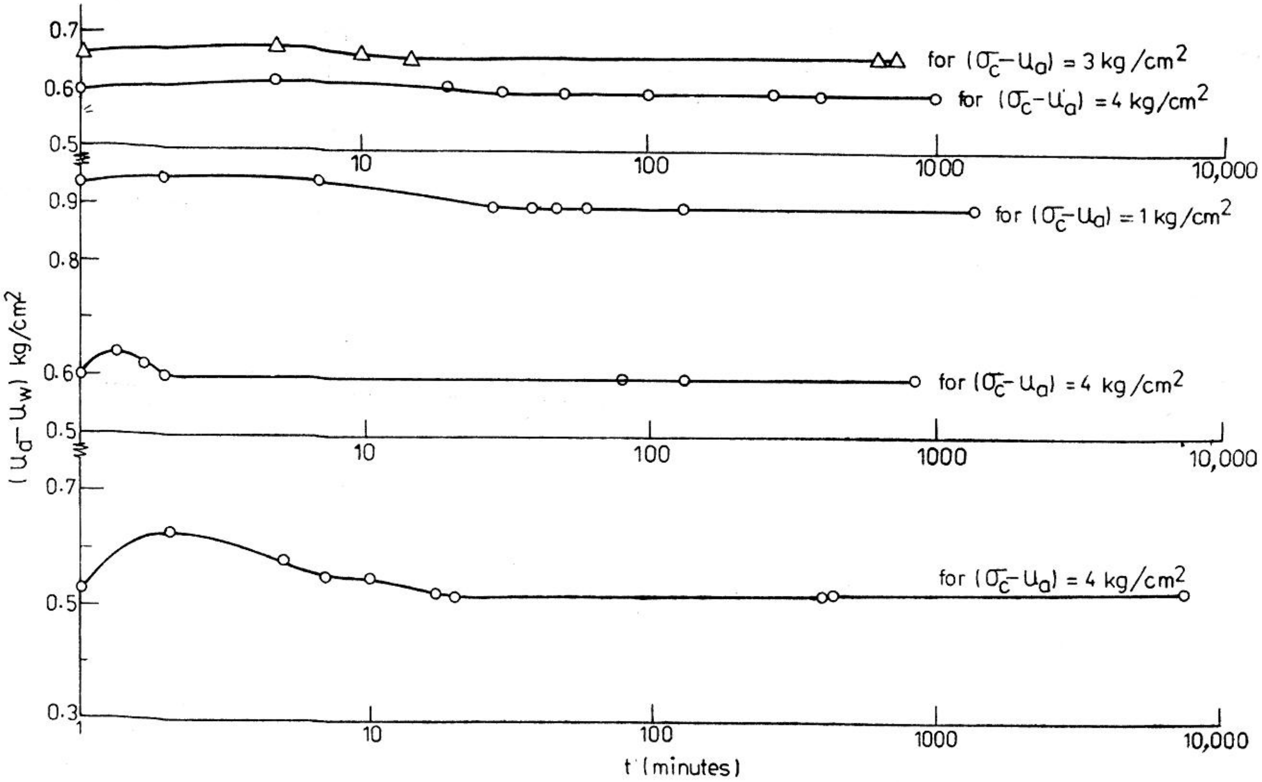

FIGURE 2. Measurement of $(u_a - u_w)$ With Time in Statically Compacted Dhanauri Clay

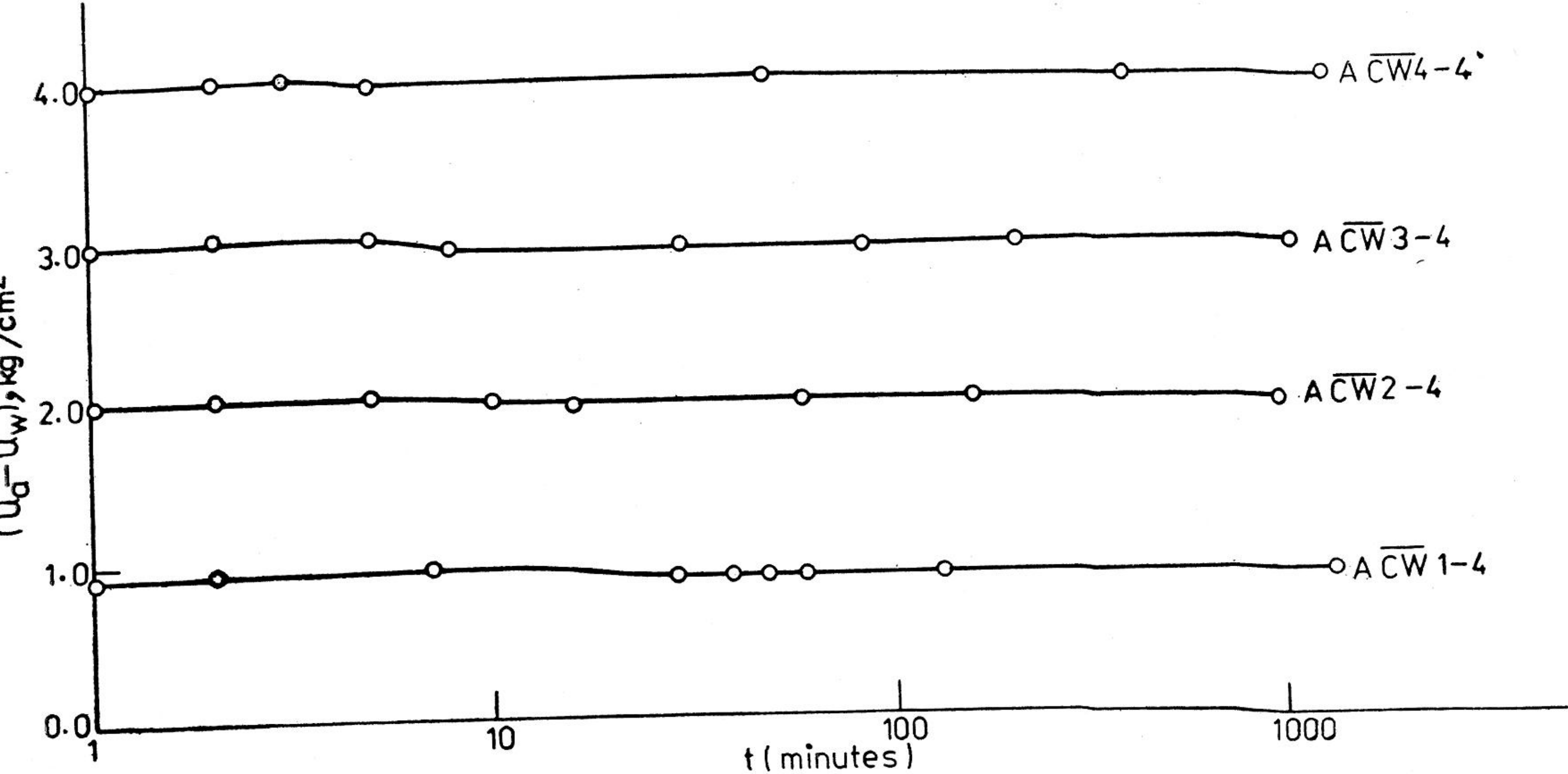

FIGURE 3. Measurement of $(u_a - u_w)$ with Time for Compacted Samples for $(\sigma_c - u_a) = 4$ Kg/cm^2

TABLE 2

Volume of air flushed out from the drainage line after desaturation to achieve $(u_a - u_w)$ of 4 kg/cm^2 and after shear

S. No.	Sample designation	After Desaturation		After Shear	
		Volume of air flushed out from drainage line	Corrected quantity of water drained	Volume of air flushed out from drainage line	Net drainage of water from the sample %
1.	$A\overline{CW}$ 4-1	No air	3.60 c.c.	No air	0
2.	$A\overline{CW}$ 4-4	0.05 c.c.	4.05 c.c.	No air	0
3.	$B\overline{CW}$ 4-1	No air	3.35 c.c.	No air	0
4.	*BCW* 4-4	No air	4.10 c.c.	No air	0
5.	*ACD* 4-1	No air	3.75 c.c.	No air	—0.70
6.	*ACD* 4-4	0.05 c.c.	4.35 c.c.	No air	—1.47
7.	*BCD* 4-1	0.05 c.c.	3.35 c.c.	No air	—0.80
8.	*BCD* 4-4	0 05 c.c.	3.95 c.c.	No air	—1.63

decrease and in them the maximum decrease was only of the order of 0.5 kg/cm^2.

Conclusion

One may, therefore, conclude that so long as adequate care has been taken to ensure that the water in ceramic disc, the pore water measurement line and the drainage line is deaired and does not harbour any sizeable bubbles, there is no mechanism to induce air to come out of solution in the pore water pressure measuring system if the pressure in the water above and below the ceramic disc is equal; a situation which usually exists during null type measurement, and shear under drained or constant water content conditions.

Air can only come out of solution when the pressure at the bottom of ceramic disc is lower than the pressure in the water in the sample as occurs during desaturation. In such event the air accumulated below the ceramic disc needs to be flushed out with a bubble pump. The volume of air so flushed can be measured to enable a correct assessment of the water flowing into or out of the sample.

It appears therefore that the fear of air diffusion causing unreliability in the measurement of negative pore water pressure is unfounded.

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Appendix—Axis Translation Technique

Negative pore water pressure can be measured in a triaxial cell in the same way as positive pore water pressure except that a saturated fine ceramic disc of high air entry value has to be used at the base of the soil sample to prevent pore air from passing into the pore water pressure measurement and drainage lines, see Fig. 4. This enables measurement of pore water pressure which is in the range of 0 to about —1 atmosphere. For lower pore water pressures this arrangement is not satisfactory since water in the measuring system cavitates.

Hilf (1956) observed that the difference in the pressures between the pore water and the pore air, is independent of the value of air pressure. He utilized this observation in evolving a technique to measure negative pore water pressure by the transfer of origin method, also known as Axis Translation Technique. The pore air pressure in the soil sample and the cell pressure are increased simultaneously by equal amounts until the water pressure in the pores of the sample becomes positive. This positive pore water pressure can then be measured in the usual way without fear of cavitation in the measuring system. The difference between the applied air pressure and the measured pore water pressure ($u_a—u_w$) is equal to the initial negative pore water pressure in the soil sample.

The procedure adopted in employing the axis translation technique is described in detail by Satija (1978), it may be briefly described as follows :

i. The fine ceramic disc, the drainage line and the pore water pressure measurement line are deaired.

ii. The soil sample is slid gently onto the saturated ceramic disc. Atmospheric pressure is maintained in the water in the drainage line to avoid cavitation in the drainage line and the pore water pressure measurement line. The sample tends to suck in some water from the drainage line through the saturated fine ceramic disc—a tendency which ceases only after the pore air pressure in the sample and the cell pressure are raised sufficiently to bring the pore water pressure in the sample in the positive range.

iii. The sample and the cell are assembled as shown in Fig. 4. The cell is then filled with deaired distilled water.

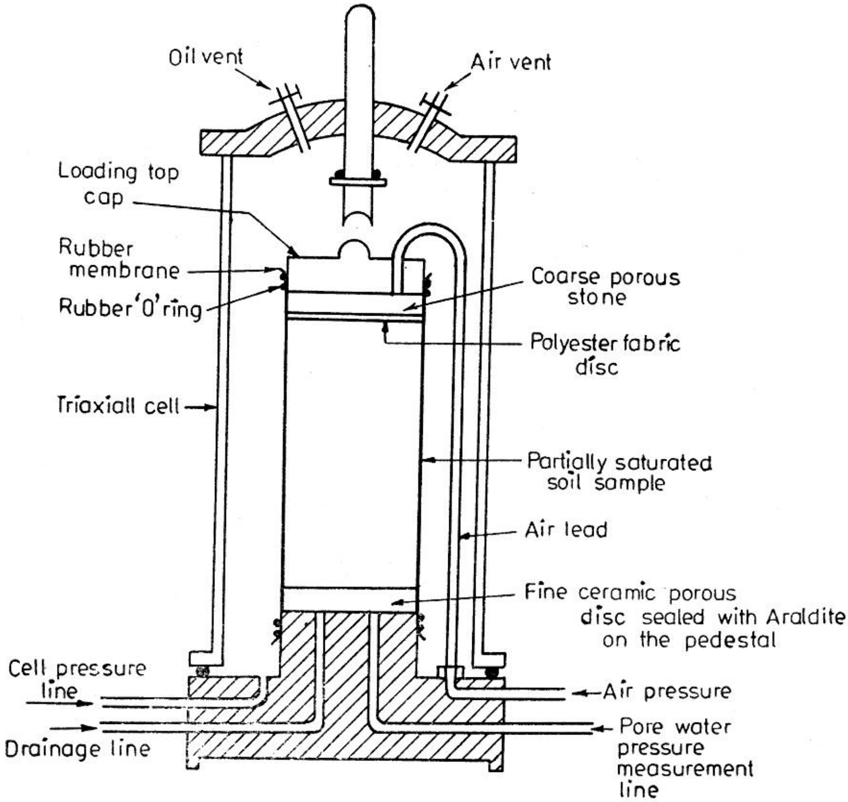

FIGURE. 4 Triaxial Cell Arrangement for Axis Translation Technique

iv. A nominal cell pressure of 0.14 kg/cm² is then applied and this is followed by gradually raising the cell pressure and the air pressure *keeping the difference ($\sigma_c - u_a$) constant* and equal to initially applied nominal cell pressure until pore water pressure in the sample rises to a value greater than one atmosphere. The drainage line is then closed and the pore water pressure line is opened to enable observation of the pore water pressure induced in the sample.

The fine ceramic disc with a rated air entry value of 3 kg/cm² used in investigation reported herein for conducting tests on samples with ($u_a - u_w$) values of 1 and 2 kg/cm² had a diameter of 3.81 cm and a thickness of 0.63 cm whereas the 5 kg/cm²—fine ceramic disc used for conducting tests on samples having ($u_a - u_w$) values of 3 and 4 kg/cm² had a diameter of 3.17 cm and a thickness of 0.95 cm. The 3 kg/cm² ceramic disc was sealed onto the top of the pedestal by Araldite as in Fig. 4. Whereas the 5 kg/cm² ceramic disc was placed in a recess in the pedestal and sealed by placing Araldite in the annular space between the disc and the walls of the recess in the pedestal.