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Pore pressure and volume change behaviour during undrained and drained loadings of an unsaturated soil

Mesure de la pression interstitielle et de la variation de volume d'un sol non saturé durant un chargement drainé et non drainé

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ABSTRACT : An apparatus has been constructed to observe the pore pressure and volume change characteristics of an unsaturated soil during constant water content loading, consolidation and increasing matric suction tests under a K_0-condition. The results show significant decrease in the pore pressure parameters when the degree of saturation decreases. The maximum past matric suction of the soil appears to have a significant effect on the soil behaviour during drained loading.

RESUME : Un appareil a été mis au point afin de mesurer la pression interstitielle et la variation de volume d'un sol non saturé au cours d'essais de chargement de type K_0 à teneur en eau constante, de consolidation et à succion contrôlée. Les résultats montrent une décroissance significative de la pression interstitielle quand le degré de saturation décroît. La succion maximale connue par le sol semble avoir des effets significatifs sur le comportement durant un chargement drainé.

1. INTRODUCTION

Many geotechnical problems involving unsaturated soils require information on the pore pressure and volume change characteristics during loadings under drained or undrained conditions. This information is important for the determination of the shear strength and volume change parameters, and the prediction of the permeability function for an unsaturated soil. These parameters and the permeability function are then used in a geotechnical analysis for seepage, slope stability and soil movements.

A research program on the pore pressure and volume change characteristics during drained and undrained loadings has been conducted. The loading was applied under K_0-conditions. Independent measurements of pore-air and pore-water pressures, total and water volume changes of a soil specimen during loading are carried out simultaneously. This paper presents some details on the design of the K_0-apparatus along with typical results of the pore pressure and volume change characteristics during constant water content loading (i.e., undrained loading for the water phase only) and drained loadings (i.e., consolidation and increasing matric suction tests).

2. SOIL PROPERTIES

The soil used in the testing program was a silty sand from Saskatchewan, Canada. The soil consists of 52.5% sand, 37.5% silt and 10.0% clay. The fines has a liquid limit of 22.2% and a plasticity index of 5.6%. The soil was intially slurried prior to testing. Results of pilot tests on initially slurried specimens indicated that the soil began to desaturate at a matric suction of approximately 10 kPa.

3. APPARATUS FOR K_0-LOADING

An apparatus for testing unsaturated soil under K_0-loading has been developed for the testing program. The K_0- apparatus consists of a bronze cylinder with a pedestal at the base and a loading cap at the top as shown in Fig. 1. The soil specimen is placed into the cylinder between a high air entry disk at the bottom and a low air entry disk at the top to control the pore-water pressure, u_w , and the pore-air pressure, u_a, in the specimen, respectively. The high air entry disk was of the high flow type and had an air entry value of 100 kPa. Its coefficient of permeability was approximately 4 to 6 x 10^{-8} m/s. The total stress, σ, is applied to the specimen through the loading cap. The soil specimens tested have a diameter of 10.2 cm and a height of 20 cm.

Pore-air and pore-water pressure measuring ports were installed along the cylinder as illustrated in Fig. 1. A pair of pore-air and pore-water pressure measuring ports were located at five different elevations along the height of the cylinder. The pore-air pressures,

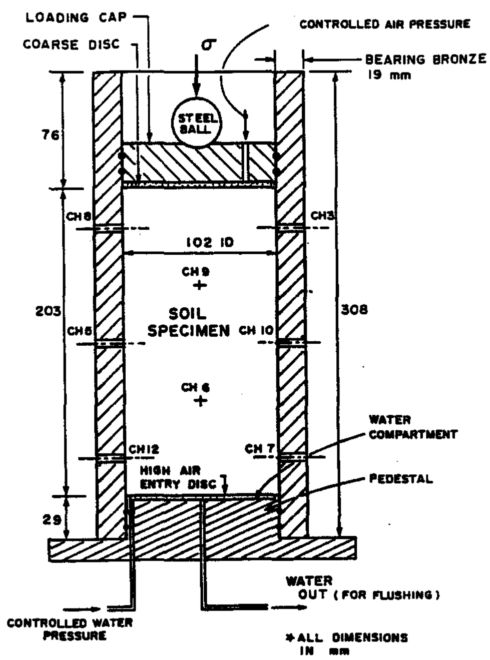

Figure 1 : K_0-cylinder for undrained loading and consolidation.

u_a, were measured through the use of low air entry disks while the pore-water pressures, u_w, were measured through the use of high air entry disks. The total volume change of the specimen was obtained by measuring the vertical deflection of the specimen using an LVDT (i.e., linear variable differential transformer) transducer. The radial deformation of the specimen was zero. The water volume change was measured using a conventional twin-burette volume change indicator connected to the water compartment in the pedestal. The K_0-apparatus is described in details by Rahardjo (1990) .

4. CONSTANT WATER CONTENT LOADING

An initially slurried soil specimen was first brought into equilibrium under specific net normal stress, (σ - u_a) and matric suction, (u_a - u_w). The soil was then loaded under a constant water content condition. Constant water content loading refers to the application of a total vertical stress, $d\sigma_y$, under a condition where the water phase is undrained while the air phase is drained. Therefore, only excess pore-water pressures, du_w, are generated during the loading while the pore-air pressures remain constant. As a result, the matric suction decreases during the loading.

Figure 2 shows the results of a constant water content loading on a specimen which has been brought into equlibrium under a net normal stress of 75 kPa and a matric suction of 56 kPa. The specimen had an initial degree of saturation, S, of 88%. An additional total vertical stress of 22 kPa was then applied to the specimen under a constant water content conditions. A small total volume change of 0.3 cm^3 occurred rapidly as a result of the compression of air during constant water content loading. The additional total stress of 22 kPa resulted in an excess pore-water pressure of 6 kPa as observed in all the pore-water pressure measuring ports along the cylinder (Fig.2) . This excess pore-water pressure develops almost instantaneously upon the application of additional total stress and its magnitude indicates that the specimen has a

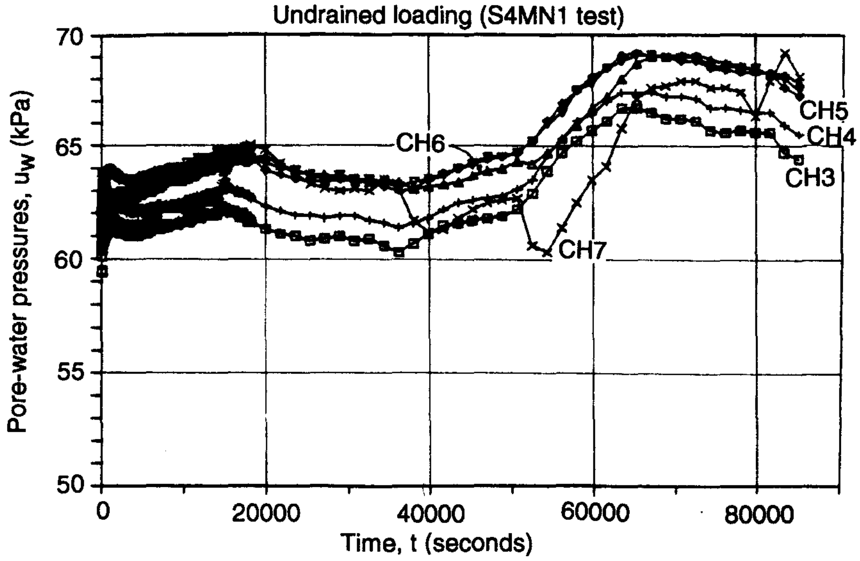

Figure 2 : Excess pore-water pressures generated during a constant water content loading.

B_w (i.e., $du_w / d\sigma_y$), pore-water pressure parameter of 0.27. The B_w parameter appears to decrease significantly with a decreasing degree of saturation of the soil.

5. CONSOLIDATION TESTS

Subsequent to constant water content loading, the excess pore-water pressure, du_w, was then dissipated in a consolidation type test by providing drainage of the water phase.through the high air entry disk at the base. The coefficient of permeability of the high air entry disk exceeded that of the soil. The pore-air pressure remains constant during the test. As a result, the matric suction in the soil specimen increases back to its intial value prior to the constant water content loading. Fig. 3 illustrates the pore-water pressure dissipation during a consolidation test on another soil specimen. Only the pore-water pressure measurements from the upper part of the soil specimen are shown in Fig. 3. The soil specimen has a net normal stress of 172 kPa and a matric suction of 62 kPa prior to the consolidation test. The degree of saturation, S, of the specimen is 70%. During the consolidation test, an excess pore-water pressure of 14 kPa was dissipated causing the matric suction to increase to 76 kPa at equilibrium. Figure 4 depicts the total and water volume changes that occur during the consolidation test. Both figures indicate that the consolidation process is associated with larger volume changes and longer equilibration times than those associated with the constant water content loading (Fig.2).

6. INCREASING MATRIC SUCTION TESTS

Having attained equilibration at the end of consolidation, the matric suction of the soil specimen can be further increased by lowering the pore-water pressure at the base plate compartment while maintaing constant total stress and pore-air pressure. As a result, the pore-water flows downward and the soil matric suction increases under a constant net normal stress. This process is referred to as an increasing matric suction test.

Figures 5 and 6 present the results of the increasing matric suction test following the consolidation test described in Figs. 3 and 4. All the tests were performed on the soil specimen. In this test, the pore-water pressure

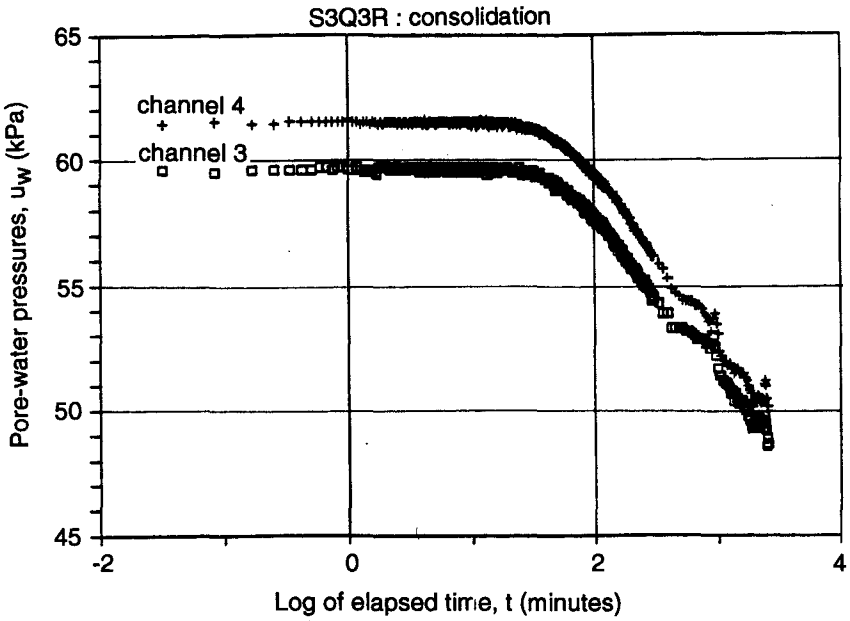

Figure 3: Excess pore-water pressure dissipation during a consolidation test.

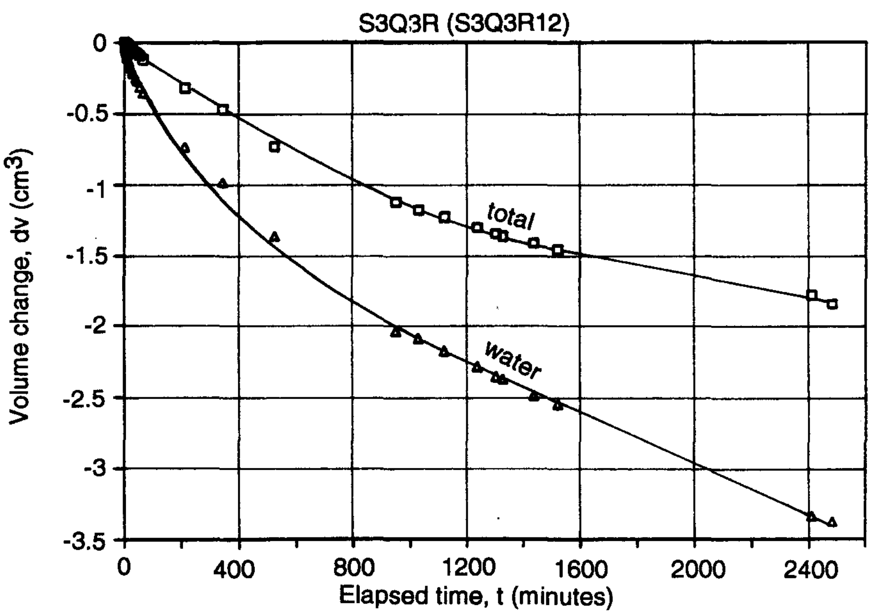

Figure 4 : Total and water volume changes during a consolidation test.

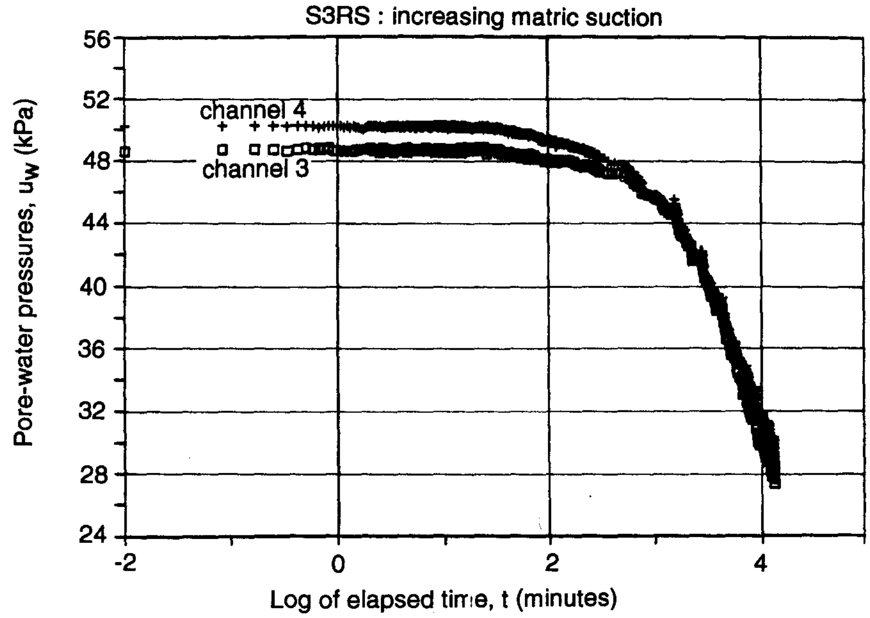

Figure 5 : Decrease in pore-water pressures during an increasing matric suction test.

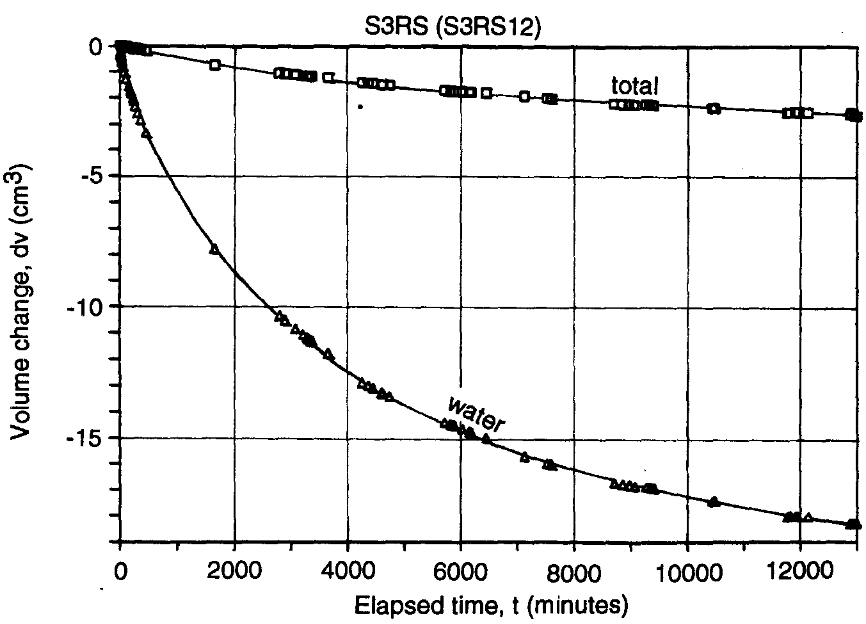

Figure 6 : Total and water volume changes during an increasing matric suction test.

is decreased by 20 kPa causing an increase in the matric suction of the same magnitude. At equilibrium, the matric suction of the soil specimen is 96 kPa and the degree of saturation is 67%. The time required for equilibration during the increasing matric suction test is much longer than the equilibration time for the consolidation test (compare Figs. 5 and 3). In addition, the amount of water volume change that takes place during the increasing matric suction test is significantly larger than the water volume change occurring during the consolidation test (compare Figs. 6 and 4). The difference in the soil behaviour during these two tests is due to the fact that in the consolidation test, the soil is only being reloaded back to its initial matric suction prior to loading while in the increasing matric suction test, the soil is loaded beyond its current matric suction (Rahardjo, 1990). This effect is similar to loading up to and beyond the preconsolidation pressure of a soil.

7. CONCLUSIONS

The above typical results demonstrate the marked difference in the pore pressure and volume change characteristics of an unsaturated soil during drained and undrained loading. The B_W pore-water pressure parameter decreases significantly with decreasing degrees of saturation. The behaviour of an unsaturated soil during drained loading depends upon whether the maximum past matric suction is exceeded or not during the loading. When the matric suction is increased beyond its maximum past value, a significant amount of water volume change occurs and the equlibration time is considerably longer.

8.ACKNOWLEDGEMENTS

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