The collapse behavior of a compacted soil during inundation

RAMBABU TADEPALLI
Clifton Associates, Saskatoon, Sask., Canada S7N 0W0
AND
D. G. FREDLUND
University of Saskatchewan, Saskatoon, Sask., Canada S7N 0W0

Received November 29, 1990
Accepted March 6, 1991

The collapse behavior of a compacted, uncemented soil is studied within a theoretical context consistent with the concepts of unsaturated soil mechanics. Experimental data are presented relating the initial matric suction of a compacted soil to its volume decrease during inundation. The laboratory results indicate a unique relationship between the changes in matric suction (i.e., $\Delta(u_a - u_w)$, where u_a is the pore-air pressure and u_w is the pore-water pressure) of the compacted soil and the resulting volume reduction during inundation. Changes in the matric suction and total volume with respect to time were modelled using the theory of transient flow through an unsaturated soil. The predicted results show reasonable agreement with the experimental observations. The comparisons between the simulated results and the experimental data indicate that the coefficient of consolidation of the soil varies linearly with matric suction during the inundation process.

Key words: unsaturated soil, matric suction, collapsible soils, negative pore-water pressures.

Le comportement en effondrement d'un sol compacté non cimenté est étudié dans un contexte théorique en accord avec les concepts de la mécanique des sols non saturés. Des données expérimentales sont présentées mettant en relation la succion matricielle initiale d'un sol compacté avec sa diminution de volume durant l'inondation. Les résultats de laboratoire indiquent qu'il y a une relation unique entre les changements dans la succion matricielle (i.e., $\Delta(u_a - u_w)$ où u_a est la pression d'air dans les pores est u_w est la pression d'eau dans les pores) du sol compacté et la diminution de volume en cours d'inondation. Les changements dans la succion matricielle et le volume total en fonction du temps ont été modélisés au moyen de la théorie d'écoulement transitoire à travers un sol non saturé. Les résultats prédits montrent une concordance raisonnable avec les observations expérimentales. Les comparaisons entre les résultats simulés et les données expérimentales indiquent que le coefficient de consolidation du sol varie linéairement avec la succion matricielle au cours du processus d'inondation.

Mots clés : sol non saturé, succion matricielle, sols effondrables, pressions interstitielles négatives.

[Traduit par la rédaction]

Can. Geotech. J. **28**, 477–488 (1991)

Introduction

The concepts of effective stress, useful in predicting the behavior of saturated soils, fails to explain the collapse behavior of unsaturated soils during inundation. The principle of effective stress would indicate that the overall volume of the soil should increase during inundation, as a result of a decrease in the effective stress. However, the overall volume decreases, producing what is termed as collapse, during the inundation process. Soils that exhibit collapse during inundation are initially unsaturated and subsequently become saturated after inundation for a period of time.

It would appear to be appropriate to use the concepts of unsaturated soil mechanics in an attempt to explain the collapse behavior. Two independent stress-state variables, namely, net normal stress $(\sigma - u_a)$ and matric suction $(u_a - u_w)$ (where σ is the total normal stress, u_a is the pore-air pressure, and u_w is the pore-water pressure), have been found to be suitable for predicting the mechanical behavior of unsaturated soils (Matyas and Radhakrishna 1968; Fredlund and Morgenstern 1976). The stress-state variable that changes during inundation is matric suction $(u_a - u_w)$. The total stress does not change during inundation, and the pore-air pressure is commonly assumed to remain at atmospheric conditions (Rahardjo 1990). A typical compression curve for a soil specimen exhibiting collapse subsequent to inundation is shown in Fig. 1. The idealized compression curve is plotted with respect to net normal stress and matric suction. The stress path before inundation is shown by the line AB, during inundation by the line BC, and after inundation by the lines CD and DE.

A research program was established with the intention of verifying whether or not the stress-state variables for an unsaturated soil could be used to describe the collapse mechanism in an unsaturated soil. In other words, is there a relationship between matric-suction change and the total volume change during inundation, as shown on the idealized plot (Fig. 1). The uniqueness of such a relationship between matric suction and collapse was studied by means of the laboratory program.

Literature review

Man-made earth structures such as embankments, road fills, and earth dams often exhibit collapse when compacted dry of optimum (Holtz 1948). It is commonly assumed that only sandy or silty soils exhibit collapse; however, in recent years it has been reported that compacted soils in general can exhibit collapse (Barden *et al.* 1973; Cox 1978). Clayton (1980) reported the occurrence of collapse in a compacted chalk-fill. It is now generally accepted that any type of soil

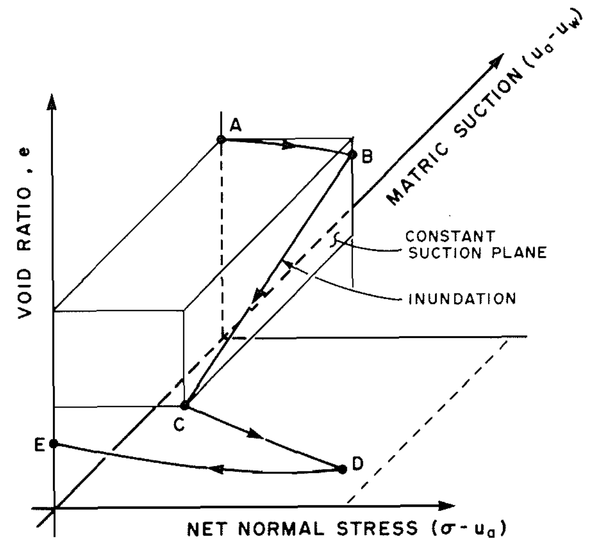

FIG. 1. Compression curve for a soil exhibiting collapse behavior with respect to net normal stress and matrix suction.

compacted dry of optimum may develop a collapsible fabric or metastable structure at low densities.

Qian and Lin (1988) reported that naturally occurring collapsing soils can be divided into two categories. There are those which collapse upon inundation under a total pressure equal to their overburden, and there are those which require a total pressure greater than their overburden to exhibit the collapse phenomenon. The later category involves soils that have significant cementation or bonding at the particle contacts. This paper deals only with collapsing soils with insignificant cementation at the particle contacts.

Compacted soils that exhibit collapse typically have an open type of structure with many void spaces, which give rise to a metastable structure. Many researchers have hypothesized regarding the structural arrangement of the particles for these soils. Common to these postulations is the description of the soil structure which states that the bulky grains are held together in a honeycomb type of fabric by some type of bonding material or force at the points of contact. The various postulated structural arrangements generally differ with respect to the size and orientation of the bonding material.

The dry density and water content of soil specimens at the time of compaction are generally considered as the primary soil properties that control the amount of collapse. Several researchers have reported that soils exhibit collapse if the dry density of the soil specimen is less than 1.6 Mg/m^3. Jennings and Knight (1975) reported that the above conclusion is a misconception and should be dispelled. It was also suggested that the collapse behavior is also dependent on other variables such as clay content and clay type. An extensive laboratory testing program has been carried out on residual clays from Kenya by Foss (1973). Popescu (1986) conducted similar test on a loess soil from Romania. Lefebvre and Benbelfadhel (1989) also conducted studies on glacial till to investigate the effect of a wide range of placement conditions on the collapse of a soil.

The soils tested by Foss (1973) were compacted at a constant water content with varying densities. The soils indicated a linear inverse relationship between the dry density and the percentage of collapse (i.e., dH/H_0, where dH = decrease in height of the specimen subsequent to inundation, and H_0 = initial height of the specimen). Popescu (1986) compacted the loess specimens at a constant density and varying water contents to study the effect of water content on the amount of collapse. The relationship observed between the water content and the percentage of collapse was essentially linear. However, the results presented by Lefebvre and Benbelfadhel (1989) show a more parabolic relationship, particularly at low water contents. Obviously, the form of the relationship may vary from one soil to another.

Meckechnie (1989) stated that unsaturated soils having a dry density lower than 1.6 Mg/m^3 are liable to collapse. However, he also noted that not all the soils with low densities are necessarily collapsible in nature. At the same time, he stated that an initially unsaturated condition is a prerequisite for collapse.

Most research has concentrated on the development of laboratory testing methods for identifying soils that exhibit collapse.

The tests are also used to estimate the probable amount of collapse. The probable mechanisms involved in the collapse phenomena have been suggested by several researchers (Holtz and Hilf 1961; Burland 1965; Larinov 1965; Dudley 1970; Barden *et al.* 1973). Collapse mechanisms differ considerably from the classical consolidation process. In the consolidation process, the total volume change of the saturated soils occurs as a transient process. Collapse, on the other hand, appears to occur in a relatively short period of time in response to the infiltration of water at a constant vertical stress. Collapse can result in a radical rearrangement of the soil particles, resulting in a significant reduction in total volume of the soil mass.

Holtz and Hilf (1961) described the mechanism of collapse accompanying wetting as the result of capillary pressures approaching zero and the degree of saturation increasing to 100%. The mechanism for cohesionless soils was explained on the basis of the "reduction of shear factor" (i.e., shear strength - shear stress) against collapse. It was postulated that during inundation, the Mohr circle translates horizontally by an amount equal to the negative pore-water pressure existing in the soil before inundation. Due to this transition, the effective stress path intersects the Mohr–Coulomb failure envelope, resulting in a general shear failure and associated settlement.

Burland (1965) explained the collapse mechanism in terms of the stability at the interparticle contact points. Due to inundation, the negative pore-water pressure at the contact points decreases, giving rise to grain slippage and distortion. This results in an irrecoverable decrease in total volume.

Larinov (1965), Dudley (1970), and Barden *et al.* (1973) described the collapse phenomena in terms of the bonding materials present at the contact points. It was suggested that in the case of silt bonds (i.e., bonding material is of silt-sized particles) the temporary strength was mainly due to capilllary tension. In this case, the temporary strength would be lost during inundation, resulting in a decrease in volume. However, it was suggested that, in general, the bonding material for collapsible soils was clay. Dudley (1970) postulated that the capillary forces provided temporary strength to the clay bonds when in a dry state.

The underlying principles associated with all postulated mechanisms are that (*i*) the soil must be unsaturated and (*ii*) the pore-water pressures must be negative. The fact that

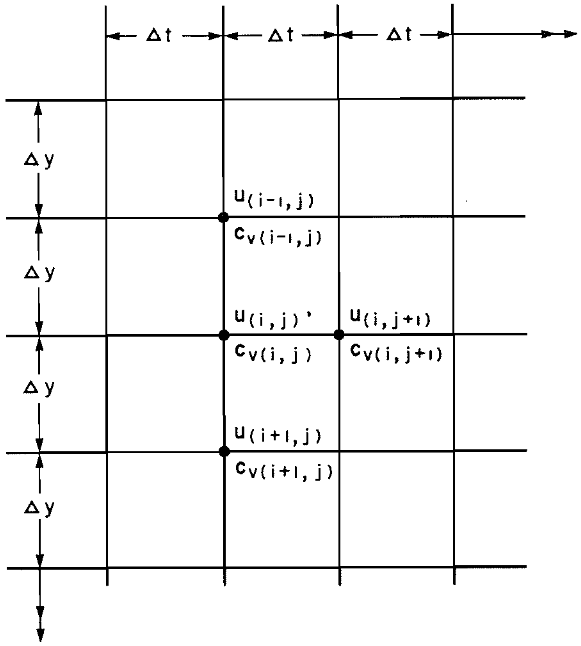

FIG. 2. Variables used in the finite-difference method.

soils must be unsaturated to exhibit collapse encourages the consideration of the unsaturated soil mechanics principles. However, few researchers have attempted to describe collapse behavior in this manner.

Matyas and Radhakrishna (1968) and Escario and Saez (1973) provided experimental data that relates the volume change of a collapsible soil to changes in the matric suction while controlling the pore-air and pore-water pressures. Matyas and Radhakrishna (1968) proposed using the concept of state surfaces relating the void ratio and degree of saturation of the stress-state variables of the soil.

Fredlund and Morgenstern (1977) provided further theoretical and experimental justification for the use of two independent stress-state variables (i.e., $(\sigma - u_a)$ and $(u_a - u_w)$) for unsaturated soils, in general. In 1977, Fredlund and Morgenstern proposed constitutive relationships for volume changes of an unsaturated soil using the two stress-state variables. The equations were equally applicable for either volume increases or decreases in response to a change in the stress-state variables. Fredlund and Hasan (1978) proposed a one-dimensional consolidation theory for unsaturated soils. Independent partial differential equations were derived for the water phase and the air phase. Both equations were to be solved simultaneously when a significant excess pore-air pressure was generated. Miranda (1988) simulated the collapse behavior of small earth dams during their first filling, using the concepts of unsaturated soil mechanics.

Theory

The volume change constitutive relationships for an unsaturated soil proposed by Fredlund and Morgenstern can be written as follows:

$$[1] \quad \frac{\mathrm{d}V_v}{V_o} = m_1^s\, d(\sigma - u_a) + m_2^s\, \mathrm{d}(u_a - u_w)$$

$$[2] \quad \frac{\mathrm{d}V_w}{V_o} = m_1^w\, \mathrm{d}(\sigma - u_a) + m_2^w\, d(u_a - u_w)$$

where $\mathrm{d}V_v$ is the change in total volume, V_o is the initial volume of soil, $\mathrm{d}V_w$ is the change in volume of water, $\mathrm{d}(\sigma - u_a)$ is the change in net normal stress, $\mathrm{d}(u_a - u_w)$ is the change in matric suction, m_1^s is the coefficient of total volume change with respect to a change in net normal stress at a constant matric suction, m_1^w is the coefficient of water volume change with respect to a change in net normal stress at a constant matric suction, m_2^s is the coefficient of total volume change with respect to a change in matric suction at a constant net normal stress, and m_2^w is the coefficient of water volume change with respect to a change in matric suction at a constant net normal stress.

During inundation, volume change occurs under a constant vertical stress. The pore-air pressures in the soil will be assumed to remain unchanged during collapse. It has been shown experimentally that the pore-air pressure in the soil may build up by a slight amount but will then quickly dissipate (Rahardjo 1990). For practical purposes, it can then be considered that the variable which changes during inundation is the negative pore-water pressure. Therefore, the constitutive equations applying to inundation can be written

$$[3] \quad \frac{\mathrm{d}V_v}{V_o} = m_2^s\, \mathrm{d}(-u_w)$$

$$[4] \quad \frac{\mathrm{d}V_w}{V_o} = m_2^w\, \mathrm{d}(-u_w)$$

The sign convention for the coefficients in the above equations are in accordance with the suggestions made by Fredlund and Morgenstern (1976). That is, if the change in the stress-state variable is in the same direction as the volume change for a particular phase, the sign of the corresponding coefficient is negative. Therefore, the signs for the coefficients m_2^s and m_2^w are negative and positive, respectively, during the collapse mechanism.

The one-dimensional water-flow equation during inundation can be derived by equating the divergence of the hydraulic head (as described by the flow law) to the time derivative of the water phase constitutive equation. Darcy's law can be used to describe the flow of water in an unsaturated soil (Childs and Collis-George 1950) and will be assumed to be applicable during the collapse process. The divergence of the hydraulic head describes the rate of water flow, and the time derivative of the water phase constitutive equation represents the water volume changes during inundation.

For the derivation, the soil is assumed to (*i*) be isotropic, (*ii*) have a continuous air phase with free flow to the boundaries, (*iii*) have a linear constitutive relationship, (*iv*) undergo infinitesimal strains, (*v*) have coefficients of volume change and permeability that are the functions of matric suction during inundation, and (*vi*) have no effects of air diffusing through water, air dissolving in water, and water-vapor movements. The partial differential equation for the water phase in the *y*-direction can be written as follows:

$$[5] \quad \frac{\partial u_w}{\partial t} = \frac{1}{c_v^w}\frac{\partial^2 u_w}{\partial^2 y} + \frac{\partial c_v^w}{\partial y}\frac{\partial u_w}{\partial y} + \rho_w g\, \frac{\partial c_v^w}{\partial y}$$

where u_w is the pore-water pressure, c_v^w is the coefficient of consolidation, ρ_w is the density of water, and g is the acceleration due to gravity.

Ignoring the effect of the elevation heads, [5] can be rewritten as follows:

TABLE 1. Summary of index properties for Indian Head silt

Grain-size distribution	
Sand	62%
Silt	32%
Clay	6%
D_{10}	0.0034 mm
D_{30}	0.025mm
D_{60}	0.090 mm
Coefficient of uniformity, $C_u = D_{60}/D_{10}$	26.4
Atterberg limits	
Liquid limit, w_L	22.2%
Plastic limit, w_P	16.6%
Plasticity index, PI	5.6%
Relative density, G_s	2.68

$$[6] \quad \frac{\partial u_w}{\partial t} = \frac{1}{c_v^w}\frac{\partial^2 u_w}{\partial^2 y} + \frac{\partial c_v^w}{\partial y}\frac{\partial u_w}{\partial y}$$

Equation [6] can be written in an explicit, finite-difference form as follows:

$$[7] \quad u_w(i, j+1) = u_w(i,j) + \frac{\Delta t}{2\Delta y}\left[\left(c_v^w(i+1,j)\,u_w(i+1,j)\right) + \left(c_v^w(i,j)\,u_w(i-1,j)\right) - \left(c_v^w(i,j)\,u_w(i,j)\right) - \left(c_v^w(i+1,j)\,u_w(i,j)\right)\right]$$

A computer program can be written for [7] which can be used to predict changes in negative pore-water pressure with respect to time and depth, subsequent to inundation. The variables used in [7] are shown in Fig. 2. The changes in the total volume and water volumes during inundation are computed using [3] and [4].

Experimental program

Laboratory tests on compacted specimens were conducted in two phases (i.e., phase I and phase II). Tests in phase I were performed to relate the amount of collapse to the soil properties (i.e., dry density and water content). Tests in phase II were conducted to study the effect of initial matric suction on collapse behavior. Six tests were performed to study the effect of initial water content on the amount of collapse at an initial dry density of around 1.6 Mg/m^3. Eight tests were conducted to study the effect of initial dry density on the amount of collapse at initial water contents of 12.8 and 7.3% (i.e., four tests on each initial water content).

The soil properties for the phase II series of tests were selected to have initial matric suctions within a range that could be measured using tensiometers.[1] At the same time, it was desirable to have a soil that would exhibit a reasonable amount of collapse. Seven tests were performed to study the transient processes of matric suction and volume changes during inundation.

[1]Manufactured by Soilmoisture Equipment Corporation, P.O. Box 30025, Santa Barbara, CA 93105, U.S.A.

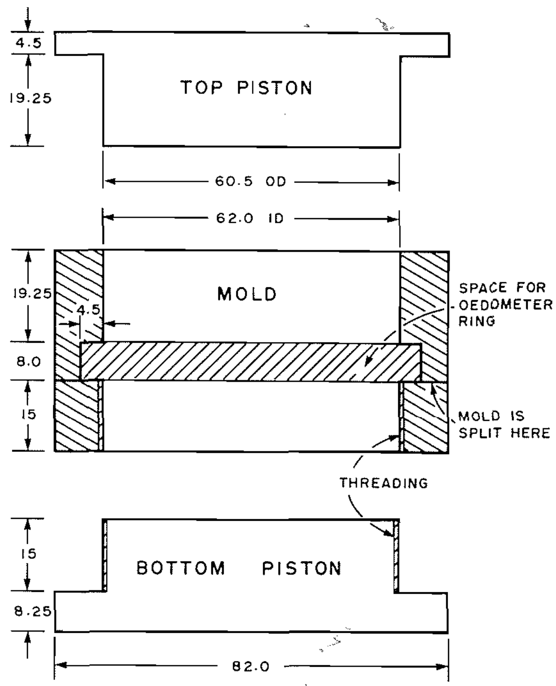

FIG. 3. Compaction mold with oedometer ring inside. Dimensions in millimetres.

Properties of the soil tested

Indian Head silt, procured from the Saskatchewan Department of Highways, was used for the laboratory testing program. The index properties of the Indian Head silt are shown in Table 1.

The optimum water content for the soil was 13.4% for full standard compaction (Aasho) and 14.4% for half standard compaction. The maximum dry density for till standard compaction was 1.87 and 1.29 t/m^3 for half standard compaction.

Equipment

Specimens were statically compacted into an oedometer ring using the compaction mold shown in Fig. 3. The mold is similar to that used by Booth (1977) and Maswoswe (1985). Tensiometers were used to measure the initial matric suction. AGWA-II[2] thermal conductivity sensors were used to check the measurements of initial matric suction.

Three sizes of oedometer rings (types I, II, and III) were used in the laboratory testing program. Oedometer ring type I was used in the study of the effect of the soil properties on the amount of collapse. The dimensions of the ring were 19.0 mm in height and 63.0 mm in diameter.

Oedometer ring types II and III were used in the study of the transient processes involving a change in matric suction and volume change during inundation. The height of oedometer ring type II was 25.4 mm and the diameter was 63.0 mm. A hole with a diameter of 7.5 mm was drilled through the side of the oedometer ring. This hole was used to insert the tensiometer tip into the compacted specimen.

[2]Manufactured by Agwatronics Inc., Merced, CA, U.S.A.

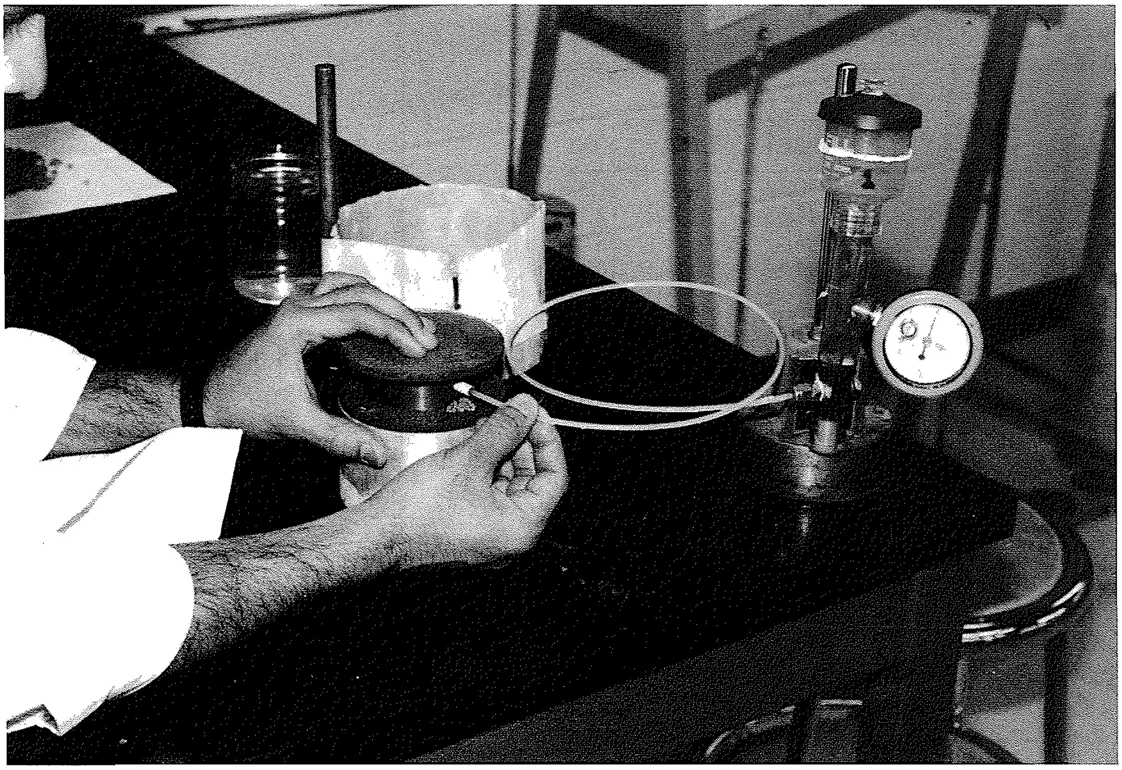

FIG. 4. Installation of the tensiometer tip into oedometer ring type II.

Oedometer ring type III was used to perform tests, with matric-suction measurements (i.e., using tensiometers) taken at different heights along the compacted specimen. The height and diameter of the oedometer ring were 60.0 and 84.9 mm, respectively. Two holes were drilled at a distance of 12.5 mm from the top and bottom of the ring. The third hole was drilled diametrically opposite at the mid-height of the ring.

The oedometer pot was adapted with a flexible extension to accommodate the flexible tubing associated with the tensiometers.

Specimen preparation

A soil mass of a known water content was compacted statically into the oedometer ring. The mold shown in Fig. 3 was used to compact the specimens into ring types I and II. After compaction, the soil specimen and the ring were weighed to obtain the initial density of the specimen.

The oedometer ring containing the soil specimen was then firmly held between two porous stones. The specimen was held in this configuration to avoid disturbance when drilling the hole(s) for the tensiometer(s). A hole was drilled horizontally into the compacted specimen through the hole provided in the ring. The drill bit was slightly smaller than the diameter of the tensiometer tip to ensure a good contact between the tensiometer tip and the soil. The depth of the hole was slightly more than the length of the ceramic tip. The ceramic tip of the flexible tube type tensiometer[3] was carefully inserted into the compacted specimen as shown in Fig. 4. The slight gap between the end of the ceramic tip and the outer edge of the oedometer ring was filled with representative soil.

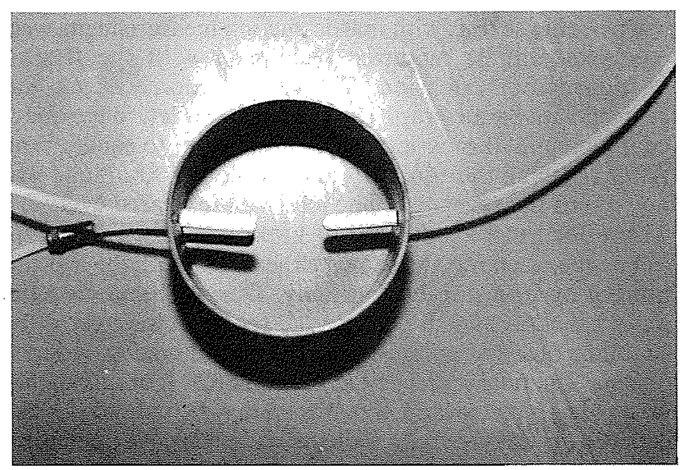

FIG. 5. Details of the three tensiometers at different heights in the oedometer ring type III.

The outer edge of the hole was sealed with silicone gel to prevent water from coming in contact with the tensiometer tip through the hole in the ring. Porous stones were then placed on the top and bottom of the soil specimen. The slight gap between the outer edge of the porous stones and the edge of the ring was sealed with silicone gel to avoid the entry of water into the specimen through this gap. This procedure was used in an attempt to provide uniform wetting of the specimen.

Similar procedures were adopted for the preparation of the specimens for ring type III. However, the soil was compacted directly into the ring instead of being compacted into

[3]Model 2100F of Soilmoisture Equipment Corporation, P.O. Box 30025, Santa Barbara, CA 93105, U.S.A.

TABLE 2. Summary of index properties, inundation pressure, and percent collapse for collapse tests

Description	Test identification			
	S1M	S2M	S3M	S4M
Dry density, ρ_d (t/m^3)	1.598	1.506	1.405	1.394
Water content, w (%)	11.8	11.79	11.8	12.75
Inundation pressure (kPa)	97	96	99	55
Collapse, dH/H_o (%)	5.84	11.62	15.26	18.62

the compaction mold. The installation of the tensiometers and the sealing procedures were similar to those used in the preparation of ring type II specimens. The arrangement of the three tensiometers along with the cylinder is shown in Fig. 5.

Testing methods

The collapse tests for phase I were conducted in a conventional oedometer. The specimen was placed between two air-dry porous stones. The top of the oedometer pot was covered with Saran wrap to minimize moisture loss. The assembly was left for 24 h. The specimen was then loaded every 2 h by doubling the previous load. When the settlement under the applied load was complete, the specimen was inundated with distilled water. Subsequent to saturation of the specimen for 24 h, further loads were applied to the specimen under the saturated condition after the end of 24 h of inundation.

The collapse tests with matric-suction measurements were conducted in the modified oedometer with the flexible oedometer pot extension. The entire oedometer pot was covered with Saran wrap. The specimen was left in the above condition until the tensiometer readings came to equilibrium. After reaching the equilibrium condition, a total load was applied to the specimen. The load was increased every 2 h with a load-increment ratio of approximately 1.0.

The specimen was inundated either from both the top and bottom or from the bottom only. During inundation the matric suction and the dial gauge readings were recorded simultaneously with times, until the matric suction dropped to zero. The final settlement at the end of 24 h of inundation was then recorded and the specimen was unloaded. The ceramic tip was carefully removed from the specimen after unloading and serviced properly for the next test.

Three collapse tests (S1M, S2M, and S3M) were conducted using one tensiometer measurements (i.e., oedometer ring type II), and one test (S4M) was performed using three tensiometers (i.e., oedometer ring type III). Initial soil properties (i.e., dry density, ρ_d; water content, w) used for all the four collapse tests are shown in Table 2.

Test results

The effect of the initial water content on the amount of collapse of an initial dry density around 1.6 t/m^3 is shown in Fig. 6. The results indicate that the amount of collapse for compacted specimens varies inversely, in a linear fashion, with initial water content for a particular initial dry density. Similarly, the relationship between the initial dry density and the amount of collapse at a constant initial water content also indicates an inverse and linear relationship (Fig. 7). The linear relationships between the amount of collapse and the

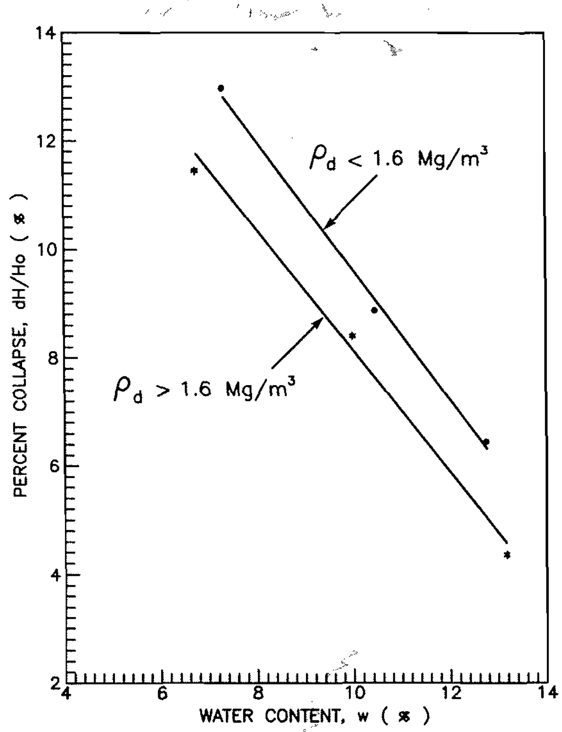

FIG. 6. Effect of the initial water content on the amount of collapse.

initial soil properties are in agreement with the observations made by Popescu (1986) and Foss (1973).

The initial matric-suction measurements indicated that an initial water content of approximately 12.0% would correspond to a matric suction of approximately 60 kPa, irrespective of the initial dry density. Changes in the matric suction and the total volume during inundation for tests S1M, S2M, and S3M are presented in Figs. 8, 9, and 10, respectively. The inundation pressure and the percent collapse for all the collapse tests are shown in Table 2.

The results obtained from the S1M test indicate that the initial matric suction at the centre of the specimen during inundation was 58 kPa. The results show that there was a significant change of the matric suction during the first minute after inundation. The matric suction continued to drop at a significant rate in the next 6 min and came close to zero in the following 3 min. This implies that the matric suction of the entire specimen dropped to zero in approximately 12 min.

The total volume of the specimen decreased slightly within 6 s after inundation. The volume decreased significantly from 6 s to 5.5 min after inundation. The volume decreased at a slower rate in the next 6–7 min and remained almost constant, 12 min after inundation. The results indicate that the decrease in total volume ceased as the matric suction at the centre of the specimen approached zero. Similar observations can be made from the S2M and S3M test results. This observation would appear to indicate that there exists a one-to-one relationship between matric-suction changes and total volume changes for collapsible soils during inundation.

Test S4M was conducted using larger specimens in which the changes in the matric suction were measured at three different heights. This test was performed to further verify the one-to-one correspondence of the relationship between matric-suction changes and the total volume change during

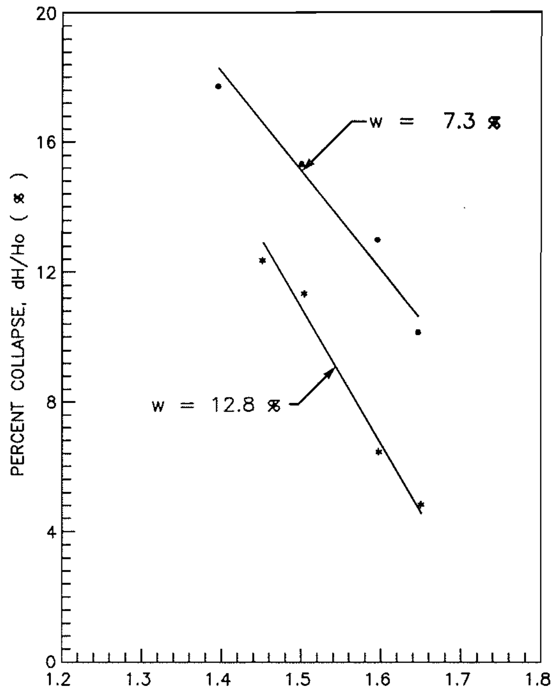

FIG. 7. Effect of the initial dry density on the amount of collapse.

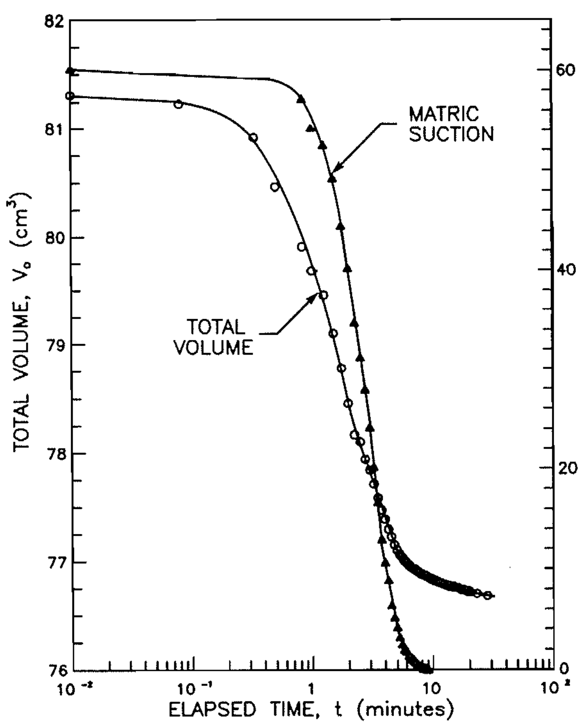

FIG. 8. Matric-suction and total volume changes vs. time during inundation of test S1M.

collapse upon inundation. The soil specimen was inundated from the bottom, unlike the previous tests (i.e., S1M–S3M) that were inundated from top and bottom. The changing matric suction at the top, middle, and bottom of the specimen along with the total volume changes are shown in Fig. 11.

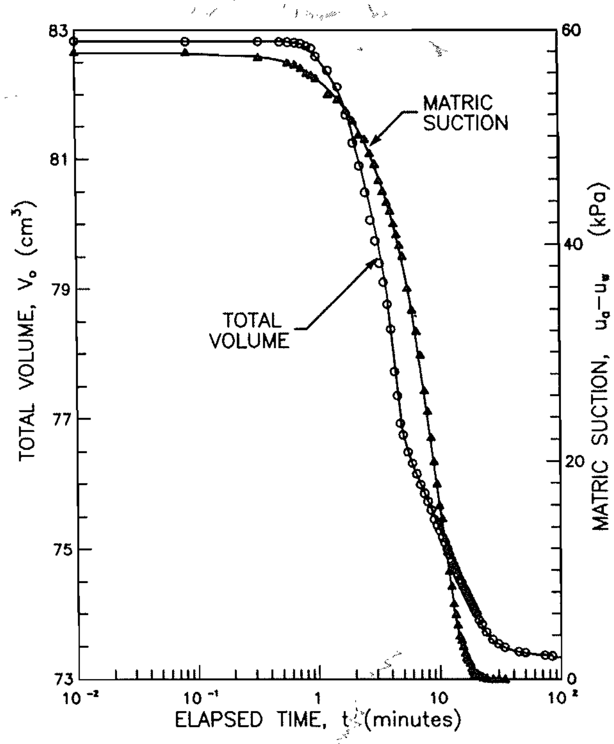

FIG. 9. Matric-suction and total volume changes vs. time during inundation of test S2M.

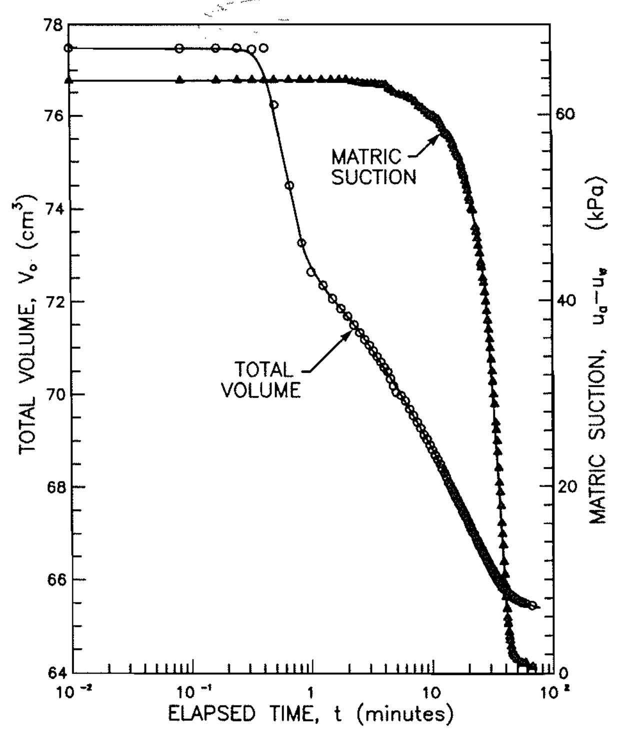

FIG. 10. Matric-suction and total volume changes vs. time during inundation of test S3M.

The results indicate that the initial matric suction of 64 kPa prior to inundation has dropped to zero around bottom tensiometer in about 9.5 min after inundation. The matric suction at the middle of the specimen did not change significantly during the first 5.5 min after inundation. It then dropped to zero at a significant rate in the following 12 min.

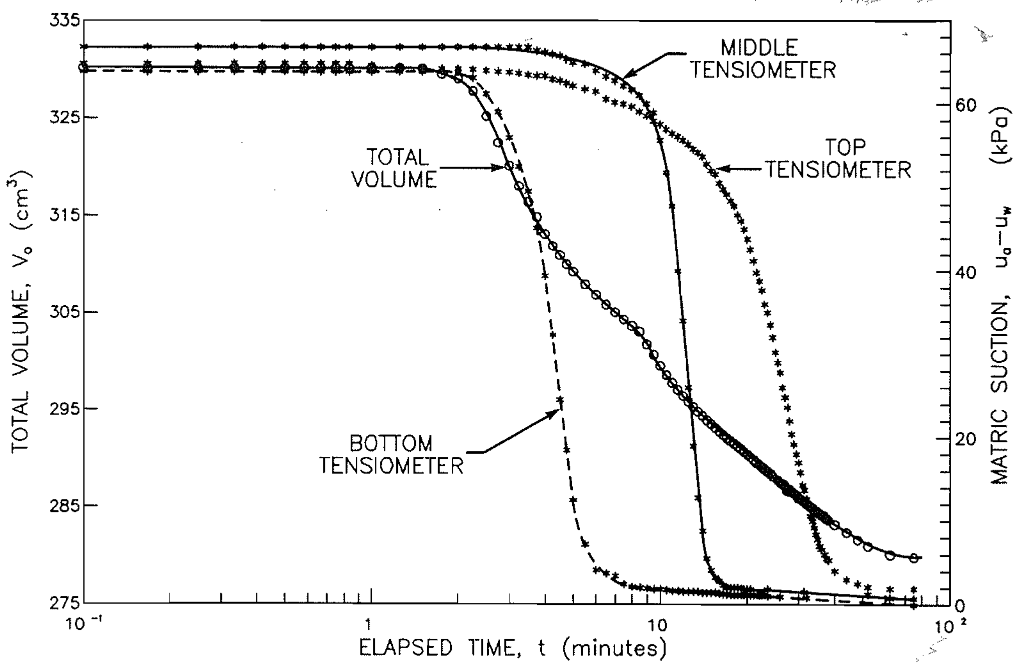

FIG. 11. Matric-suction and total volume changes vs. time during inundation of test S4M.

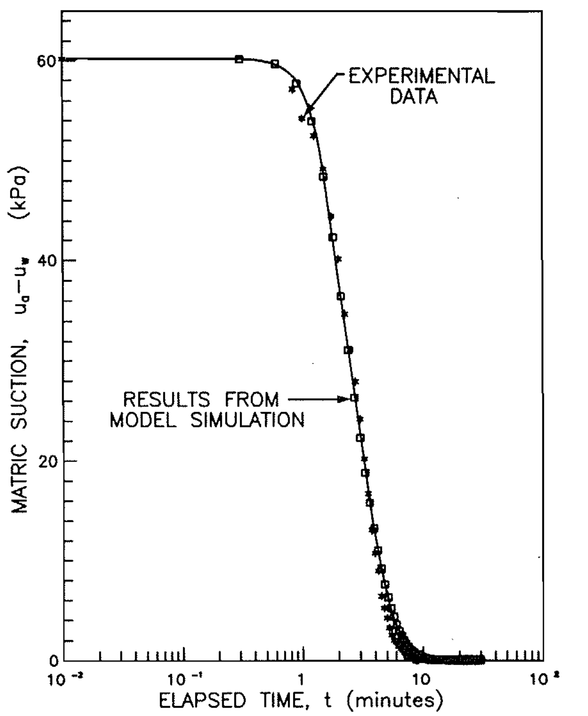

FIG. 12. Comparison between the theoretical simulations and experimental results for matric-suction changes from test S1M.

TABLE 3. Summary of coefficients used in S1M test simulation

Matric suction, $u_a - u_w$ (kPa)	Coefficient of consolidation, c_v^W (cm^2/s)	Coefficient of volume change, m_2^s (L/kPa)
0	6.87E−3	4.7E−4
60.2	1.77E−3	4.7E−4

The matric suction around the top tensiometer dropped by 7 kPa in the first 10 min after inundation. This was due to the accidental application of a small amount of water to the top of the specimen at the beginning of the test. The wetting of the specimen can be considered as being predominantly from the bottom of the specimen. The matric suction around the top tensiometer dropped to zero by 1 h after inundation. The matric suction in the portion of the specimen above top tensiometer would have dropped to zero in a couple of minutes after the matric suction around the top tensiometer dropped to zero as the wetting front was moved upwards.

The total volume of the specimen remained unchanged during the first 2 min after inundation and then decreased significantly between 2 and 60 min after inundation. The volume of the specimen decreased at a slow rate in the next 20 min, and no further volume change was noticed 80 min after inundation.

The experimental results indicate that there is a one-to-one correspondence relationship between the matric-suction and the total volume changes during collapse due to inundation. The volume of the specimen decreased significantly within 2 min after inundation, and the matric suction around the bottom tensiometer began to drop at about 2.5 min after inundation. The centre of the bottom tensiometer was located at 12.5 mm from the base of the specimen. A decrease in the total volume occurred prior to a decrease being registered on the bottom tensiometer. This decrease in volume was due to the decrease in matric suction in the region below the bottom tensiometer.

The soil volume decreased at a continuous rate during the next several minutes as the wetting front moved from the bottom to the top of the specimen. The matric suction around the top tensiometer dropped initially because of the accidental leakage of water onto the top of the specimen.

The matric suction around the top tensiometer dropped to zero slightly earlier than the time when no further change

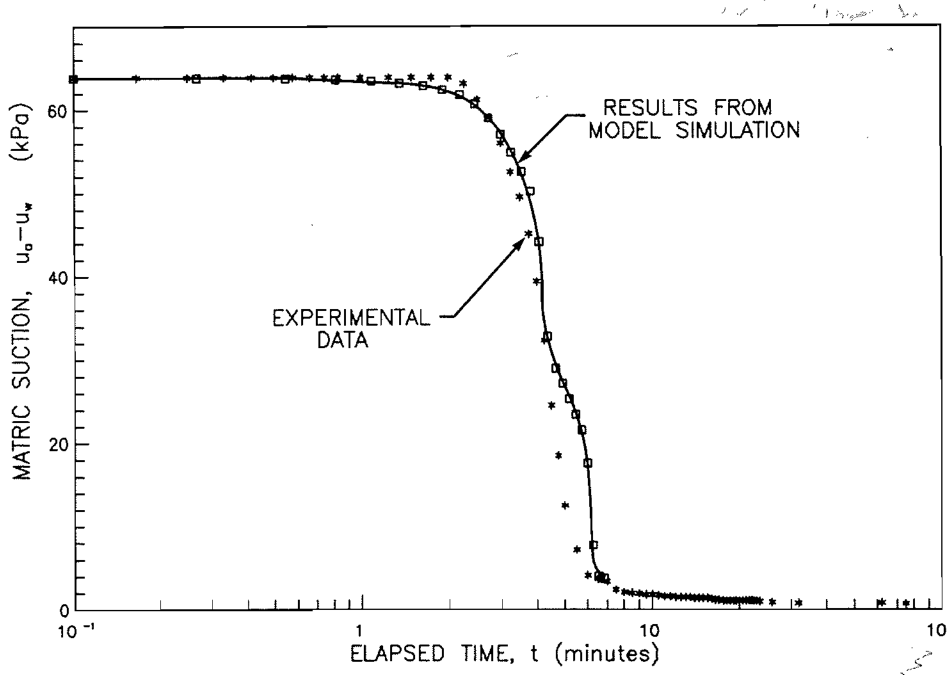

FIG. 13. Comparison between the theoretical analysis and experimental results for matric-suction changes at the bottom tensiometer of large specimen from test S4M.

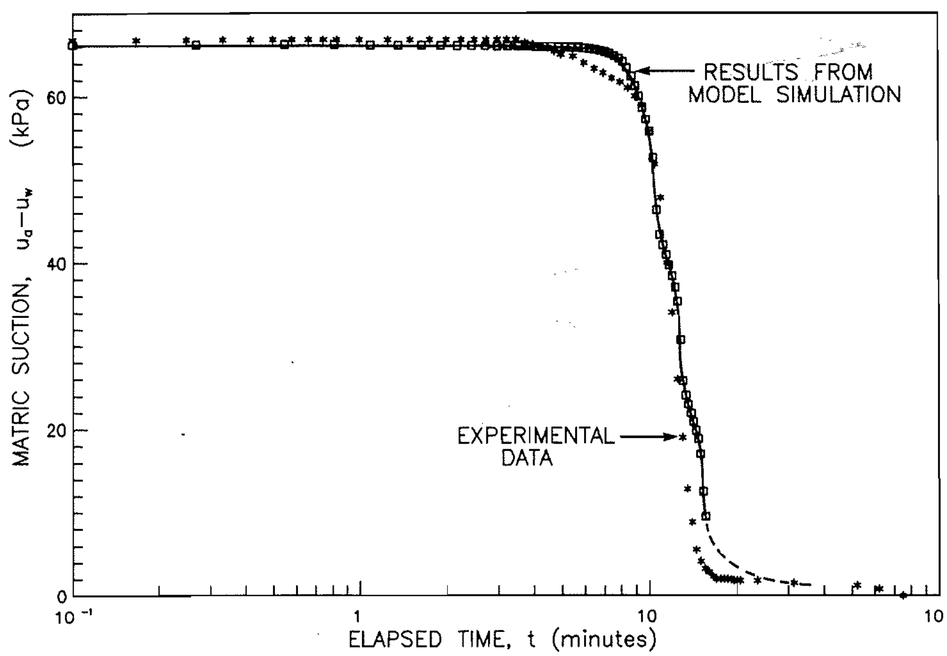

FIG. 14. Comparison between the theoretical analysis and experimental results for matric-suction changes at the middle tensiometer of large specimen from test S4M.

in total volume was noticed. This indicates that the volume changes during the last few minutes were due to the decreasing matric suctions in the region above the top tensiometer. The top tensiometer was located at 12.5 mm from the top surface of the specimen. The experimental results clearly indicate that the total volume of the specimen started and continued to decrease until the matric suction in the entire specimen decreased to zero.

Theoretical simulations

Theoretical simulations between the matric-suction and the total volume changes during collapse were carried out in accordance with the theory suggested earlier in the paper. A computer program was written to solve the water-flow, partial differential equation that was written in a finite-difference form [7]. The theoretical simulations of all test results indicated that the coefficient of consolidation, c_v^w, varied during inundation. It was higher than the value deduced from the experimental data using the semilog-plot method suggested by Casagrande (1938) for saturated soils. Best-fit theoretical simulations using a linear variation of the coefficient of consolidation value with respect to matric suction are compared with the experimental results for the S1M test (Fig. 12). The coefficient of consolidation values

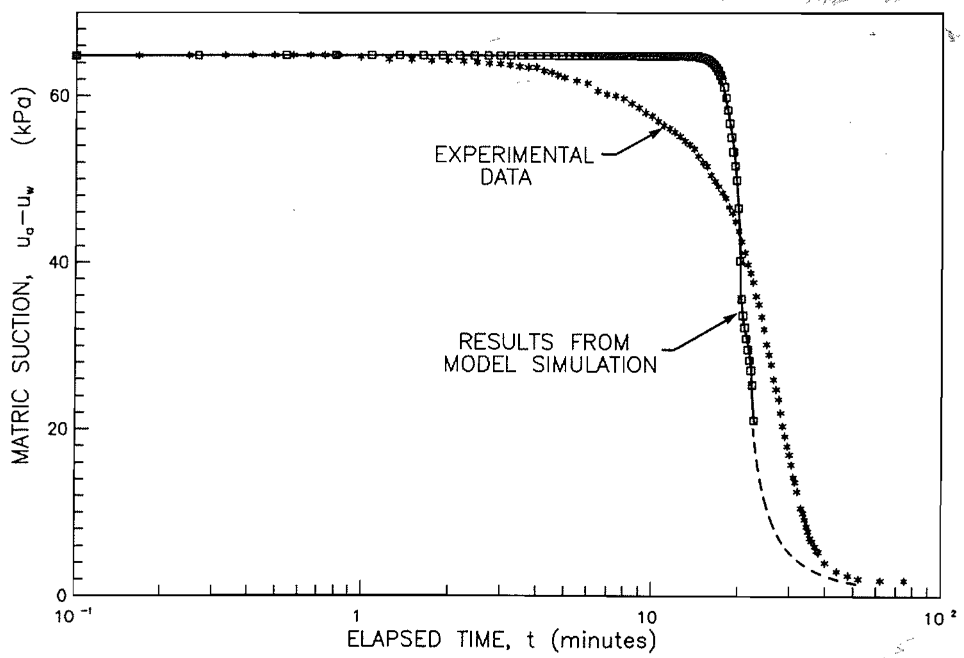

FIG. 15. Comparison between the theoretical analysis and experimental results for matric-suction changes at the top tensiometer of large specimen from test S4M.

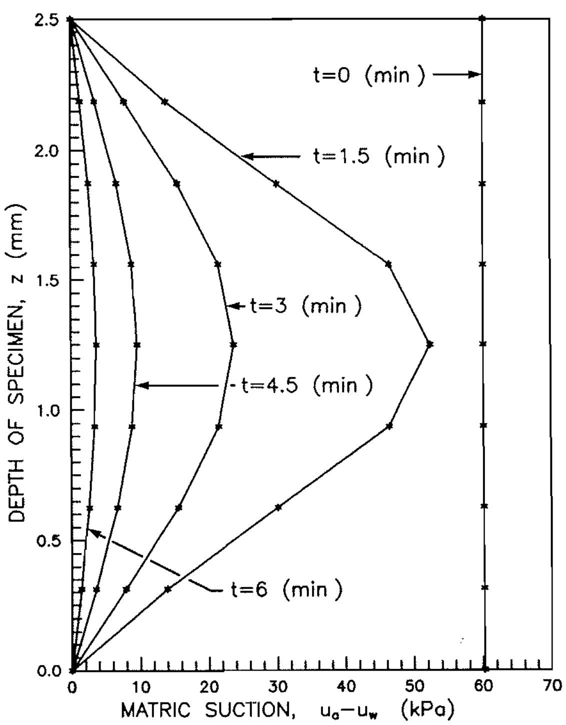

FIG. 16. Matric-suction isochrones from S1M test.

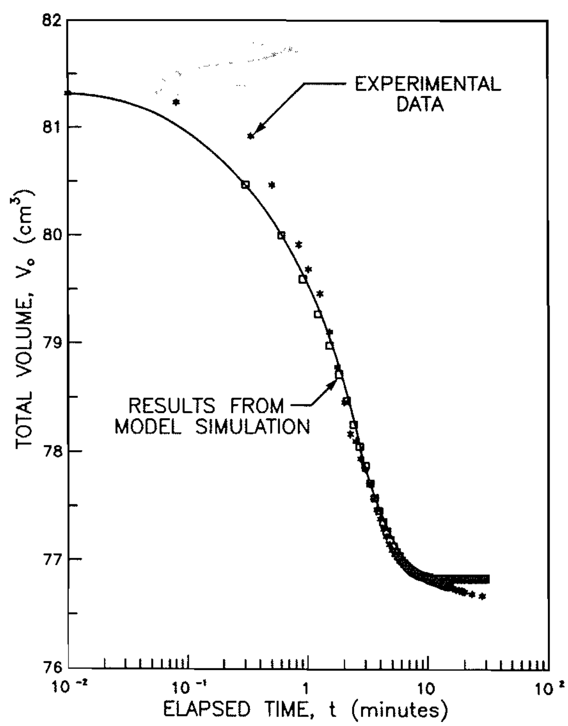

FIG. 17. Comparison between the theoretical analysis and experimental results for total volume changes from test S1M.

required to obtain a "best-fit" are shown in Table 3 against matric suction.

The varying matric suctions at the bottom, middle, and top of the specimen during the S4M test, obtained from the theoretical simulations, are compared with the experimental results in Figs. 13–15. The coefficient of consolidation was assumed to vary linearly with matric suction, and the values used to obtain the "best-fit" are shown in Table 4. Large variations in the coefficient of consolidation and the technique used in programming are the main reasons for numerical instability and scatter in the simulated results shown in Figs. 14 and 15. The accidental application of a small amount of water to the top of the specimen at the beginning of text is also partly responsible for the scatter in the simulated results, particularly around the top tensiometer.

Matric-suction isochrones obtained for the theoretical simulations of test S1M, by using the "best fit" values of c_v are shown in Fig. 16. It can be observed from the isochrones that suction is dropping at the top and bottom

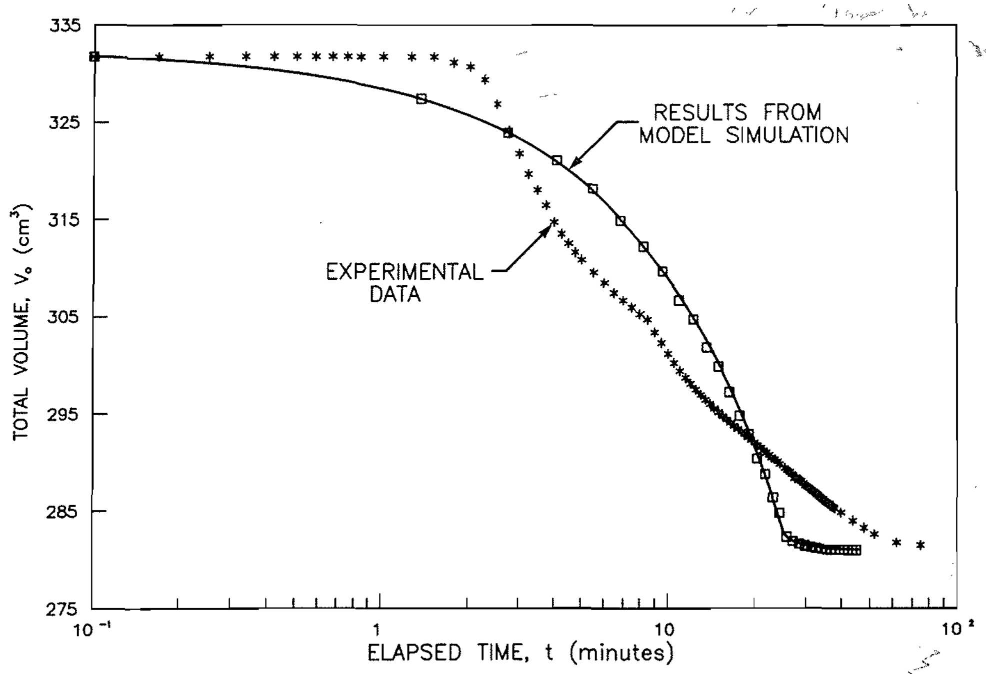

FIG. 18. Comparison between the theoretical analysis and experimental results for total volume changes from test S4M.

TABLE 4. Summary of coefficients used in S4M test simulation

Matric suction, $u_a - u_w$ (kPa)	Coefficient of consolidation, c_v^W (cm^2/s)	Coefficient of volume change, m_2^s (L/kPa)
0	1.0E−2	3.0E−5
20	5.0E−3	8.0E−4
40	4.6E−4	1.6E−3
66.8	1.0E−4	2.6E−3

of the specimen as the specimen was inundated from both ends. These results are in good agreement with the observations of numerical modelling studies of Lloret and Alonso (1980).

Theoretical simulations for the total volume changes were computed once the changes in the matric suction in the specimen had been predicted. Best-fit results of the total volume changes for test S1M were obtained using a constant value of m_2^s throughout the process. The measured total volume changes are compared with the "best-fit" simulations in Fig. 17, for test S1M.

The "best-fit" simulation values obtained for the S4M test are compared with the experimental results in Fig. 18. The simulations were obtained using a linearly varying value of m_2^s with respect to matric suction. The m_2^s values are shown against the respective matric-suction values in Table 4.

The comparison between the simulated and the experimental results for changes in the matric suction with respect to time indicate that the theory of the consolidation equation for unsaturated soils can be used to simulate changes in matric suction for soils exhibiting collapse behavior. The values for the coefficient of consolidation were found to vary (usually within about one order of magnitude) during the collapse process. The values of the coefficient of consolidation appear to vary by two orders of magnitude for specimen S4M. This was the thicker soil specimen. The coefficient of consolidation values were found to increase as the degree of saturation of the specimen increased during inundation.

Volume-change comparisons between the theoretical simulations and the experimental results also support the use of unsaturated-soil theories to predict collapse behavior. Constant values of m_2^s could be used in simulations for higher density soil specimens (i.e., specimens having a dry density equal to or higher than 1.5 t/m^3). The m_2^s values were found to be varying linearly with respect to matric suction for the lower density specimens. There was good agreement of the total volume decreases due to inundation for all the tests irrespective of their initial dry density or water content. The m_2^s values were found to decrease with decreasing matric suctions during inundation of the lower density specimens.

The experimental results and the theoretical analyses provide evidence that a reduction in matric suction is the primary cause of a reduction in overall volume when a soil collapses upon inundation. The collapse phenomenon is a gradual process with respect to time, although it does occur over a relatively short period of time. The decrease in volume and changes in matric suction during inundation can be satisfactorily simulated using the concepts and formulations associated with unsaturated soil behavior.

Conclusions

The following conclusions can be drawn from the results presented in this paper.

(1) The collapse phenomenon is primarily related to the reduction of the matric suction during inundation. Matric suction is one of the two stress-state variables that control the behavior of an unsaturated soil.

(2) There is a one-to-one relationship between matric suction and total volume change for a soil exhibiting collapse behavior during inundation.

(3) The theory of consolidation for an unsaturated soil can be used to predict the matric suction and total volume

changes with respect to time during inundation, for a collapsing soil.

(4) The experimental data relating matric suction and total volume change during collapse can be obtained using slight modifications of a conventional oedometer.

(5) Theoretical simulations of matric-suction changes indicate that the coefficient of consolidation, c_v^w, of the collapsing soil increases during inundation.

(6) The theoretical simulations of total volume change during collapse indicate that the coefficient of volume change with respect to matric suction, m_2^s, is either constant or decreases (in an absolute sense) with the reduction in matric suction during collapse.

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