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Measurements of Matric Suction and Volume Changes During Inundation of Collapsible Soil

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ABSTRACT: Reduction in soil volume due to inundation under a constant total stress is a phenomenon referred to as *collapse*. Collapse is exhibited by soils during a change of state from an unsaturated to a saturated condition. Several researchers have postulated various theories to explain collapse behavior. Recent published research has attempted to explain the collapse phenomenon using theories of unsaturated soil mechanics. However, the theoretical explanations require further verification by experimental data.

A simple experimental procedure is suggested in this paper to measure changes in matric suction and soil volume during inundation. The suggested measurements provide experimental data that can be used to verify the applicability of the unsaturated soil mechanics theories to collapsible soil behavior. Typical test results from this experimental program indicate that collapsible soil behavior can be explained using unsaturated soil mechanics theories.

KEY WORDS: collapsing soils, matrix, volume, unsaturated, matric suction, volume change, inundation

Soils which exhibit a reduction in total volume change during inundation at a constant total stress are called *collapsible soils*. The collapse of a soil mass upon inundation causes a significant engineering problem in many parts of the world. The problems range from the performance of foundations to earth fill structures. Understanding the collapse phenomenon from a theoretical standpoint is helpful in design for ensuring satisfactory performance of earth structures built on collapsible soils.

Research on collapsible soils has primarily concentrated on the identification or determination of the probable amount of collapse. Several researchers (Holtz and Hilf 1961; Burland 1965; Dudley 1970; and Barden, McGowan, and Collins 1973) have proposed various possible collapse mechanisms. Postulations found in the research literature agree that collapsible soils are always unsaturated and that the reduction in matric suction is one of the major causes for the occurrence of collapse. This implies that the constitutive relations for volume change in unsaturated soils (Fredlund and Morgenstern 1976) could be used to explain the behavior of collapsible soils.

The applicability of the unsaturated soil mechanics theories to collapsible soils can be experimentally verified by relating changes in the stress state variable to total volume change during inundation. However, there were no such experimental data available in the literature. This is partly due to the difficulties associated with the measurements of matric suction, $u_a - u_w$, where u_a = pore-air pressure; u_w = pore-water pressure. Matric suction is the only stress state variable that changes during inundation (Tadepalli and Fredlund 1991). In this paper, a testing procedure is suggested which utilizes slight modifications to regular consolidometer testing.

Several researchers (Matyas and Radhakrishna 1968; Escario and Saez 1973; and Cox 1978) had presented data on volume changes occurring in collapsible soils as a result of step-wise inundation. The inundation was conducted by controlling the pore-air and pore-water pressures in a closed system. However, there were no data available that relate the total volume changes to matric suction changes during each step of inundation.

Literature Review

Matyas and Radhakrishna (1968) carried out two series of tests on a collapsible soil. The results indicated that the compressibility of the soil is a function of matric suction. The soil structure was shown to be more rigid (or less compressible) at high matric suctions. Escario and Saez (1973) conducted three series of tests on a Madrid clayey sand using a modified oedometer apparatus. It was reported that there was a reduction in total volume as a result of a matric suction decrease and that the volume change became most significant at relatively low suction values.

Cox (1978) tested a clay till in an oedometer constructed within a suction plate apparatus. A dry clay till was found to exhibit swelling or collapse depending on various factors as the soil was progressively wetted under a constant overburden pressure. Lloret and Alonso (1980) explained the collapse phenomenon using a model developed on the concept of state surfaces. Maswoswe (1985) conducted suction-controlled tests on a collapsible clay soil. It was concluded that the occurrence of collapse was not due to overall shear failure but quite likely due to reduction in matric suction.

Experimental data discussed above were obtained by controlling the pore-air pressure, u_a, and the pore-water pressure, u_w, at each end of the specimen (i.e., by applying the desired

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TABLE 1—*Summary of index properties.*

	Indian Head Silty Sand	Mississippi Delta Silt (Vicksburg)
Grain-size distribution	Sand sizes = 62% Silt sizes = 32% Clay sizes = 6% D_{10} = 0.0034 mm D_{30} = 0.025 mm D_{60} = 0.090 mm	Sand sizes = 5.9% Silt sizes = 84.3% Clay sizes = 9.8% D_{10} = 0.002 mm D_{30} = 0.043 mm D_{60} = 0.017 mm
Coefficient of uniformity, C_u	$C_u = D_{60}/D_{10} = 26.4$	$C_u = D_{60}/D_{10} = 8.5$
Atterberg limits	Liquid limit, w_L = 22.2% Plastic limit, w_P = 16.6% Plasticity index, PI = 5.6%	Liquid limit, w_L = 35.5% Plastic limit, w_P = 21.55% Plasticity index, PI = 14.0%
Specific gravity, G_s	= 2.68	= 2.68

matric suctions to the specimen). Inundation was indirectly imposed by reducing the applied matric suctions. This type of test could not yield data on the changes in the matric suction and changes in the total volume *during* inundation. Therefore, the uniqueness of the relationship between matric suction and the total volume could not be verified from these available experimental data.

Theory

Fredlund and Hasan (1978) proposed a general equation to describe the one-dimensional consolidation of unsaturated soils. The water flow equation can be written with an assumption of constant pore-air pressures during inundation as:

$$\frac{\partial u_w}{\partial t} = \frac{1}{c_v^w} \frac{\partial^2 u_w}{\partial^2 y} + \frac{\partial c_v^w}{\partial y} \frac{\partial u_w}{\partial y} \qquad (1)$$

where

u_w = pore-water pressure,
c_v^w = coefficient of consolidation with respect to the water phase,
y = vertical cartesian coordinate, and
t = time.

Constitutive relations for volume change in unsaturated soils were proposed by Fredlund and Morgenstern (1976). The proposed soil structure constitutive relation can be used to predict the volume change of collapsible soils during inundation as well as volume changes associated with the swelling of a soil (Tadepalli and Fredlund 1991). The equation for volume change is

$$\frac{dV_v}{V_0} = m_2^s \, d\,(-u_w) \qquad (2)$$

where

dV_v = change in total volume,
V_0 = initial volume of soil,
$d\,(-u_w)$ = change in pore-water pressure, and
m_2^s = coefficient of total volume change with respect to a change in matric suction at a constant net normal stress.

The rate of matric suction (or negative pore-water pressure) change and total volume change during inundation can be computed by solving Eqs 1 and 2, respectively.

Soils

Tests were conducted on statically compacted specimens and on undisturbed specimens of collapsible soils. An Indian Head silty sand obtained from the Saskatchewan Department of Highways was used for the compacted specimens. Undisturbed loess specimens were procured from the Mississippi Delta near Vicksburg, Mississippi. The index properties of the Indian Head sand and the Mississippi loess soil are presented in Table 1.

Pilot tests were conducted on compacted specimens in order to relate the soil properties (i.e., water content and dry density at the time of compaction) to the total amount of collapse. Details of the test procedure are presented in the following sections.

Results from the study of initial water content and dry density effects on the percent collapse for Indian Head silty sand are presented in Figs. 1 and 2, respectively. Percent collapse is defined as a ratio between the change in height of a soil specimen upon inundation in a consolidation ring dH, to the initial height of the specimen, H_0 (i.e., dH/H_0). Both figures indicate an inversely linear relationship between the initial soil properties and the percent collapse. The percent collapse decreases with an increase in the initial water content or dry density. These results are in general agreement with observations made by Popescu (1986) and Foss (1973).

Equipment

Tensiometers were used to measure matric suctions in the collapsible soil specimens prior to and during inundation. A tensiometer consists of a water-filled tube which is connected to a high air entry porous ceramic cup at one end and to a vacuum gauge at the other end. Many types of tensiometers are presently available. The flexible tube type of tensiometers[4] was used in this program.

The ceramic cup of the tensiometer is inserted into the soil specimen for matric suction measurements. Water in the tensiometer tube flows in or out through the ceramic cup in order to establish equilibrium with the negative pore-water pressures

[4] Model 2100F, Soilmoisture Equipment Corp., Santa Barbara, CA 93105.

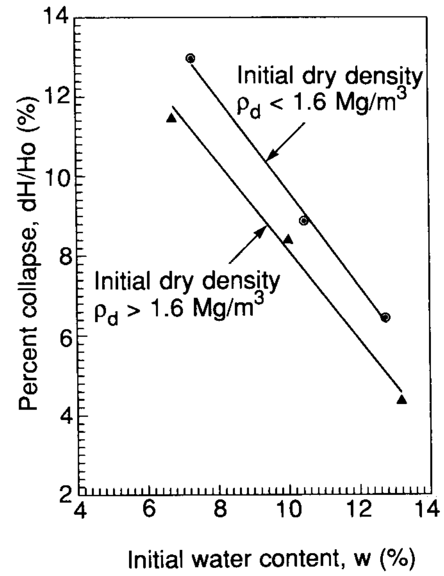

FIG. 1—*Effect of the initial water content on the percent collapse of statically compacted specimens of Indian Head silty sand.*

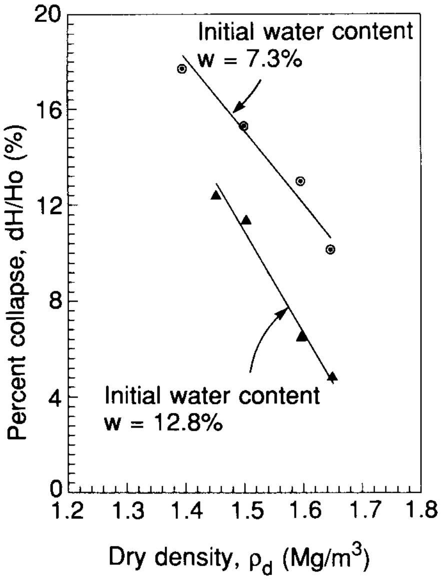

FIG. 2—*Effect of the initial dry density on the percent collapse of statically compacted specimens of Indian Head silty sand.*

in the soil. The water flow stops when an equilibrium condition has been achieved. As a result, the water in the tensiometer tube will be under tension as recorded on the vacuum gauge. The vacuum gauge reading at equilibrium is equivalent to the soil matric suction when the pore-air pressure is assumed to be atmospheric.

Flexible tube type tensiometers (Fig. 3) have a flexible, coaxial plastic tube approximately 1 m in length. One end of the tube is connected to the main water tube, and the other end is connected to the porous ceramic tip. The main water tube is approximately 150 mm long and serves as a water reservoir which is connected to a vacuum gauge. The outer tube of the flexible coaxial tubing has an internal diameter of 3.2 mm. A smaller inner tube is contained within the outer tube. One end of the inner tube is chamfered and embedded in the ceramic tip. The other end is vented to a hole on the main water tube. The ceramic tip is hollow with a diameter of 6 to 7 mm and a length of 25 mm.

Flexible tube type tensiometers are reasonably sensitive to changes in the matric suction at the tip of the ceramic cup. The

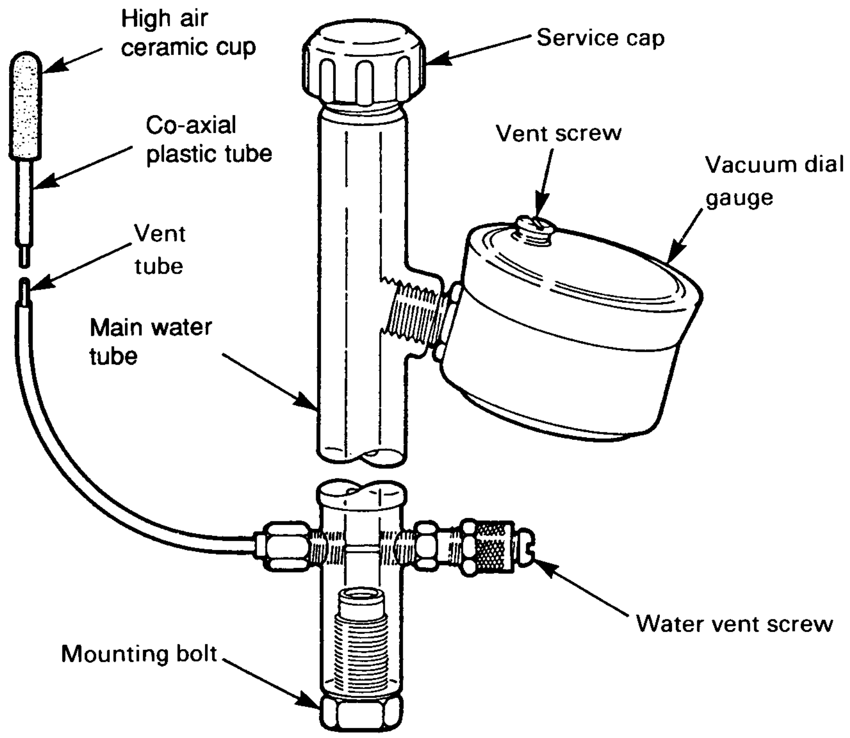

FIG. 3—*Details of flexible tube type tensiometer (Model 2100F, Soilmoisture Equipment Corp.).*

response curve of a flexible type tensiometer during a complete inundation is illustrated in Fig. 4.

Four types of oedometer rings (Type I, II, III, and IV) were used in the testing program. Type I oedometer ring was used in the study of the effect of the soil properties on the amount of collapse. The dimensions of the ring are 19.0 mm in height and 63.0 mm in diameter.

Type II, Type III, and Type IV oedometer rings were used in the study of the transient processes during inundation that involve changes in matric suction and soil volume. The height of the Type II oedometer ring is 25.4 mm, and its diameter is 62.0 mm. A hole with a diameter of 7.5 mm was drilled through the side of the oedometer ring. This hole was to allow for the insertion of the tensiometer tip into the compacted specimen. A Type IV oedometer ring was used for testing undisturbed specimens. The Type IV Oedometer ring is similar to ring Type II but has a chamfered end to facilitate the trimming of undisturbed specimens.

The Type III Oedometer ring was used to perform tests with matric suction measurements (i.e., using tensiometers) at different heights along the compacted specimen. The height and diameter of the oedometer ring is 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, respectively. The third hole was drilled diametrically opposite at the midheight of the ring.

The oedometer pot was adapted with a flexible extension in order to accommodate the tubing from the tensiometers.

The static compaction mold consisted of a cylinder with a 70.4-mm internal diameter into which an oedometer ring could be fitted (Fig. 5). The load was applied through a movable top piston while the bottom piston was screwed onto the mold. Both pistons were provided with flanges to prevent them from entering the oedometer ring. The mold split horizontally to facilitate the removal of the oedometer ring containing the compacted soil. No drains were provided in the compaction mold since all of the specimens were well below the saturation water content.

Preparation of Specimens

Soil particles passing the No. 10 sieve were air-dried and then mixed with the required amount of water in order to reach a specified water content. The soil was kept in polyethylene bags and stored in the humidity room for several days for equalization. Three sizes of oedometer specimens were prepared for the collapse tests on compacted specimens. Type I oedometer ring was used for collapse tests without matric suction measurements.

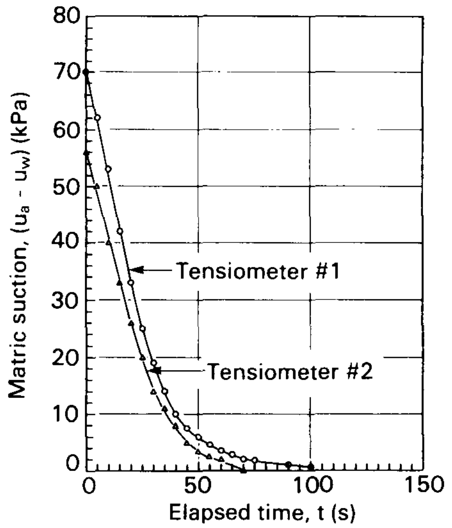

FIG. 4—*Test results indicating a quick response of tensiometer with respect to time upon complete submersion.*

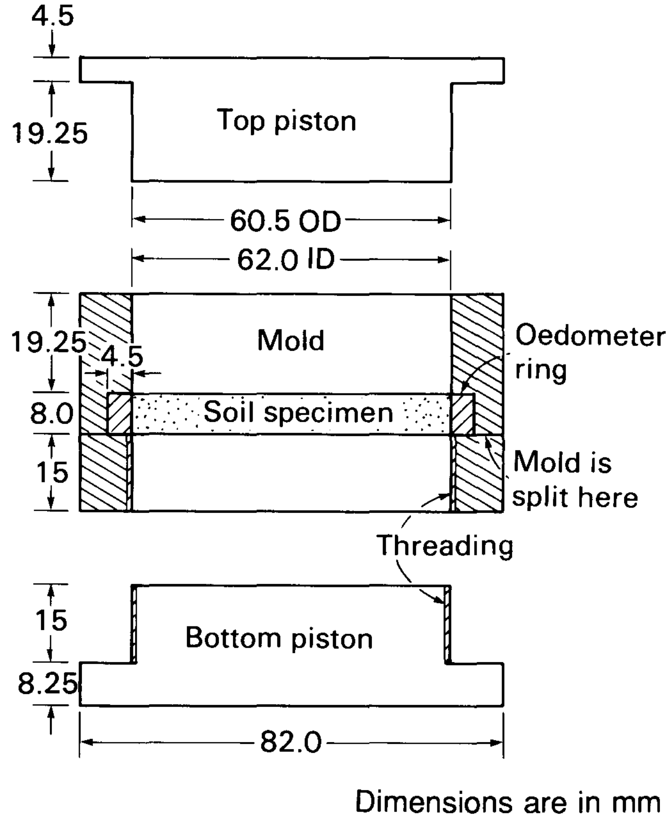

FIG. 5—*Oedometer ring inside the compaction mold.*

Compacted Specimens

Soils were statically compacted into the oedometer rings. The smaller specimens were compacted using the static compaction mold while the larger specimens were compacted directly into the oedometer ring. Prior to compaction, a slight amount of silicone grease was applied to the inner side of the ring in order to minimize side friction between the soil and the ring's wall during compaction, as well as subsequent collapse. The water content of the soil, which was stored in a polyethylene bag, was determined before compacting the soil. The weight of the soil required for the mold could then be calculated in order to achieve a specified initial dry density.

The compaction mold was assembled with its bottom piston in place. The required amount of soil was placed and then gently leveled into the mold. The top piston was placed into position and a static load was applied using a loading frame. The top piston was pressed slowly until the flanges touched the mold. The mold was pressed tightly in the compaction machine for a few minutes in order to reduce rebound effects. The mold was then removed from the compaction equipment and dismantled. The compacted specimen along with the oedometer ring were weighed prior to mounting them into the oedometer. This allowed for the determination of the density of the specimen.

Collapse tests with suction measurements require the installation of tensiometers. A hole was drilled into the compacted specimen through the hole provided in the oedometer ring. The specimen was held tightly in between two wide porous stones during the drilling process. The hole was drilled using a 5.7-mm-diameter drill bit. This was approximately 1 mm smaller than the diameter of the tensiometer tip. This was to ensure good contact between the ceramic tip and the soil specimen. The hole was about 2 mm longer than the length of the ceramic tip.

After drilling the hole, the ceramic tip of the tensiometer was carefully inserted into the specimen as shown in Fig. 6. Porous stones were held tightly against both ends of the oedometer ring during the insertion of the ceramic tip into the soil specimen. The tip was pushed all the way to the end of the hole. The small gap (around 2 mm) between the back end of the tip and the edge of the oedometer ring was filled with soil. The outer edge of the hole was then sealed with silicone gel (Fig. 7) in order to prevent water from moving into the specimen through the hole during inundation.

Dry porous stones were carefully placed on the top and bottom of the specimen in a floating ring arrangement. A slight gap between the porous stones and the inner wall of the ring was sealed with silicone grease to avoid water movement into the specimen during inundation (Fig. 8). This procedure was used in order to provide a uniform wetting front inside the soil specimen during and after inundation.

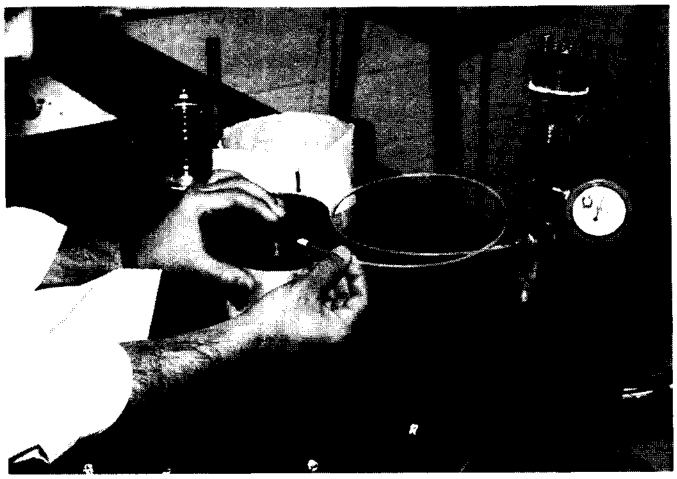

FIG. 6—*Installation of the tensiometer tip into the Type II oedometer ring.*

The larger specimens were prepared in a similar procedure with the exception that the soil was compacted directly into the oedometer ring. Tensiometers at different heights were installed into the compacted specimen inside the oedometer ring.

Undisturbed Specimens

Undisturbed samples of loess from the Mississippi were trimmed into the Type IV oedometer ring. The installation procedure for the tensiometer was similar to that used for the compacted specimens.

Testing Procedure

Filter papers were not used at each end of the specimen. The oedometer pot was covered with a plastic wrap after placing the specimen into the pot. The plastic wrap was secured to the pot using "masking tape." The test setup was left for 24 h to allow the pore-water pressures to equalize.

Collapse tests without suction measurements were conducted by loading the specimens at the end of the 24-h period. The load was doubled every 2 h. The vertical deflection under each load was then recorded. The specimen was inundated with distilled water when the vertical pressure on the soil was approximately equal to the compaction pressure. Inundation was performed by filling the oedometer pot with distilled water as quickly as possible. Dial gauge readings were noted manually during inundation. The final deflection was recorded after 24 h for calculating the percent collapse. Further loadings were applied after the saturated condition was reached, and then the specimens were unloaded.

The procedure for performing collapse tests with matric suction measurements was slightly different from the above test procedure. The soil specimen along with the ceramic tip was left in the pot until the readings on the vacuum gauge of the tensiometer reached a constant value. Once the tensiometer reading stabilized, the initial matric suction value of the specimen was noted and the specimen was ready for loading. The load was

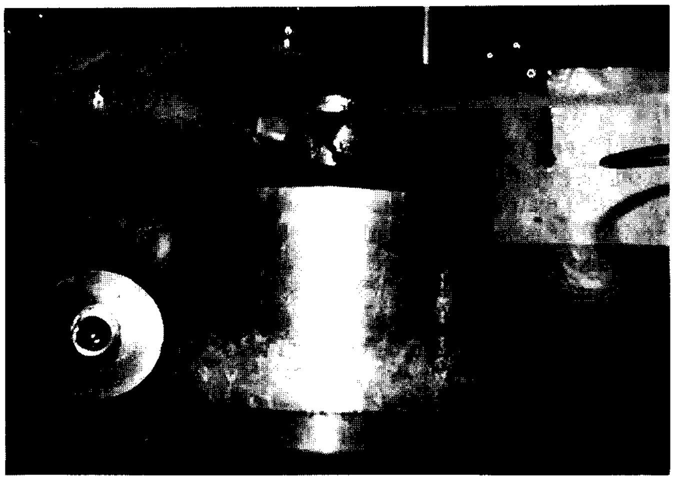

FIG. 7—*Sealing the hole on the surface of the oedometer ring after installing the tensiometer tip.*

FIG. 8—*Sealing the gap between the oedometer ring wall and the edge of the porous stones.*

increased every 2 h with a load increment ratio of approximately 1.

The deflections under each load were recorded along with the matric suction values. A negligible change in the matric suction was commonly observed during the loadings prior to inundation. The load was increased until the compaction pressure was reached. The specimen was then completely submerged in distilled water.

During inundation, changes in the matric suction and in the dial gauge readings were recorded at various elapsed times. Readings were taken frequently until the matric suction dropped to zero. The soil specimen was left in the inundated condition for 24 h. Most of the collapse occurred in the first few minutes after inundation. The final deflection at the end of 24 h was noted.

After inundation, the specimen was unloaded. The specimen was unloaded either in stages or in a single stage. At the end of the test, the ceramic tip of the tensiometer was carefully removed from the soil specimen and placed in distilled water. The collapsed test, with matric suction measurements using a single tensiometer, is illustrated in Fig. 9.

The test procedure for the larger specimens with three tensiometers was the same as the above procedure with the exception that the specimen was inundated only from the bottom. This was done in order to study the response of the tensiometers at three different positions. Readings were taken frequently until all the tensiometer readings reached zero. A photograph of the Type III oedometer ring with three tensiometers at different heights is illustrated in Fig. 10.

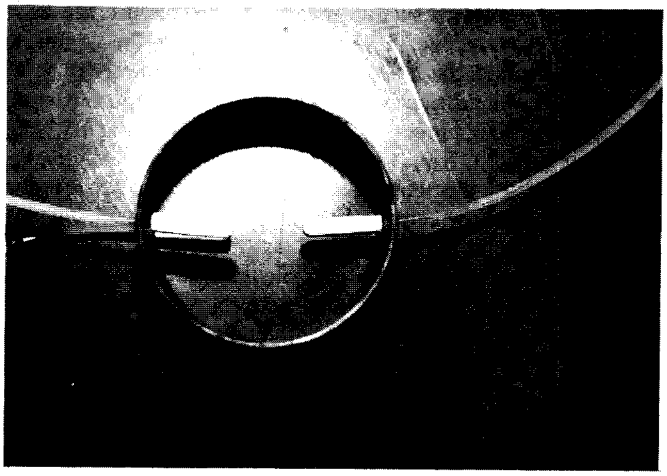

FIG. 10—*Details of the three tensiometers at different heights in the Type III oedometer ring.*

Test Results

Typical test results for the collapse tests with matric suction measurements on compacted specimens and undisturbed specimens are presented in Figs. 11 to 13. Details of the index properties, percent collapse, and inundation pressure (i.e., vertical stress at which the specimen was inundated) associated with the test data are given in Table 2. Changes in the matric suction and the total volume change for the smaller and larger compacted specimens (i.e., Figs. 11 and 12, respectively) indicate that there exists a unique relationship between changes in matric suction and changes in total volume during inundation. The results in Fig. 12 show that the soil volume changed progressively with the reduction in matric suction and that the volume change ceased when the matric suction dropped to zero. A similar type of observation can be made from Fig. 13 as obtained from collapse tests on an undisturbed specimen. As an example, Tadepalli and Fredlund (1991) obtained a close comparison between the theoretical simulation and the matric suction versus total volume changes measured during inundation tests. The theoretical simulations are based on Eqs 1 and 2.

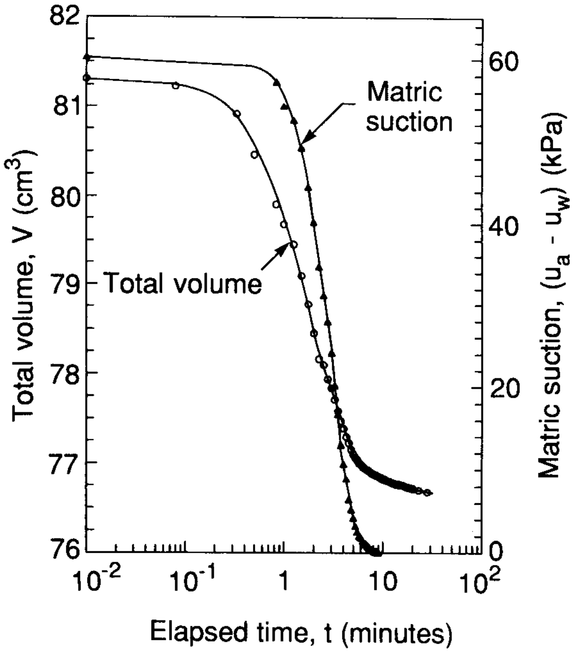

FIG. 11—*Matric suction and total volume changes versus time during inundation of a smaller compacted specimen of Indian Head silty sand with a single tensiometer.*

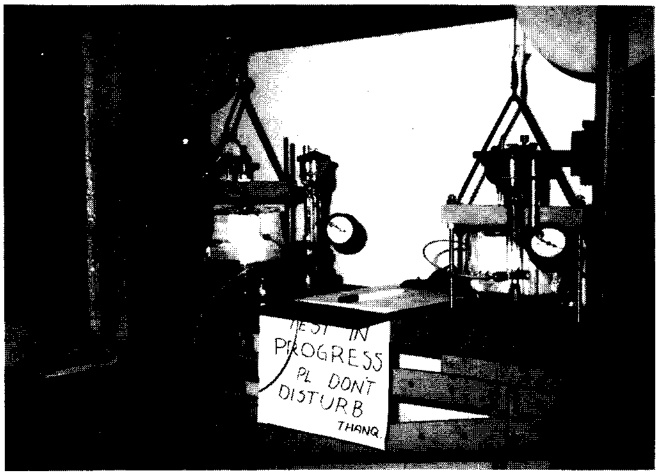

FIG. 9—*Experimental setup for collapse tests with matric suction measurements using a single tensiometer.*

The results also demonstrate that the suggested simple testing procedure can be used to verify the applicability of the unsaturated soil mechanics principles to the collapse of soils during inundation.

The testing range for the suggested procedure is limited to 100

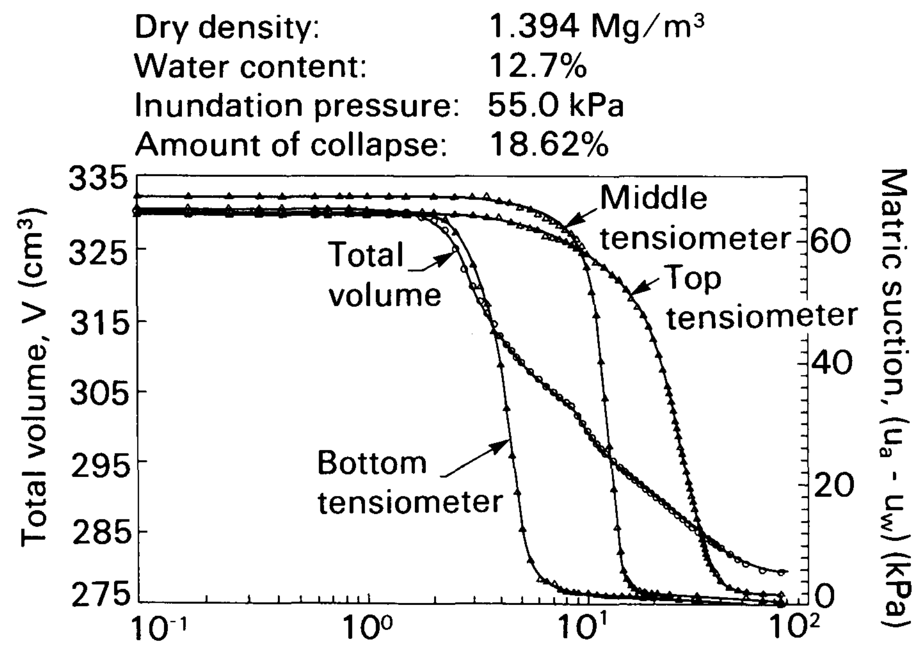

FIG. 12—*Matric suction and total volume changes versus time during inundation of a larger compacted specimen of Indian Head silty sand with three tensiometers.*

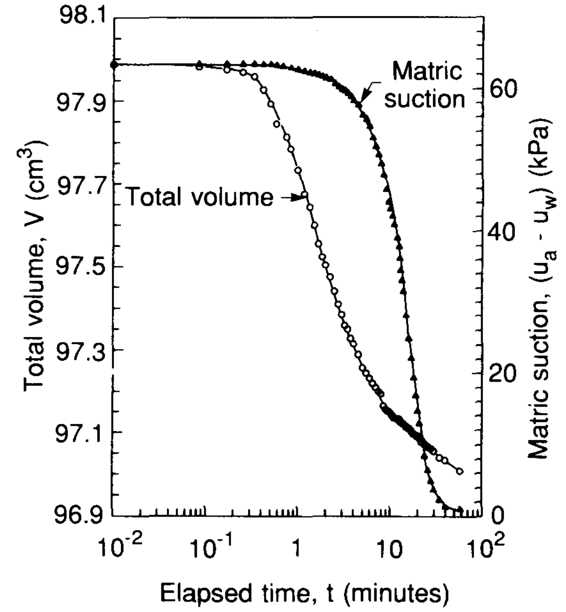

FIG. 13—*Matric suction and total volume changes versus time during inundation of an undisturbed specimen of Mississippi Delta silt with a single tensiometer.*

kPa of matric suction since this is the theoretical limitation of the tensiometer.

Conclusion

The following conclusions can be drawn from the results of the above testing program:

1. Experimental data relating matric suction and total volume change during soil structure collapse can be obtained using a conventional oedometer with slight modifications.
2. Flexible tube type tensiometers with proper servicing and installation provide a reliable means of measuring small changes in matric suction during inundation within a reasonable period of testing.

References

Barden, L., McGowan, A., and Collins, K., 1973, "The Collapse Mechanism in Partly Saturated Soil," *Engineering Geology*, Vol. 7, pp. 49–60.

Burland, J. B., 1965, "Some Aspects of the Mechanical Behavior of Partly Saturated Soils," *Moisture Equilibria and Moisture Changes in Soils Beneath Covered Areas*, Butterworths, Sydney, Australia, pp. 270–278.

TABLE 2—*Summary of index properties, inundation pressures, and percents of collapse for three collapse tests.*

Description	Compacted Specimens of Indian Head Silty Sand		Undisturbed Specimen of Mississippi Delta Silt Single Tensiometer
	Single Tensiometer	Three Tensiometers	
Dry density, ρ_d (Mg/m³)	1.60	1.39	1.32
Water content, w(%)	11.8	12.8	31.5
Inundation pressure, (kPa)	97.0	55.0	49.0
Percent collapse, dH/H_0[a]	5.8	18.6	1.1

[a] dH = change in height as a result of inundation.
H_0 = original height of the specimen.

Cox, D. W., 1978, "Volume Change of Compacted Clay Till," Institution of Civil Engineers Conference on Clay Fills, London, pp. 79–86.

Dudley, J. H., 1970, "Reviewing of Collapsing Soils," *Journal of Soil Mechanics and Foundation Engineering Division, ASCE*, Vol. 96, SM3, pp. 925–947.

Escario, V. and Saez, J., 1973, "Measurement of the Properties of Swelling and Collapsing Soils Under Controlled Suction," *Proceedings*, 3rd International Conference on Expansive Soils, Vol. 1, Jerusalem Academic Press, pp. 195–200.

Foss, I., 1973, "Red Soil from Kenya as a Foundation Material," *Proceedings*, 8th International Conference of Soil Mechanics Foundation Engineering, Vol. 2.3, Moscow, pp. 73–80.

Fredlund, D. G. and Hasan, J. U., 1978, "One-Dimensional Consolidation Theory: Unsaturated Soils," *Canadian Geotechnical Journal*, Vol. 16, No. 3, pp. 521–531.

Fredlund, D. G. and Morgenstern, N. R., 1976, "Constitutive Relations for Volume Change in Unsaturated Soils," *Canadian Geotechnical Journal*, Vol. 13, No. 3, pp. 261–276.

Holtz, W. G. and Hilf, J. W., 1961, "Settlement of Soil Foundations due to Saturation," *Proceedings*, 5th International Conference on Soil Mechanics Foundation Engineering, Vol. 1, Dunod, Paris, pp. 673–679.

Lloret, A. and Alonso, E. E., 1980, "Consolidation of Unsaturated Soils Including Swelling and Collapse Behavior," *Geotechnique*, Vol. 30, No. 4, pp. 449–477.

Maswoswe, J., 1985, "Stress Paths for a Compacted Soil During Collapse due to Wetting," Ph.D. thesis, Imperial College, London.

Matyas, E. L. and Radhakrishna, H. S., 1968, "Volume Change Characteristics of Partially Saturated Soils," *Geotechnique*, Vol. 18, No. 4, pp. 432–448.

Miranda, A. N., 1988, "Behavior of Small Earth Dams During Initial Filling," Ph.D. thesis, Colorado State University, Fort Collins, CO.

Popescu, M. E., 1986, "A Comparison between the Behavior of Swelling and of Collapsing Soils," Engineering Geology, Vol. 23, pp. 145–163.

Shackel, B., 1970, "The Compaction of Uniform Replicate Soil Specimens," *Australian Road Research*, Vol. 4, No. 5, pp. 12–31.

Tadepalli, R. and Fredlund, D. G., 1991, "The Collapse Behavior of a Compacted Soil during Inundation," *Canadian Geotechnical Journal*, Vol. 28, No. 4, pp. 477–488.