SOIL COLLAPSE AND MATRIC SUCTION CHANGE

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ABSTRACT: The objective of this paper is to demonstrate the relationship between soil collapse and matric suction for an uncemented, collapsing soil. An experimental program involving oedometer tests with special instrumentation, was conducted on compacted specimens of a fine silty sand and on an undisturbed silt. Small tip tensiometers were installed in the specimen to measure the matric suction. The soil specimens were inundated and the resulting collapse was monitored. During inundation, the matric suction and volume changes were measured simultaneously at various elapsed times. The results indicate a direct relationship between the reduction in volume and the decrease in matric suction during collapse in oedometer test.

1. INTRODUCTION

Compacted soils often exhibit a swelling behavior. However, soils with low clay content, compacted at low densities can exhibit collapse behavior upon inundation. Soil collapse is the term used to refer to the phenomenon of a decrease in the volume of the soil due to inundation at constant vertical stress.

2. THEORETICAL CONSIDERATIONS

A general partial differential equation to describe the one-dimensional consolidation of an unsaturated soil (Fredlund and Hasan, 1978) can be rewritten for a collapsible soil (Tadepalli and Fredlund, 1991) as follows,

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

where:
u_w = pore-water pressure
c_v^w = coefficient of consolidation with respect to the water phase
y = vertical Cartesian coordinate
t = time

The constitutive relations for unsaturated soils can be used to predict the volume change of a collapsible soil during inundation. The equation can be written as follows (Tadepalli and Fredlund, 1991),

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

where:
dV_v = change in total volume
V_o = initial volume of the soil
$d(-u_w)$ = change in pore-water pressure
m_2^s = coefficient of total volume change with respect to a change in matric suction at a constant net normal stress

Equation [1] can be written in an explicit, finite difference form. Changes in the volume of the soil subsequent to inundation can be estimated using Eq. [2].

3. SOILS USED IN THE TESTING PROGRAM

Tests were conducted on remolded and on undisturbed soil specimens. Silty sand from Indian Head, Saskatchewan, was used to prepare the remolded specimens. Undisturbed specimens were procured from the Mississippi delta area near Vicksburg, United States. The index properties of the silty sand and of the deltaic soil are presented in Table 1.

4. EQUIPMENT USED IN TESTING PROGRAM

Matric suction in the collapsible soil mass before and during inundation was measured using flexible tube type tensiometers [Figure 1].

Three types of oedometer rings (Type I, II and III) were used for the testing program. Type I oedometer ring has a height of 25.4 mm and a diameter of 63.0 mm. A 7.5 mm hole was drilled through the side of the oedometer ring. This hole allowed for the insertion of the tensiometer

Table 1. Summary of Index Properties

	Indian Head Silty Sand	Mississippi Delta (Vicksburg) Silt
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	

tip into the compacted soil specimen. Type III ring was used for testing undisturbed specimens. Type III ring was similar to Type I but had a chamfered end to facilitate trimming of undisturbed specimens.

The Type II oedometer ring was used to perform tests with matric suction measurements at different heights along the compacted specimen. The height and diameter of the oedometer ring were 60.0 mm 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.

5 TEST PROGRAM

Collapse tests were conducted on compacted specimens and on undisturbed specimens using Type I oedometer rings and Type III oedometer rings, respectively. These rings were of 63 mm in diameter. Tests on larger specimens of 84.9 mm diameter were tested using Type II oedometer rings.

The ceramic tip of the tensiometer was carefully installed into the sides of the specimen through the holes provided in the modified oedometer ring. The specimen was placed between two dry porous stones in a floating ring type of set up. A slight gap that exists between the porous stones and the inner edge of the ring was sealed with silicone gel to prevent water entering the specimen during inundation.

The soil specimen with the ceramic tip installed was left in the pot until the tensiometer reading was stabilized. The initial matric suction value of the specimen was noted and the specimen was ready for loading. Loads were increased every two hours with a load increment ratio of approximately one. Deflections under each load were noted along with the matric suction values. There was usually no change in the matric suction when the loads were applied prior to inundation. Loads were increased until the desired load was attained. Once consolidation under the desired load was complete, the specimen was inundated from the top and from the bottom by filling the oedometer pot quickly with distilled water.

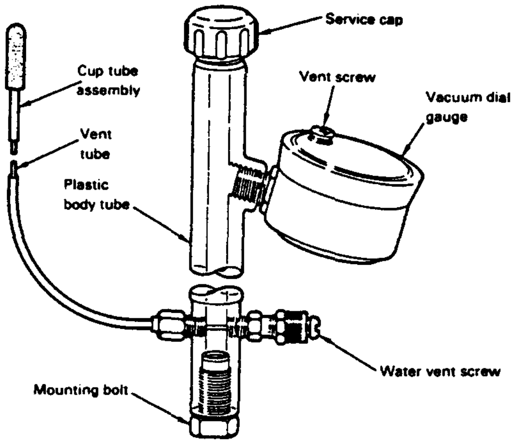

Figure 1 Details of flexible tube type tensiometer (Model 2100F, Soilmoisture Equipment Corporation)

During inundation, changes in the matric suction and the dial gauge readings were noted simultaneously with respect to time. Readings were taken frequently until the matric suction value dropped to zero. The soil specimen was left inundated for 24 hours. Significant settlement took place in the first few minutes of inundation. The final settlement at the end of twenty four hours was noted and was used to calculate the percent collapse. The specimen was unloaded either in stages or in a single stage.

The test procedure for the larger specimens using Type II oedometer ring with three tensiometers was similar to the above procedure, except that the specimen was inundated from the bottom only.

6. TYPICAL TEST RESULTS

The results from a pilot test program are presented in Fig. 2. It appears that there are two unique relationships between void ratio and vertical stress, one for specimens loaded under constant water content conditions and another for specimens loaded in a saturated condition (i.e., $(u_a - u_w)$ equals zero). The void ratio difference between these two relationships indicates the amount of collapse that will occur when the compacted specimen is inundated under a specific vertical stress. These relationships for a collapsible soil are best understood when plotted three-dimensionally in the form of a constitutive surface for an unsaturated soil with respect to the independent stress state variables, $(\sigma - u_a)$ and $(u_a - u_w)$ as illustrated in Fig. 3.

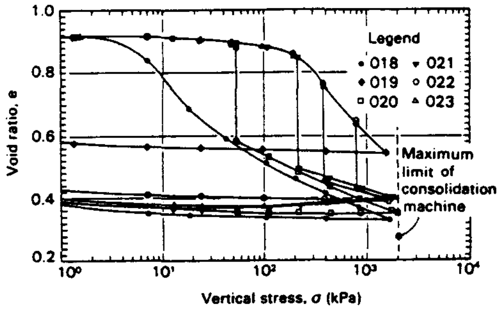

Figure 2 Effect of vertical pressure on the amount of collapse.

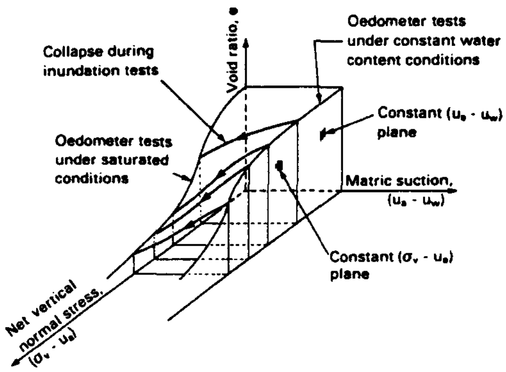

Figure 3 Constitutive surface of a collapsible soil.

The curves in Fig. 2 are essentially the projections of the constitutive surface onto the net normal stress plane. The surface in Fig. 3 clearly demonstrates that collapse during inundation will cause the void ratio to decrease to values corresponding to the saturated condition. The unsaturated soil specimens appeared to yield at a vertical pressure around 200 kPa [Fig. 2].

Typical test results for the collapse tests with suction measurement using single tensiometer on compacted specimens and undisturbed specimens are presented in Figs. 4 and 5, respectively. The index properties, the inundation pressure (i.e., vertical stress at which the specimens were inundated) and percent collapse (i.e., dH/H_0; where H_0 is the initial height of the specimen, and dH is the change in height of the specimen due to inundation at the end of 24 hours) are presented in Table 2.

The initial matric suction at the center of the compacted specimen, prior to inundation was approximately 60 kPa. There was a significant change in the matric suction during the first minute after inundation. The matric suction dropped at a significant rate in the next couple of minutes and was close to zero ten minutes after inundation.

Table 2. Summary of Index Properties, Inundation Pressure and Percent Collapse for Collapse Tests

DESCRIPTION	Compacted Specimens		Undisturbed Specimen
	Single Tensiometer	Three Tensiometer	Single Tensiometer
Dry density, ρ_d (Mg/m^3)	1.40	1.40	1.33
Water Content, w (%)	13.9	12.7	31.5
Inundation Pressure (kPa)	48	55	49
Percent Collapse, dH/H_0	15.3	18.6	1.2

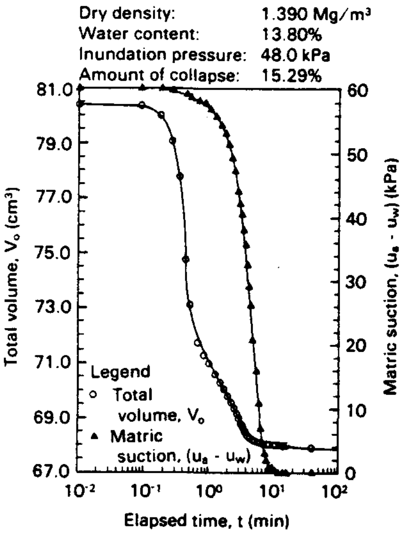

Figure 4 Matric suction and total volume changes with respect to time during inundation from tests on a compacted specimen with single tensiometer.

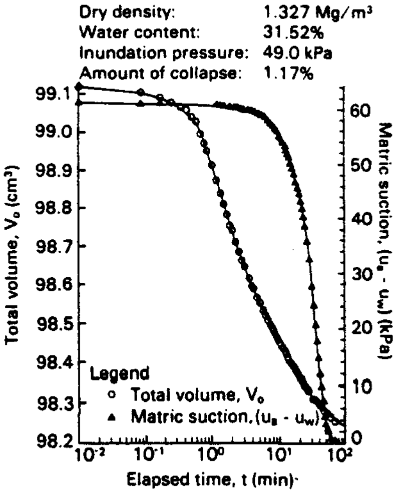

Figure 5 Matric suction and total volume changes with respect to time during inundation from tests on an undisturbed specimen with single tensiometer.

The volume of the specimen decreased significantly in the first few minutes after inundation. The volume decreased at a slower rate subsequent to the initial drop and remained almost constant after 10 minutes following inundation. The decrease in total volume ceased as the matric suction at the center of the specimen approached zero. Test results from the undisturbed specimens show similar behavior.

When the matric suction at the center of the specimen approached zero, this indicates that the matric suction in the entire specimen was near to zero. The stabilization of the volume changes as the matric suction in the middle of the specimen approaches zero suggests that there exists a one-to-one relationship between matric suction and total volume changes for collapsible soils during inundation.

Index properties of the larger specimens tested using Type II oedometer rings are given in Table 2. These specimens were inundated from the bottom only. The matric suctions at the top, middle and the bottom of the specimen along with the total volume changes are shown in Fig. 6.

The volume of the specimen did not change significantly in the first 2 minutes after inundation. The matric suction at the bottom tensiometer began to drop at about 2.5 minutes after inundation [Fig. 6]. 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 in the matric suction being registered at the bottom tensiometer. This volume change was due to a decrease in the 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 at the top tensiometer dropped initially because of the accidental spillage of water onto the top of the specimen.

The matric suction at the top tensiometer dropped to zero before the total volume change completely stopped. This indicates that the volume changes during the last few minutes were due to decreasing matric suctions in the region above the top tensiometer. The top tensiometer was located at 12.5 mm below the top surface of the specimen. No further change in volumes occur when the suction had dropped to zero in the entire specimen.

7. THEORETICAL SIMULATIONS

The total volume change with change in matric suction during collapse were simulated using the theory suggested earlier in the paper. The partial differential equation for water flow written in a finite difference form, was solved. Simulated results for all tests indicated that the coefficient of consolidation, c_v^w, varied during

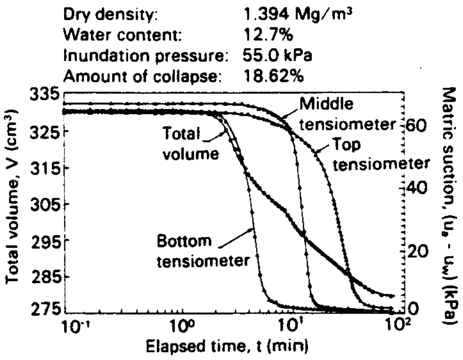

Figure 6 Matric suction and total volume changes with respect to time during inundation from tests on a compacted specimen with three tensionmeters.

inundation. This would appear to be reasonable due to the highly nonlinear nature of the coefficeient of permeability. It was found that the value of the coefficient of consolidation, c_v^w, was higher than the value deduced from the experimental data using the semi-log plot method for saturated soils. Theoretical simulations were obtained by using a linear variation of the coefficient of consolidation with respect to matric suction. Simulated matric suction changes for the compacted and the undisturbed specimens are compared with the experimental results in Fig. 7 and Fig. 8, respectively. The coefficients of consolidation required to obtain the "best-fit" simulations are shown in Tables 3 and 4 for the compacted and the undisturbed specimens, respectively.

Volume changes were computed once the changes in the matric suction in the specimen had been predicted. In the higher matric suction range, varying values of m_2^w were used. In the lower matric suction range, constant values of m_2^w were used. These m_2^w values are presented

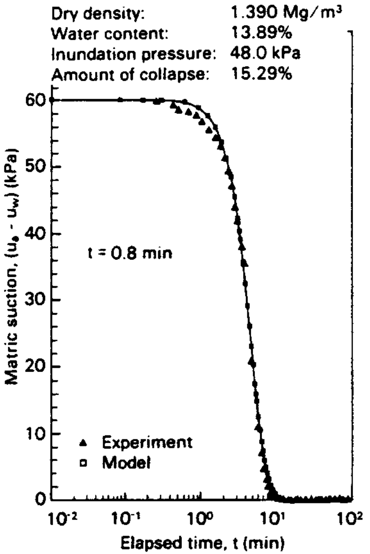

Figure 7 Experimental results and theoretical simulations of changes in matric suction obtained with single tensiometer during inundation of compacted specimen.

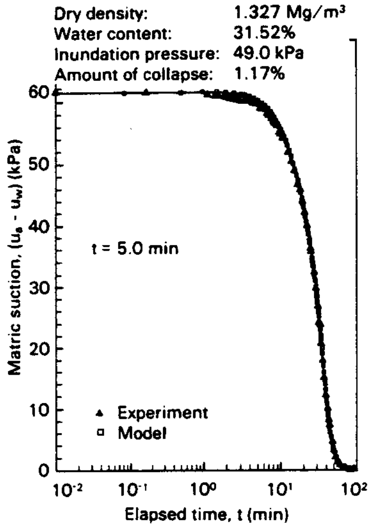

Figure 8 Experimental results and theoretical simulations of changes in matric suction obtained with single tensiometer during inundation of undisturbed specimen.

Table 3. Summary of c_v^w values used in the Simulation of Compacted Specimens with Single Tensiometer

Matric Suction $(u_a - u_w)$ (kPa)	Coeff. of Consolidation c_v^w, (cm²/s)	Matric Suction $(u_a - u_w)$ (kPa)	Coeff. of Volume Change m_2^s (1/kPa)
0	7.0E-3	0	2.2E-4
20	2.7E-4	45	2.2E-4
40	1.7E-4	60	7.0E-3
60	1.4E-4		

Table 4. Summary of c_v^w values used in the Simulation of Undisturbed Specimens with Single Tensiometer

Matric Suction $(u_a - u_w)$ (kPa)	Coeff. of Consolidation c_v^w, $(\mathrm{cm}^2/\mathrm{s})$	Matric Suction $(u_a - u_w)$ (kPa)	Coeff. of Volume Change m_2^s (1/kPa)
0	2.5E-3	0	1.0E-5
20	5.0E-4	40	1.0E-5
40	4.2E-4	61.4	2.2E-4
61.4	3.8E-4		

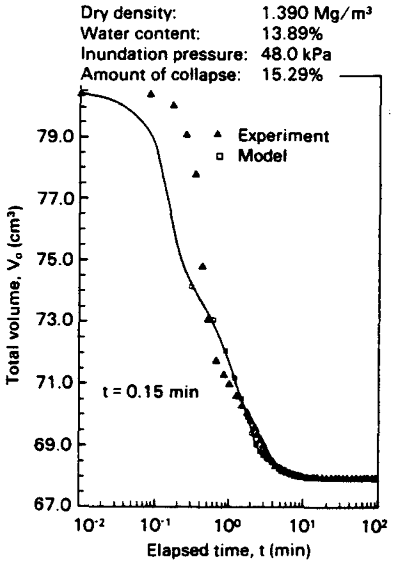

Figure 9 Experimental results and theoretical simulations of changes in volume obtained with single tensiometer during inundation of compacted specimen.

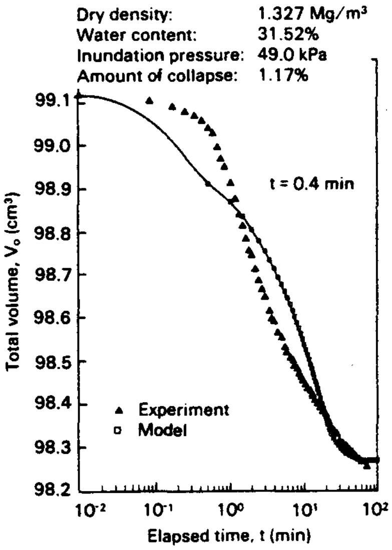

Figure 10 Experimental results and theoretical simulations of changes in volume obtained with single tensiometer during inundation of undisturbed specimen.

in Tables 3 and 4. Volume changes obtained from the simulations and from the actual measurements were compared in Fig. 9 and Fig. 10, respectively, for compacted and undisturbed specimens.

8. CONCLUSION

1. The collapse phenomenon is primarily related to the reduction of the matric suction during inundation. There is a one-to-one relationship between matric suction and total volume change for a soil exhibiting collapse behavior during inundation.
2. The mechanical behavior of the collapsing soil can be simulated using the theory of consolidation for an unsaturated soil. The collapse process appear to occur in a transient manner, though the process itself takes place in a relatively short period of time.
3. The coefficient of consolidation, c_v^w, of the collapsing soil increases during inundation.
4. The coefficient of volume change, m_2^s can either remain constant or decrease linearly with the decrease in matric suction during inundation of collapsible soils.

9. REFERENCES

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