TESTING PROCEDURES FOR OBTAINING VOLUME CHANGE INDICES DURING LOADING OF AN UNSATURATED SOIL

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ABSTRACT

The paper presents a brief review of the volume change theory for an unsaturated soil. Several testing procedures for obtaining volume change indices during loading of an unsaturated soil are described. Procedures and equipments associated with each test are also outlined. Typical results from loading tests on a compacted silt are presented and analyzed. The analyses are given in order to illustrate the application of the volume change theory to practical problems.

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INTRODUCTION

Many geotechnical works involve unsaturated soils. Natural soils above the groundwater table and compacted soils in roads and earth dams are typical examples of an unsaturated soil. Volume changes of the soil due to applied loads or environmental changes (i.e., rainfall and evaporation) are of interest to practicing engineers. The current volume change theory and testing procedures were developed primarily for saturated soil conditions. An extension to the theory and testing procedures is required for the prediction of volume changes in an unsaturated soil. This extension is reviewed in the paper. Typical volume changes during loadings of an unsaturated, compacted silt are presented and analyzed in order to illustrate the application of the extended theory.

VOID RATIO AND WATER CONTENT RELATIONS

In saturated soils, volume changes due to loading are usually calculated using the relationship between void ratio, e, and the logarithm of effective stress (i.e., $(\sigma - u_w)$; where: σ = total normal stress and u_w = pore-water pressures) (Terzaghi, 1943). The slope of this relationship is called compression index, C_c, which is a soil property. The (e vs. $\log(\sigma - u_w)$) relationship is obtained from conventional consolidation tests. The soil volume change in a saturated soil is equal to the water volume change since only water fills the soil pores.

In unsaturated soils, two stress state variables govern the volume change behavior; namely, net normal stress, $(\sigma - u_w)$, and matric suction, $(u_a - u_w)$ (where: u_a = pore-air pressure). Therefore, void ratio, e, should now be related to the logarithms of $(\sigma - u_a)$ and $(u_a - u_w)$ as plotted in Fig. 1a. In addition, an independent relationship for the soil water content, w, (Fig. 1c) is required in order to obtain a complete description of the volume change in an unsaturated soil. The difference between the soil structure and water volume changes is equal to the air volume change.

The void ratio and water content relationships for an unsaturated soil constitute a three-dimensional surface as illustrated in Fig. 1a and 1c (Fredlund and Morgenstern, 1976). The equations defining void ratio and water content changes upon loading can be written as follows:

$$de = C_t \, d\log(\sigma - u_a) + C_m \, d\log(u_a - u_w) \qquad [1]$$

and,

$$dw = D_t \, d\log(\sigma - u_a) + D_m \, d\log(u_a - u_w) \qquad [2]$$

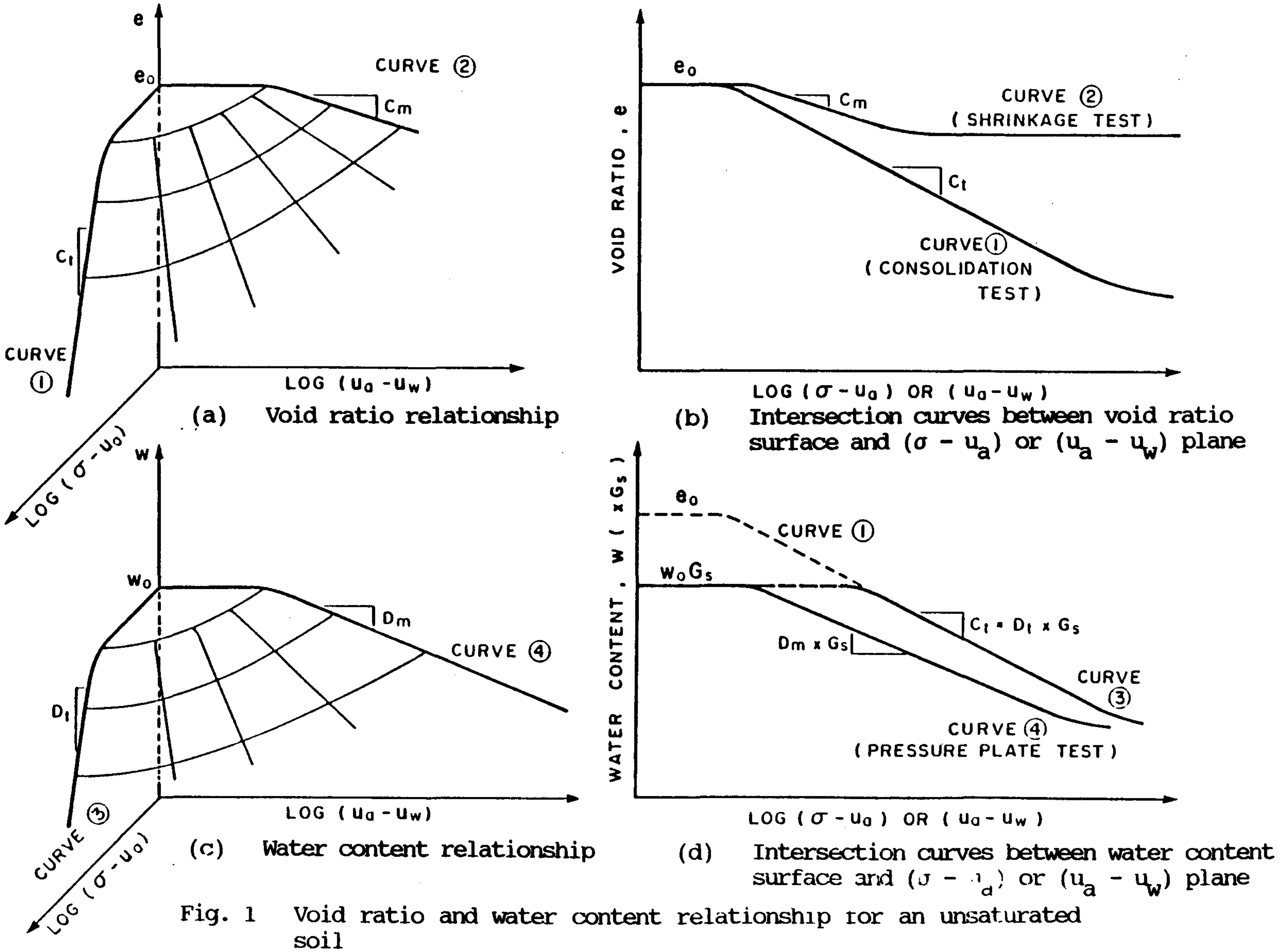
where:

de = decrease in void ratio

dw = decrease in water content

$d\log(\sigma - u_a)$ = increase in the logarithm of net normal stress

$d\log(u_a - u_w)$ = increase in the logarithm of matric suction



(a) Void ratio relationship

(b) Intersection curves between void ratio surface and $(\sigma - u_a)$ or $(u_a - u_w)$ plane

(c) Water content relationship

(d) Intersection curves between water content surface and $(\sigma - u_a)$ or $(u_a - u_w)$ plane

Fig. 1 Void ratio and water content relationship for an unsaturated soil

C_t = compressive index with respect to increase in net normal stress (i.e., $-\partial e/\partial \log(\sigma - u_a)$)

C_m = compressive index with respect to increase in matric suction (i.e., $-\partial e/\partial \log(u_a - u_w)$)

D_t = water content index with respect to increase in net normal stress (i.e., $-\partial w/\partial \log(\sigma - u_a)$)

D_m = water content index with respect to increase in matric suction (i.e., $-\partial w/\partial \log(u_a - u_w)$).

The intersection curves between the surfaces and the $(\sigma - u_a)$ or $(u_a - u_w)$ plane (i.e., curves 1, 2, 3 and 4 in Fig. 1) were assumed to adequately represent the entire surfaces (Ho, 1988; and Ho and Fredlund, 1989). In other words, the four volume change indices obtained from these four intersection curves (i.e., C_t, C_m, D_t and D_m) are assumed to be applicable to every point on the void ratio or water content surfaces.

The relationship between the volume change indices can best be visualized by presenting the intersection curves on one plot. The intersection curves 1 and 2 from the void ratio surface are combined in Fig. 1b. The slopes of curves 1 and 2 are called C_t and C_m volume change indices, respectively. The intersection curves 3 and 4 from the water content surface are combined in Fig. 1d. The water content, w, can be multiplied by the specific gravity, G_s, (i.e., $w\,G_s$) in order to make use of the basic equation (i.e., $S\,e = w\,G_s$; where S = degree of saturation) in obtaining one of the index relationships. This means that curves 3 and 4 in Fig. 1c are translated vertically by a magnitude of G_s in Fig. 1d. As a result, the slopes of curves 3 and 4 in Figure 1d are the products of G_s and the volume change indices (i.e., $(D_t \times G_s)$ and $(D_m \times G_s)$, respectively).

Curve 1 in Fig. 1 is essentially the consolidation curve for the soil in a saturated condition (i.e., $(u_a - u_w) = 0$ or $u_a = u_w$). The curve exhibits a linear relationship between void ratio and the logarithm of net normal stress, over a wide loading range. The slope of curve 1, C_t, is equal to the compression index, C_c, of the saturated soil. Curve 3 in Fig. 1d coincides with curve 1 from Fig. 1b since $w\,G_s$ is equal to the void ratio, e, when the soil is saturated (i.e., $S = 1$). Therefore, the volume change index D_t can be computed as (C_t / G_s).

Curve 4 in Fig. 1 is called a soil-water characteristic curve that can be obtained from a pressure plate test (see next sections). A shrinkage curve (explained in next sections) combined with the soil-water characteristic curve can be used to construct curve 2 in Fig. 1. In other words, the four volume change curves and their corresponding indices (i.e., C_t, D_t, D_m and C_m) can be obtained from routine soil tests.

The combined plot of curves 1, 2, 3 and 4 is presented in Fig. 2 which is essentially a combination of Figs. 1b and 1d. The arrows in Fig. 2 indicate the direction of curves 2 and 4 approaching curve 1 as the initial degree of saturation of the soil increases. In this case, curve 1 is assumed to remain constant for various initial degrees of saturation. When the soil is saturated (i.e., $(u_a - u_w) = 0$ or $u_a = u_w$) the e and $w\,G_s$ vary only with respect to net normal stress or the

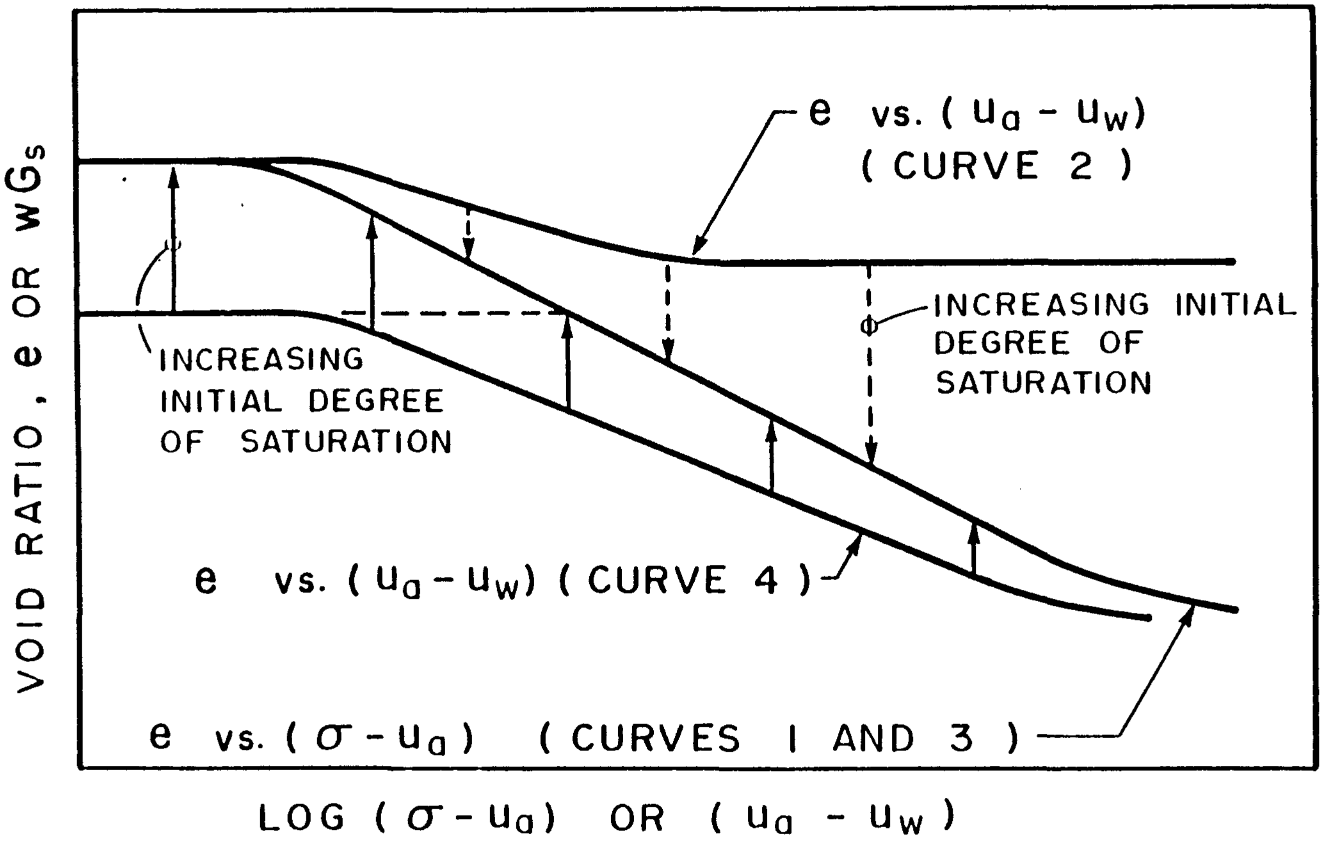


Fig. 2 Relationship between curves that define the volume change behavior of an unsaturated soil

effective stress, $(\sigma - u_w)$, following the same curve (i.e., curve 1 in Fig. 2).

TEST PROCEDURES AND EQUIPMENTS

In addition to the conventional consolidation tests, there are two other tests required for obtaining the volume change indices of an unsaturated soil. The other two tests are referred to as the pressure plate test and the shrinkage test.

Consolidation Tests

Procedures for consolidation tests on unsaturated soil specimens (e.g., compacted specimens) are outlined in ASTM D4546. This ASTM standard describes three methods for inundating the soil specimen prior to consolidation tests. During inundation, the soil matric suction is brought to zero and the results can be used to calculate the swelling potential of the soil. The inundation can be conducted under constant volume or free swelling conditions. Curve 1 in Figs. 1 and 2 illustrate the consolidation test results with the constant volume inundation at the beginning of the test. Having inundated the soil specimen, the test can proceed with the conventional procedure commonly used on saturated specimens (ASTM D2435). The decreasing void ratios, e, are plotted against the logarithms of effective stress, $(\sigma - u_w)$, to yield curves 1 and 3 as shown in Figs. 1 and 2.

Pressure Plate Tests

The soil-water characteristic curve (i.e., curve 4 and Figs. 1 and 2) of a soil relates the water content, w, to the applied matric suction, $(u_a - u_w)$, in the soil. In an unsaturated soil, the pore-air pressure, u_a, is usually atmospheric (i.e., $u_a = 0$) and the pore-water pressure, u_w, is negative. The difference in pressures is called the soil matric suction, $(u_a - u_w)$. In the laboratory, a matric suction is commonly applied to a soil specimen by maintaining a zero pore-water pressure (i.e., $u_w = 0$) and applying a positive pore-air pressure. Therefore, the matric suction in the soil specimen (i.e., $(u_a - u_w)$; where u_w is maintained zero) can be varied by applying different air pressure to the specimen. This procedure is referred to as the axis-translation technique (Hilf, 1956).

Pressure plate extractors are manufactured by Soilmoisture Equipment Corporation, Santa Barbara, California, U.S.A (Figs. 3 and 4). The extractors are commonly used to apply the various matric suctions to the soil specimen and the test is called a pressure plate test (ASTM D2325). The pressure plate extractor consists of a high air entry ceramic disc contained in an air pressure chamber. The high air entry disc is saturated and always in contact with water in a compartment below the disc that is maintained at zero water pressure.

A soil specimen is placed on top of the disc and the air tight chamber is pressurized to a desired matric suction. The disc does not allow the passage of air as long as the applied matric suction does not exceed the air entry value of the disc. This air entry value is related

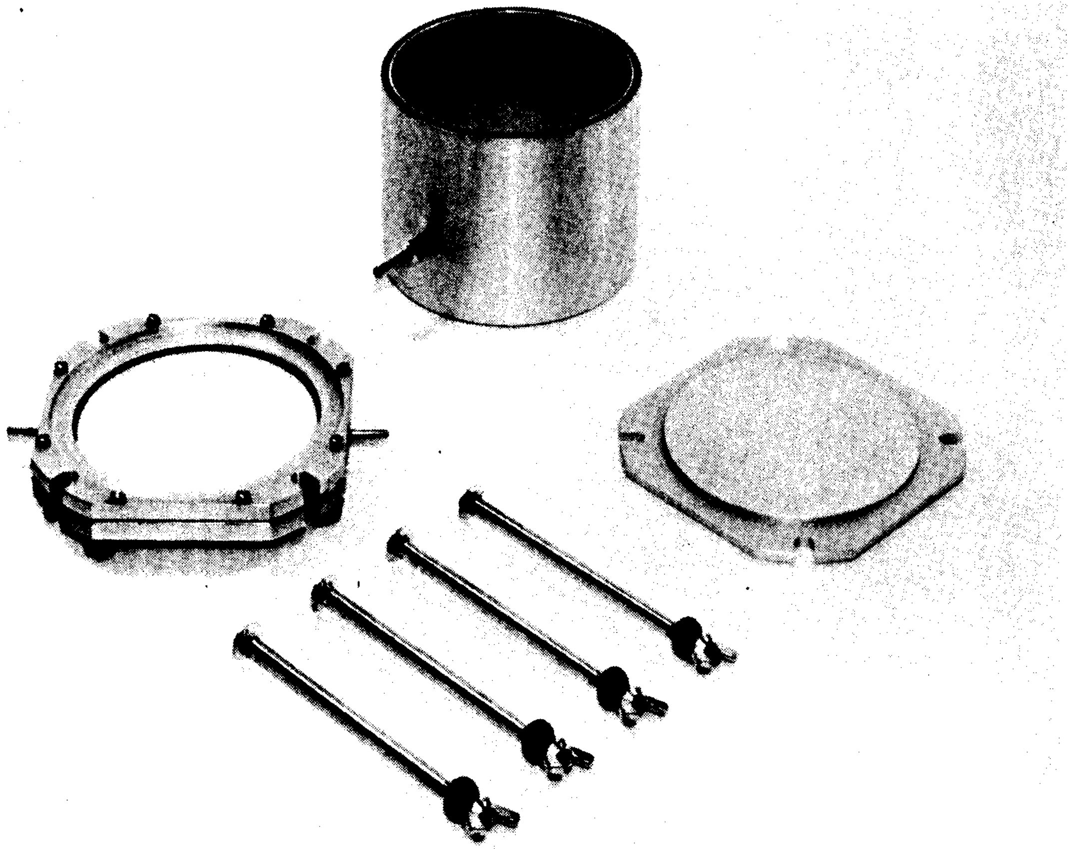


Fig. 3 Volumetric pressure plate extractor (i.e., maximum applied matric suction is 200 kPa) (Photograph courtesy of Soilmoisture Equipment Corporation, Santa Barbara, California, U.S.A.)

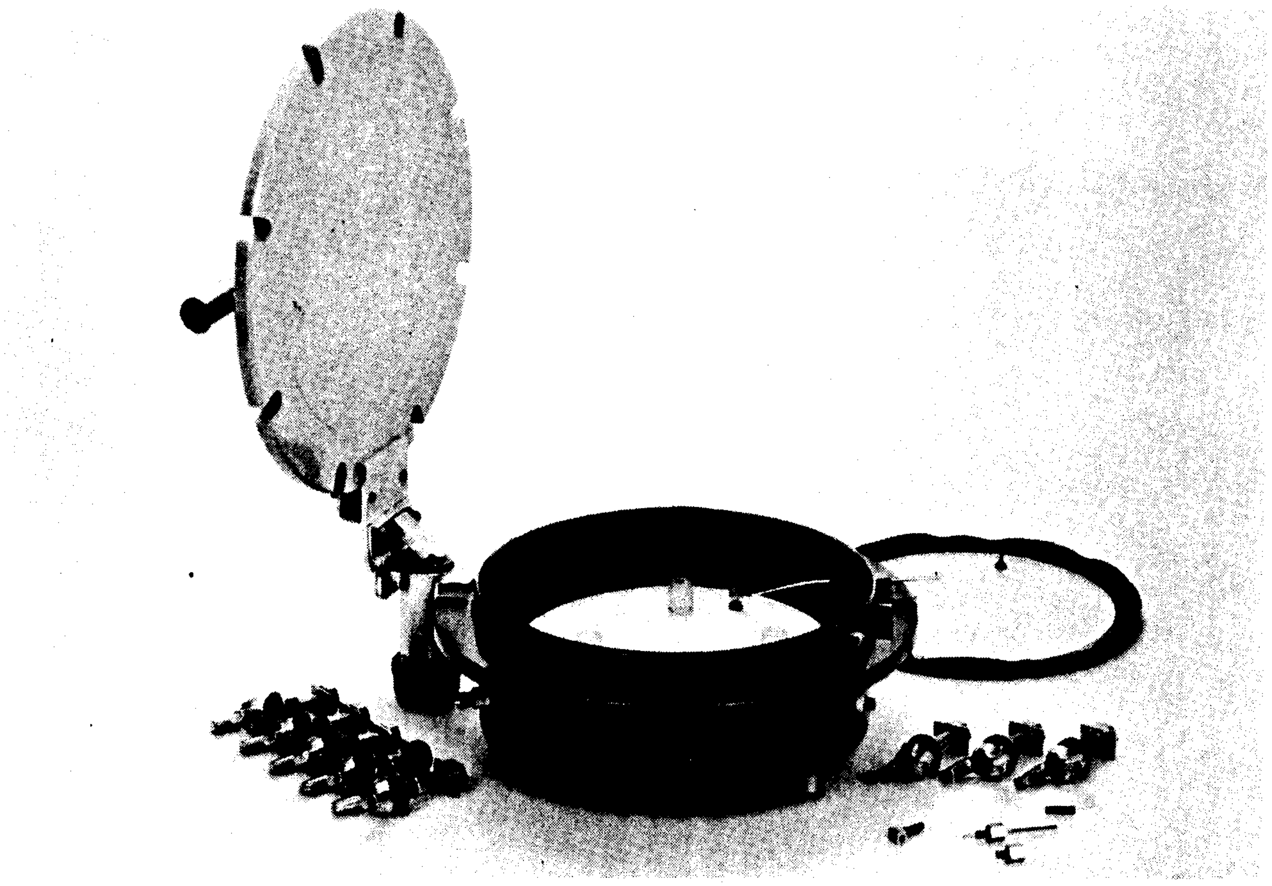


Fig. 4 15 Bar ceramic plate extractor (i.e., maximum applied matric suction is 1500 kPa) (Photograph courtesy of Soilmoisture Equipment Corportation, Santa Barbara, California, U.S.A.)

to the diameter of the fine pores in the ceramic disc. Therefore, the air entry value of the disc and the strength of the chamber control the maximum air pressure or matric suction that can be applied to the specimen.

The application of matric suction to the soil causes the pore-water to drain to the water compartment through the disc. A burette can be connected to the compartment to measure the water volume changes. At equilibrium, the soil will have a reduced water content at a high matric suction. The changing water content can also be measured directly at each equilibrium condition by dismantling the chamber and measuring the weight of the specimen. This procedure is commonly used with 15 bar ceramic plate extractor. The plot between the equilibrium water contents and the logarithms of the corresponding matric suctions gives rise to curve 4 in Figs. 1 and 2.

Shrinkage Tests

A shrinkage relationship for a soil relates the void ratio, e, to the water content, w, at various matric suctions. A soil specimen can either be allowed to dry in the air or it can be subjected to various matric suctions using the pressure plate extractors. In either case, the void ratio and water content of the specimen can be measured at various equilibrium states. When the specimen is allowed to dry in air, the process should be interrupted at various stages while the sample is covered and allowed to come to equilibrium.

Accurate measurements of void ratio can be performed following the techniques used in the shrinkage limit test (ASTM D427). The shrinkage test involves the measurements of total volume of the soil specimen using the mercury displacement technique. The total volume of a soil specimen can be measured by immersing the specimen into a full cup of mercury (Fig. 5). The volume of the displaced mercury during immersion is equal to the total volume of the specimen.

Direct measurements of total volume can also be performed using calipers. The shrinkage curve can be constructed by plotting the decreasing void ratios against the decreasing water contents as the soil matric suction increases.

TEST RESULTS

The above three tests were conducted on unsaturated, compacted silt specimens. The properties of the silt are given in Fig. 6 along with the consolidation test results. The consolidation tests were performed in accordance with the constant volume test method. The loading curves are essentially curves 1 and 3 in Figs. 1 and 2 and their slopes are equal to C_t or $(D_t \times G_s)$. The soil-water characteristic curve of the silt (Fig. 7) was obtained from the pressure plate tests. In this plot, the water content, w, was multiplied by the specific gravity, G_s, for the purpose of combining the void ratio and water content plots as previously illustrated in Fig. 2 (i.e., curve 4). The slope of the curve is equal to $(D_m \times G_s)$.

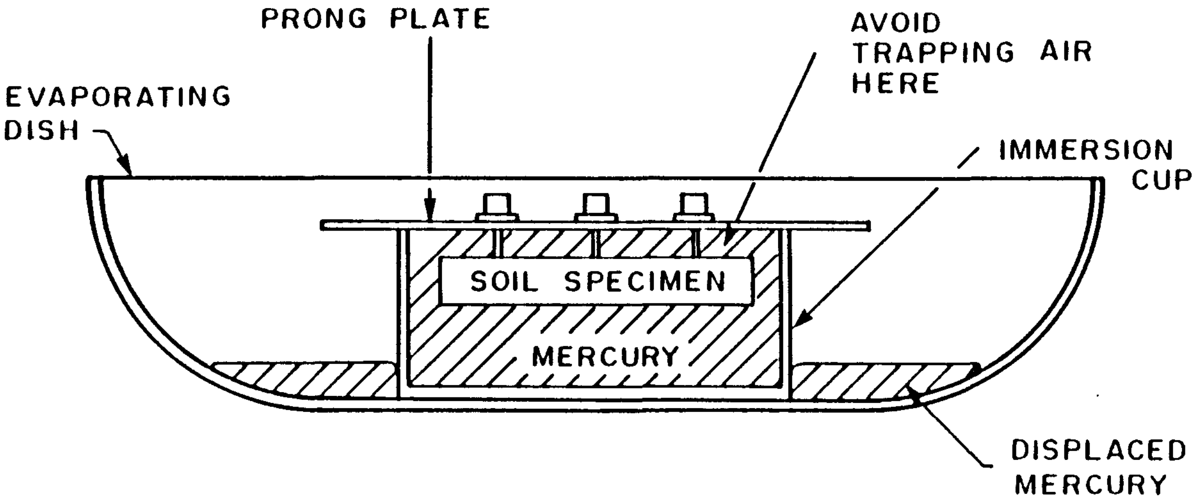


Fig. 5 Immersion of sample in shrinkage limit test (from Head, 1984)

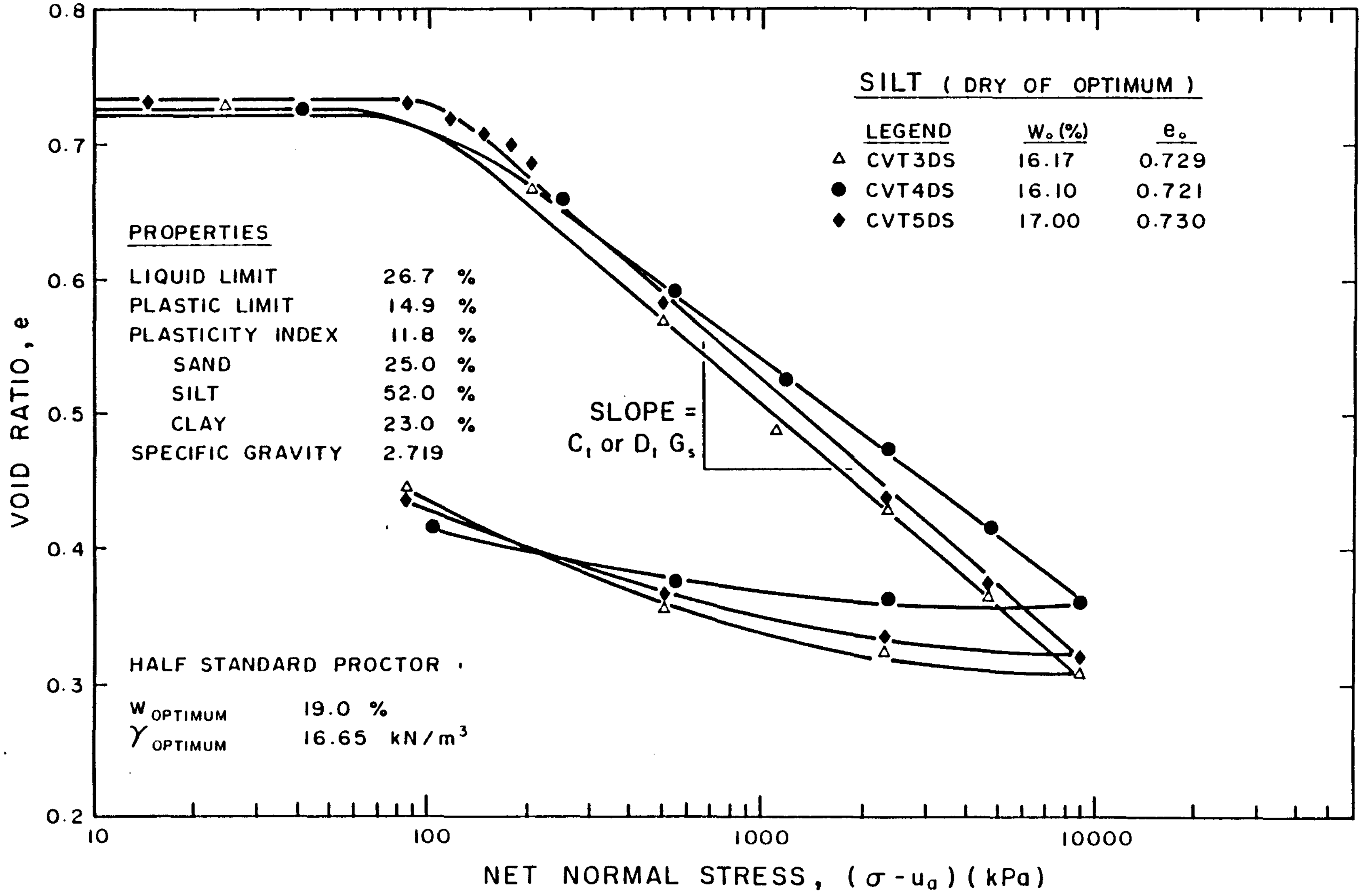


Fig. 6 Results from one-dimensional constant volume tests on a compacted silt

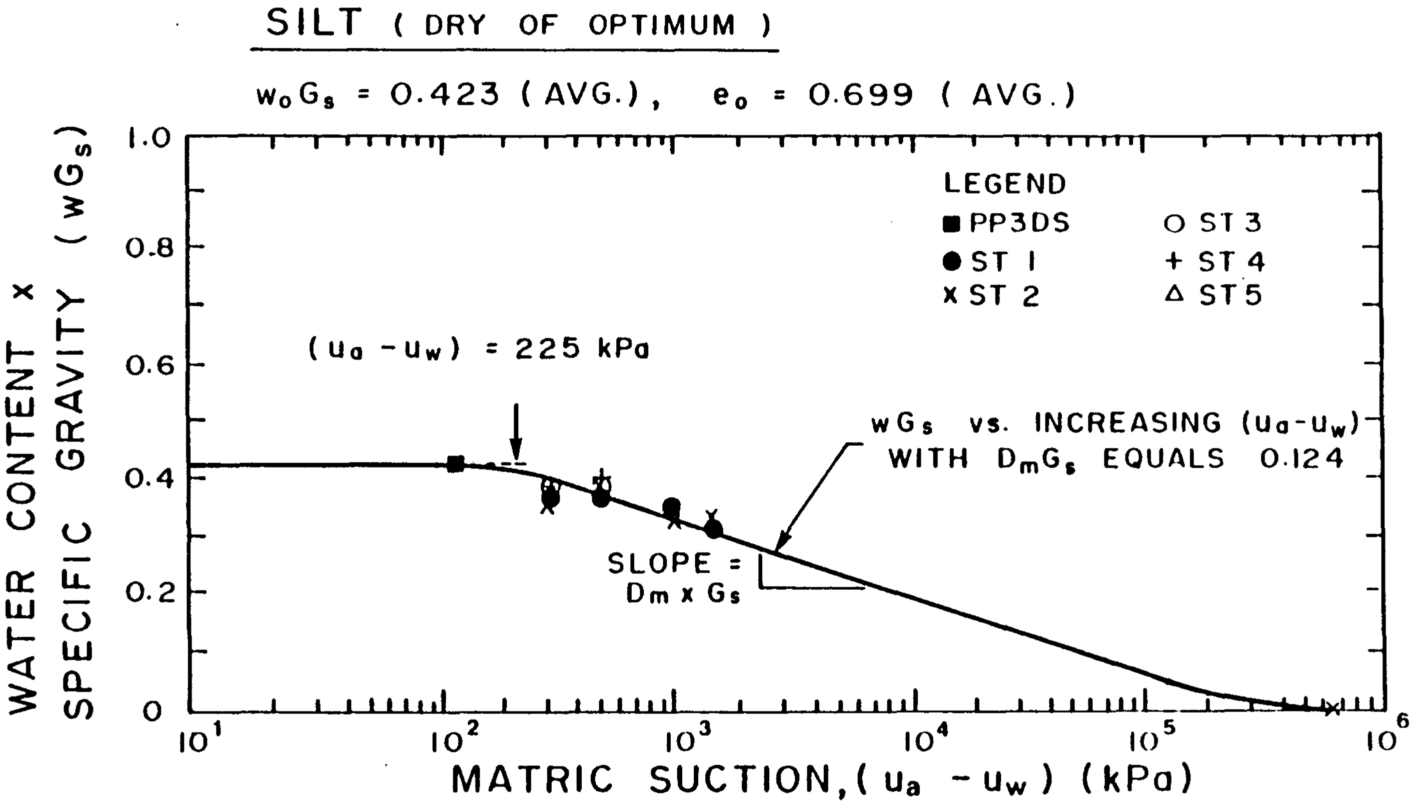


Fig. 7 Soil-water characteristic curve of a compacted silt

The shrinkage curve of the compacted silt is shown in Fig. 8. The water content, w, was also mulitiplied by the specific gravity, G_s, in Fig. 8. The void ratios, e, corresponding to the various water contents (i.e., w G_s) in Fig. 7 can now be found using the shrinkage relationship in Fig. 8. As a result, the void ratio versus matric suction relationship (i.e., curve 2 in Figs. 1 and 2) can be constructed using Figs. 7 and 8. The slope of the shrinkage curve (i.e., $de/d(w\ G_s)$ or $(\partial e/\partial(u_a - u_w))/(\partial(w\ G_s)/\partial(u_a - u_w))$) is essentially the ratio of volume change indices (i.e., C_m / D_m G_s).

The combined plot of Figs. 6, 7 and curve 2 (i.e., constructed from Figs 7 and 8) is depicted in Fig. 9. Figure 9 illustrates the volume change characteristic of an unsaturated, compacted silt. The volume change indices (i.e., C_t, C_m, D_t and D_m) can be computed from Fig. 9. Changes in void ratio and water content due to an increase in total stress or suction can now be predicted using the computed volume change indices (Fig. 9).

SUMMARY

Consolidation, pressure plate and shrinkage tests are the required experiments for obtaining the volume change indices corresponding to the loading of an unsaturated soil. These ordinary tests are performed using conventional soil mechanics testing procedures. The test results provide the volume change relationship for an unsaturated soil.

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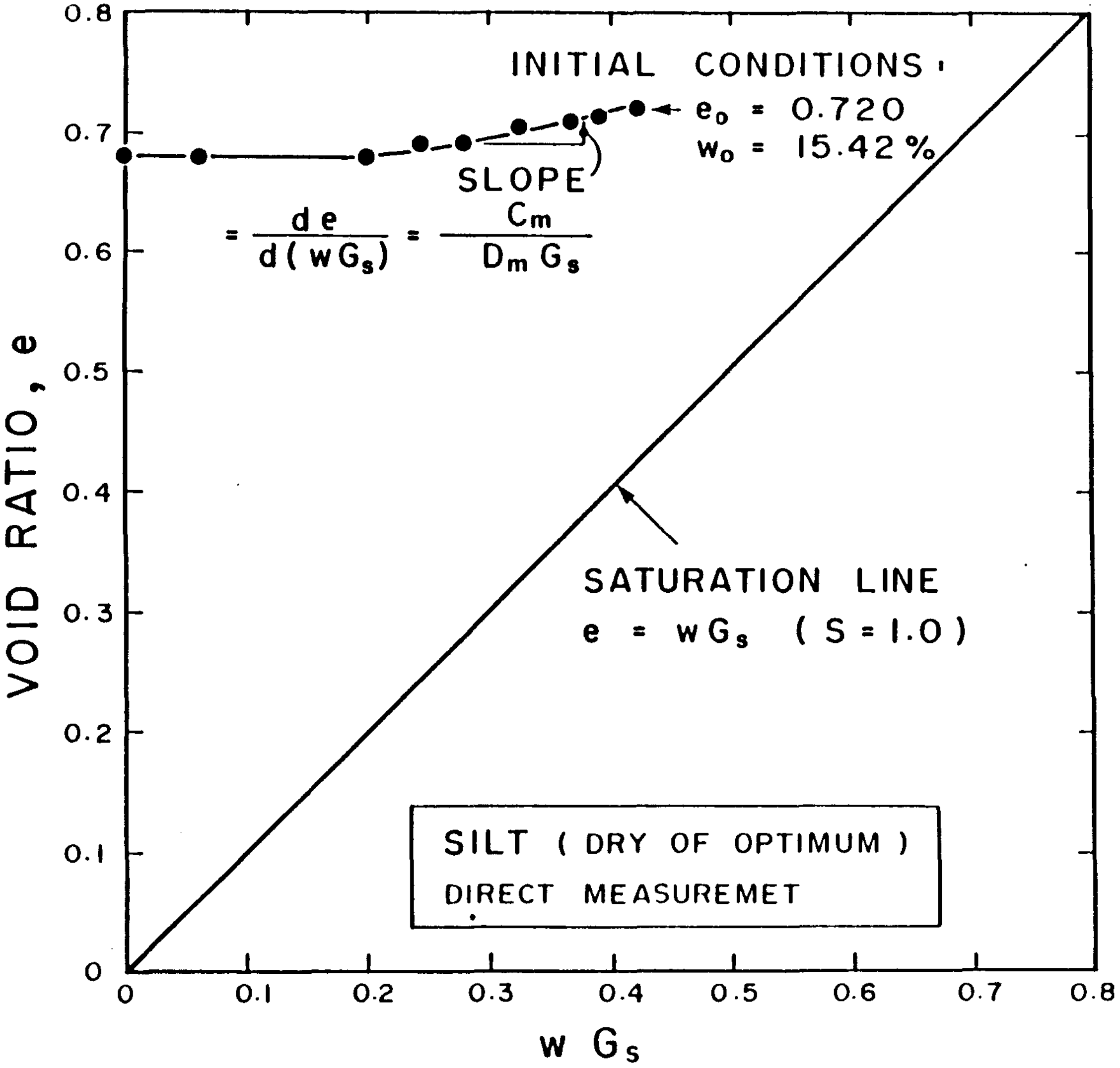

Fig. 8 Shrinkage curve for the compacted silt

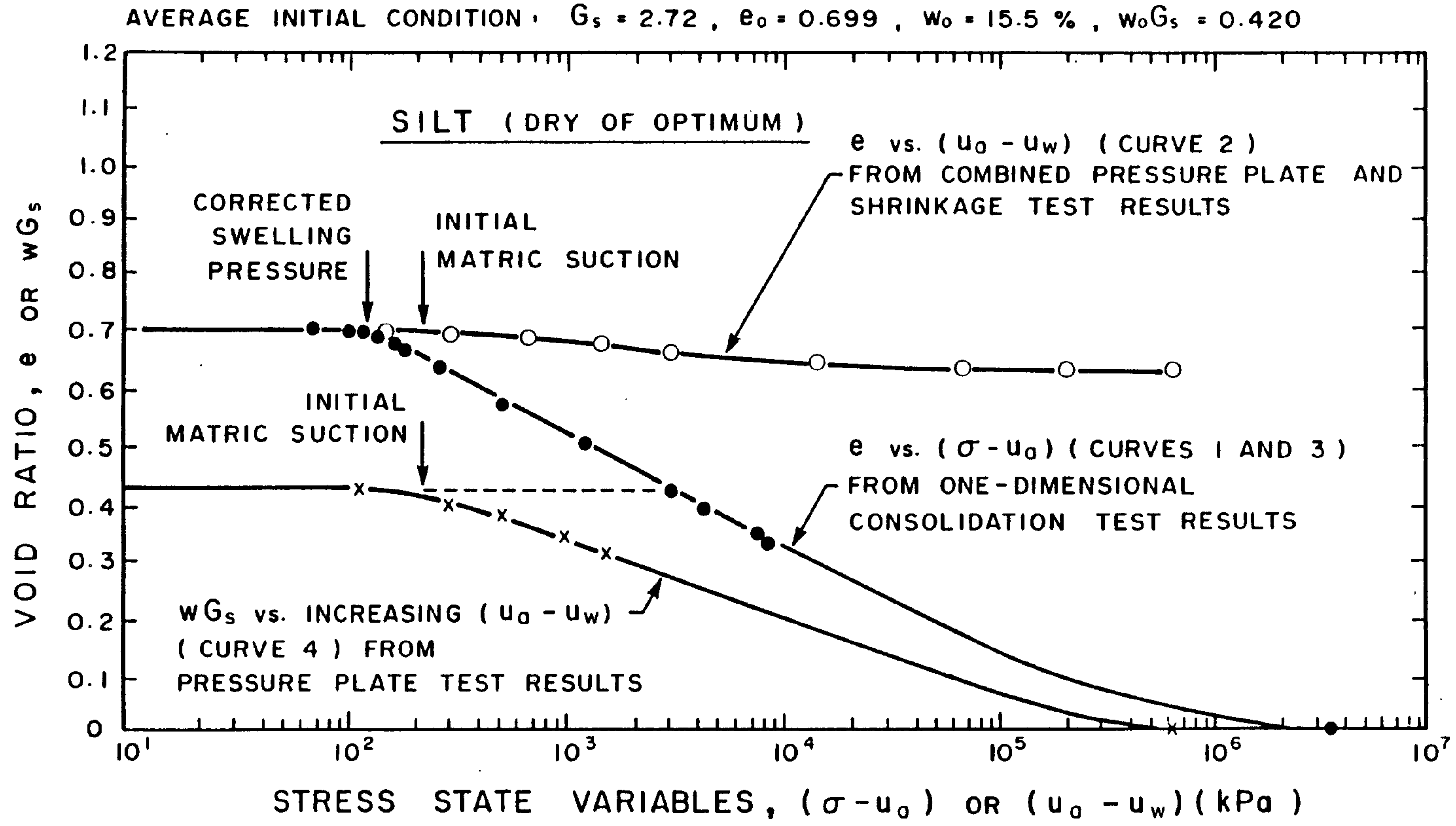

Fig. 9 Volume change relationships for an unsaturated, compacted silt

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