Unsaturated Soils/Sols Non Saturés, Alonso & Delage (eds) © 1995 ISBN 90 5410 583 6 / 2 85978 241 9

Determination of the volume change moduli and respective inter-relationships for two unsaturated soils

Détermination des modules de variations volumiques de deux sols non saturés, et de leur inter-relations mutuelles

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ABSTRACT: A high percentage of earth engineering problems involve unsaturated soils. The ability to describe and predict the volume change behaviour of unsaturated soils is important for geo-environmental and geotechnical analyses. Volume change for an unsaturated soil is described by two independent constitutive relations defined by stress state variables and material properties called volume change moduli. Understanding the volume change behaviour requires a knowledge of the volume change moduli on four state planes. This paper presents the findings of a test program which has measured the volume change moduli for two unsaturated soils, on "identical" specimens. The results are used to illustrate the inter-relationships between moduli.

RESUME : Les sols non saturés interviennent dans une grande partie des problèmes reliés aux ouvrages en terre. La description et la prédiction de leur comportement volumique est essentielle dans les analyses geotechniques et géoenvironnementales. Les variations volumiques d'un sol non saturé sont décrites par deux relations constitutives définies par l'état de contraintes et les propriétés du matériau, qu'on appelle modules de variation volumique, et qu'il est nécessaire de déterminer sur quatre plans d'état. On présente ici les résultats d'un programme expérimental dans lequel ces modules ont été mesurés pour deux sols non saturés, sur des échantillons « identiques ». Ces résultats permettent d'illustrer les inter-relations entre ces modules.

1. CONSTITUTIVE RELATIONS

The continuity requirement justifies the representation of volume change in an unsaturated soil through use of the volume change relation for the soil structure and water phase (Fredlund, 1973). The mathematical relations between the stress state variables and the volume change of the soil structure and the pore-water phase are called constitutive relations. The graphical representations of the constitutive relations are called constitutive surfaces. There are four basic moduli (i.e., C_t, C_{ts}, C_m and C_{ms}) associated with the semi-logarithmic representation of the soil structure constitutive surface. The constitutive surface can be defined in terms of void ratio, e versus the logarithm of net total stress, $(\sigma - u_a)$ and matric suction, $(u_a - u_w)$ (Figure 1) (Ho and Fredlund, 1989). These moduli are defined as follows,

C_t, C_{ts} = compressive and swelling index with respect to the net total stress for monotonic volume decrease and increase, respectively

C_m, C_{ms} = compressive and swelling index with respect to matric suction for monotonic volume decrease and increase, respectively

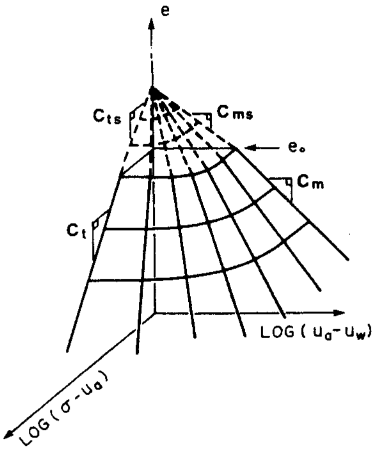

Figure 1: A schematic diagram of the soil structure constitutive surfaces for monotonic volume changes on a semi-logarithmic scale

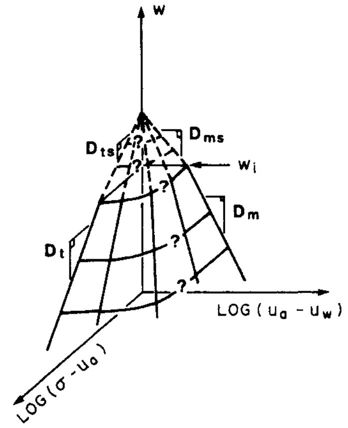

Figure 2: A schematic diagram of the water phase constitutive surfaces for monotonic volume changes on a semi-logarithmic scale

There are four moduli (i.e. D_t, D_{ts}, D_m and D_{ms}) associated with the semi-logarithmic representation of the water phase constitutive surfaces in terms of water content, w, $(\sigma - u_a)$ and $(u_a - u_w)$ (Figure 2) (Ho and Fredlund, 1989). These moduli are defined as follows,

D_t, D_{ts} = water content and rebound water content index with respect to the net total stress for monotonic water content decrease and increase, respectively

D_m, D_{ms} = water content and rebound water content index with respect to matric suction for monotonic water content decrease and increase, respectively

Any volume change can be approximated by the above described moduli defined on the net total stress and matric suction planes. The net total stress and matric suction planes are state planes on which the net total stress and matric suction are at a nominal value (Ho, 1988; Ho et al., 1992).

2. LABORATORY TEST PROGRAM

Two soils, a uniform silt and a glacial till, were tested. An attempt was made to prepare specimens with near identical initial conditions. Each soil was oven-dried and hand mixed with a pre-determined quantity of distilled water. The wet soil was placed in a sealed plastic bag and left to cure in a constant humidity and temperature room. The difference in water content between batches of the same soil was controlled to within 0.5%. Specimens were formed by static compaction at one-half standard proctor compaction effort at either "dry of optimum" or "at optimum" initial water contents. The index and compaction characteristics of the silt and glacial till are given in Table 1.

Table 1 Index and compaction properties of the silt and glacial till used in the test program

	Silt	Glacial Till
Liquid Limit	26.7%	33.2%
Plastic Limit	14.9%	13.2%
Plasticity Index	11.8%	20.2%
Percent Sand Sizes	25.0%	32.0%
Percent Silt Sizes	52.0%	39.0%
Specific Gravity, G_s	2.72	2.76
Half Standard Effort Compaction:		
$w_{optimum}$	19.0%	18.8%
$\gamma_{d\,maximum}$	16.7 kN/m^3	17.1 kN/m^3

The main objective of the test program was to experimentally establish the form of the constitutive surfaces on the net total stress and matric suction planes for various loading and unloading conditions. Two sub-programs were performed to achieve this purpose. Sub-program 1 tested soils under stress changes involving no lateral expansion. The term "no lateral expansion", indicates a K_o loading condition as long as there is no tendency for lateral expansion. Sub-program 2 tested soils under isotropic changes of total stress and matric suction. For both programs, specimens were tested in the loading and the unloading modes. In all cases, changes in void ratio and water content were independently measured. Tests included suction, unconfined shrinkage, free swell and constant volume loading and unloading tests. In addition to conventional apparatuses, modified Anteus consolidometers (Figure 3) and stress controlled isotropic cells (Figure 4) were used for testing under K_o and isotropic conditions, respectively (Ho and Fredlund, 1989; Ho et al., 1992). A summary of the experimentally measured volume change moduli is presented in Tables 2 and 3.

3. RELATIONSHIPS BETWEEN MODULI

Eight independent volume change moduli are required to describe the volume change behaviour of an unsaturated soil, four for monotonic volume increase (i.e., C_{ts}, C_{ms}, D_{ts} and D_{ms}) and four for monotonic volume decrease (i.e., C_t, C_m, D_t and D_m). When a soil is saturated, the soil structure moduli, C_t and C_{ts} are equal to the specific gravity, G_s multiplied by the water phase moduli, D_t and D_{ts} respectively. The convex semi-logarithmic soil structure constitutive surfaces can be approximated by composite planar surfaces (Ho et al., 1992). The approximate constitutive surface for monotonic volume increase may be assumed to coverage towards a single point on the void ratio axis at a numerical value of unity for the net total stress and matric suction. Under these assumptions, the moduli, C_{ts} and C_{ms}, may be related as follows:

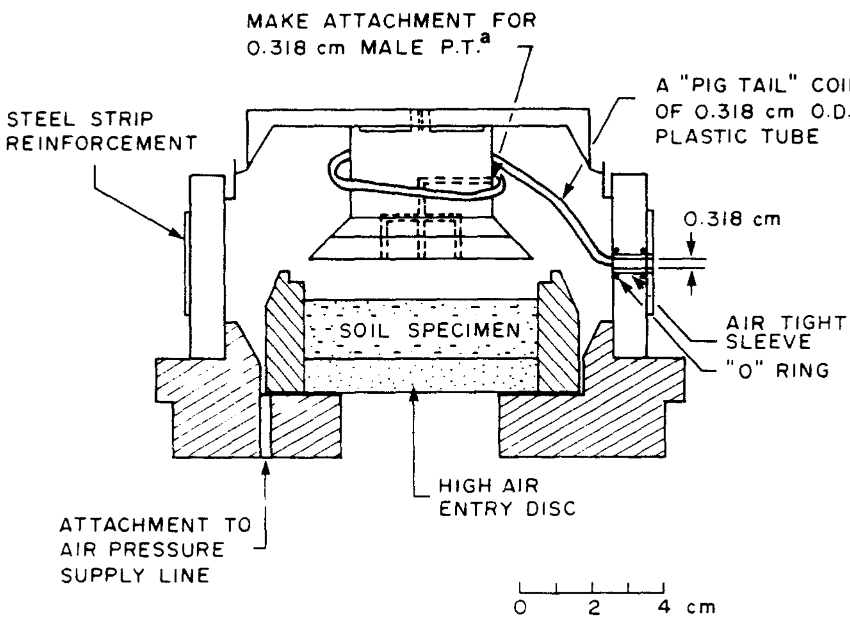

Figure 3: Schematic layout of the modified Anteus consolidometer

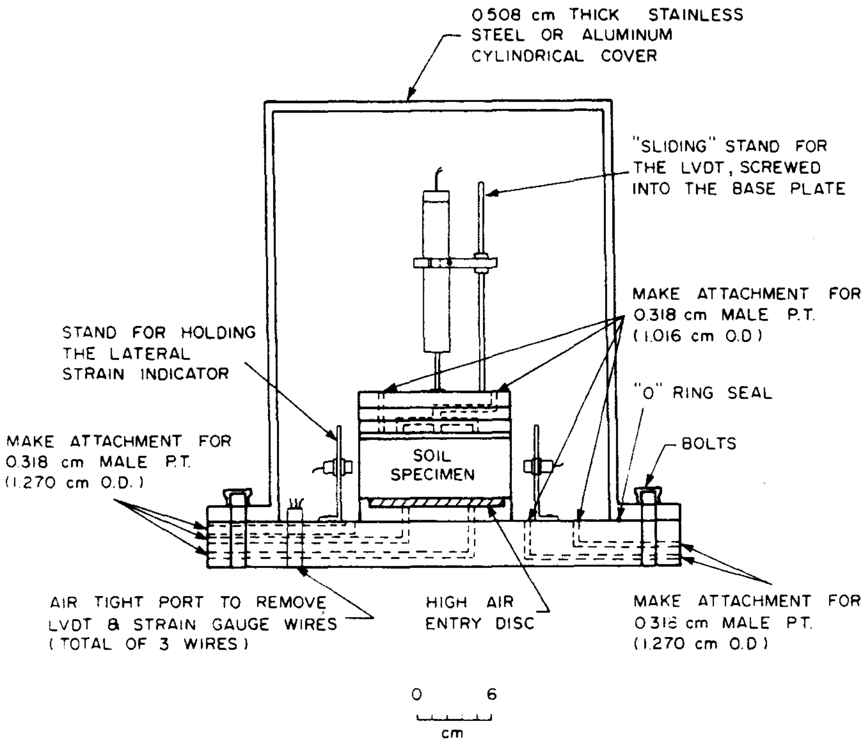

Figure 4: General assembly of the stress controlled isotropic cell

Table 2 A summary of the experimentally measured volume change moduli under loading conditions

Soil Type+	$w_f G_s$	e_o	P'_s (kPa)	$(u_a-u_w)^e_o$ (kPa)	One-dimensional			Isotropic		
					C_t or $D_t G_s$	C_m	$D_m G_s$	C_t or $D_t G_s$	C_m	$D_m G_s$
DS	0.420	0.699	120	225	0.196	0.030	0.124			
DS	0.424	0.700	113	225				0.230	0.030	0.124
OS	0.516	0.606	140	185	0.177	0.082	0.158			
OS	0.511	0.609	170	185				0.187	0.082	0.158
DT	0.427	0.642	90	580	0.206	0.089	0.159			
OT	0.516	0.567	145	430	0.179	0.106	0.171			

NOTES: +) "DS" stands for silt at dry of optimum initial water content
"OS" stands for silt at optimum initial water content
"DT" stands for till at dry of optimum initial water content
"OT" stands for till at optimum initial water content

Table 3 A summary of the experimentally measured volume change moduli under unloading conditions

Soil Type[+]	w_iG_s	e_o	P'_s (kPa)	$(u_a-u_w)^e_o$ (kPa)	One-dimensional * C_{ts}	** $D_{ts}G_s$	C_{ms}	$D_{ts}G_s$	Isotropic * C_{ts}	** $D_{ts}G_s$	* C_{ms}	$D_{ts}G_s$
DS	0.419	0.702	120	225	0.040	0.126	0.033	0.263				
DS	0.421	0.699	113	225					0.024	0.024	0.020	0.194
OS	0.517	0.616	140	185	0.055	0.076	0.052	0.101				
OS	0.514	0.609	170	185					0.024	0.040	0.022	0.050
DT	0.436	0.693	90	580	0.066	0.084	0.056	0.122				
OT	0.523	0.571	145	430	0.037	0.057	0.024	0.060				

NOTES: +) "DS" stands for silt at dry of optimum initial water content
"OS" stands for silt at optimum initial water content
"DT" stands for till at dry of optimum initial water content
"OT" stands for till at optimum initial water content
*) average slope of the unloading curve
**) slope of the linear potion of the unloading curve

$$C_{ms} / C_{ts} = \log P'_s / \log (u_a - u_w)^e_o \quad (1)$$

P'_s is the corrected swelling pressure and $(u_a - u_w)^e_o$ is the matric suction corresponding to zero net total stress at a constant void ratio. This proposed relationship was found to predict the moduli ratio, C_{ms}/C_{ts} to within an average of 5% difference of the measured values for the silt and till used in the test program. To approximate the soil structure constitutive surface for monotonic volume decrease, it may be assumed that the surface has a projected point of convergence on the void ratio axis. With this assumption, the relationship between the moduli, C_m and C_t may be presented as follows:

$$C_m / C_t = [\log P'_s - \log P_{pr\text{-}cnv}] / [\log (u_a - u_w)^e_o - \log P_{pr\text{-}cnv}] \quad (2)$$

$P_{pr\text{-}cnv}$ is the net total stress and matric suction at the projected point of convergence. This parameter was found to be in the approximate range of 100 to 150 kPa for the silt and 20 to 30 kPa for the till. This proposed relationship was found to predict the moduli ratio, C_m/C_t to within an average of 1% difference of the measured values for the soil specimens tested.

Experimental data from the test program demonstrated that the moduli, D_{ts} and D_{ms}, D_t and D_m may be related as follows:

$$D_{ts} = D_{ms} S_i \quad (3)$$

$$D_t = D_m / S_i \quad (4)$$

S_i is the initial degree of saturation. measured D_{ts} and D_{ms}, D_t and D_m values for the silt and till tested were found to be within a 6% and 4% difference of the proposed relationships, respectively.

4. SUMMARY

A knowledge of four moduli are needed to completely describe the volume change behaviour of an unsaturated soil in a monotonic volume change process. Special tests are required to determine these four moduli in the laboratory. The compressive and swelling indices with respect to the net total stress (i.e., C_t and C_{ts},, respectively) can be measured using a conventional oedometer or triaxial equipment. These two may be regarded as "basic" moduli. It appears to be possible to estimate the remaining moduli by the relationships presented in this paper.

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