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Pressuremeter testing in a calibration chamber with unsaturated minco silt

Tests pressiométriques dans une chambre de calibration sur du minco silt non saturé

Norman K. Tan & Gerald A. Miller
School of Civil Engineering and Environmental Science, University of Oklahoma, Norman, Oklahoma, USA

ABSTRACT

The pressuremeter is an excellent test to determine the in situ stress-strain relationship for soil. Many of the theories and methods of analysis for the pressuremeter have been developed using saturated soil or dry soil mechanics. Unsaturated soil is frequently encountered during subsurface exploration, especially in arid regions of the world where the ground water table can be at substantial depth. Thus, there is a need for methods to interpret pressuremeter test data from unsaturated soil. At the University of Oklahoma, multiple pressuremeter tests have been conducted in unsaturated soil in a laboratory controlled environment via the use of a calibration chamber. The soil beds were built of a clayey silt to encompass a range of matric suction from 15 kPa to 90 kPa. In addition to the influence of matric suction, the influence of net normal stress on pressuremeter test results was also investigated. Thus, the soil beds were compressed at three different net normal stresses. Multiple approaches were taken to control and measure the matric suction in the soil beds. The active approach involved regulating the pore air and pore water pressure of the soil beds via a pressure control system and high air-entry porous discs. The passive approach involved compacting the soil beds at moisture contents with reference to a target matric suction based on the soil-water characteristic curves and taking measurements of the pore water pressure in the soil beds via tensiometers. Cavity expansion theory was incorporated in the analyses of the experimental results. This paper presents the results of the pressuremeter tests in unsaturated Minco Silt beds conducted in the calibration chamber at different levels of matric suction, and discusses the influence of various testing parameters on the results

RÉSUMÉ

Le Pressiomètre est un excellent test permettant de déterminer la relation contrainte-déformation in situ des sols. La plupart des théories et des méthodes d'analyses liées au pressiomètre a été développée sur les bases de la mécanique des sols saturés et des sols secs. Les sols non saturés sont fréquemment rencontrés lors d'investigations souterraines, spécialement dans les régions arides du globe où la nappe phréatique peut atteindre une profondeur conséquente. Ainsi, la nécessité de trouver des méthodes d'interprétations d'essai pressiométrique au sein de milieu non saturés, se fait ressentir. A l'Université d'Oklahoma, de multiples tests pressiométriques ont été effectués sur des sols non saturés dans un environnement contrôlé en laboratoire via l'utilisation d'une chambre de calibration. Les échantillons de sol ont été construit, à partir de silt argileux , de façon à obtenir dans le sol une succion comprise entre 15 kPa et 90 kPa. En plus de s'intéresser à l'influence de la matrice de succion, l'influence de la contrainte normale nette sur les résultats des tests pressiométriques a été étudiée. Dans cette perspective, chaque échantillon de sol a été soumis à trois différentes contraintes normales nettes. Différentes approches ont été utilisées pour contrôler et mesurer la succion matricielle des échantillons. L'approche active implique la régulation des pressions interstitielles de l'air comme de l'eau au sein du sol, par l'intermédiaire d'un système de contrôle de pression et de disques poreux (high air-entry porous discs). L'approche passive consiste à compacter le sol à différentes teneur en eau, avec comme objectif une succion matricielle déterminée à l'aide de la courbe caractéristique sol-eau et en mesurant la pression d'eau interstitielle à l'aide de tensiomètres. La théorie de l'expansion de cavité a été incorporée à l'analyse des résultats expérimentaux. Cette publication présente les résultats des essais pressiométriques en chambre d'étalonnage conduit sur des spécimens non-saturés de Minco Silt soumis à différentes succions matricielles,et discute de l'influence de divers paramètres expérimentaux sur les résultats des essais pressiométriques.

1 INTRODUCTION

Pressuremeter testing (PMT) is a relatively popular in situ testing instrument for subsurface exploration. The PMT is an excellent test to determine the in situ mechanical behavior of the soil and it is one of few in situ tests that provides a stress-strain relationship for soil. The information obtained from the PMT is used in foundation design such as bearing capacity prediction and settlement analysis.

During subsurface exploration it is common for geotechnical engineers to encounter an unsaturated soil zone, which is located above the ground water table. Much research has been conducted on unsaturated soil and it is understood that the behavior of unsaturated soil is different from saturated or dry soil. Therefore, methods to interpret PMT data from unsaturated soil are needed. A research program involving PMTs in a calibration chamber with unsaturated soil beds is being conducted at the University of Oklahoma (OU). The data presented in this paper is part of the testing program to investigate the influence of matric suction on limit pressure (P_L).

2 TEST APPARATUS AND PROCEDURE

The University of Oklahoma's calibration chamber (OUCC) was designed and fabricated for laboratory testing with both miniature and standard pressuremeters. In Fig. 1 the schematic diagram of OUCC is shown. The chamber is a self-reacting flexible wall chamber with design working pressure up to 1380 kPa and BC1 type boundary conditions, where the axial and radial stress can be controlled independently. The pore water and pore air pressure can be controlled independently in the chamber and thus axis translation can be performed if desired. Details regarding the chamber design can be found in Lauder (2000), Miller et al. (2002) and Tan and Miller (2003).

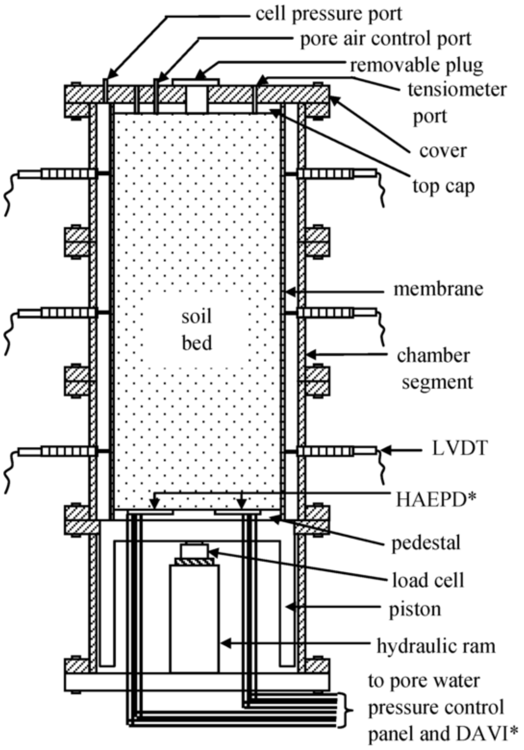

Figure 1. Schematic of OU Calibration Chamber (Miller et al. 2002)

The preparation of soil beds is a crucial activity in calibration chamber testing. Tan (2000) conducted a study at OU on preparation of unsaturated Minco silt beds in bench scale models and concluded that static compaction is a repeatable method and capable of producing unsaturated Minco silt test beds with consistent properties. Details regarding calibration chamber soil bed preparation are discussed in Miller et al. (2002) and Tan and Miller (2003). Minco silt was used because it is an ideal soil for unsaturated soil research; it is slightly cohesive, easy to compact and trim, capable of supporting its own weight and develops low matric suctions, which allows measurements of reliable accuracy with small tip tensiometers. It is classified as CL (CL-ML borderline) soil according to the Unified Soil Classification System (USCS). Table 1 shows the properties of Minco Silt.

Table 1: Properties of Minco Silt

Liquid limit, %	28
Plasticity index, %	8
Specific gravity	2.68
Sand, %	27
Fines, %	73
Clay size fraction, %	18
USCS classification	CL
γ_d (standard proctor), kN/m^3	17.9
Optimum moisture content, %	12.8

In order to minimize boundary effects, a miniature pressuremeter (MPMT) with diameter of 15.2-mm and inflatable length of 130-mm was used. This gives a height to diameter ratio of 8.5, which exceeds the recommended value of 6.5 needed (Briaud 1992) to simulate plane strain cylindrical cavity expansion. Based on work of other researchers (Penumadu and Chameau 1998, Anderson et al. 1987) the soil bed to probe diameter ratio of 40 is considered sufficient to minimize the radial boundary effects for the test soil used in this research. The procedure used to conduct MPMT testing is similar to that described in ASTM D 4719 (Standard Test Method for Pressuremeter Testing in Soil) Method A. A complete description of the test procedure can be found in Miller et al. (2002).

3 RESULTS AND DISCUSSION

To date, seven test beds have been prepared at different moisture contents with matric suction ranging from 12 to 55 kPa. Test beds were isotropically compressed with net normal stress up to 203 kPa. In Fig. 2 typical volumetric strain of the soil bed as a function of time is shown. A major portion of the compression generally occurs within the first 30 minutes of stress increments. Thus, in order to reduce the time required for the experimentation, the first two stages were shortened to approximately one day as no tests were performed at the end of the first two stages. However, for the remaining three stages, the soil beds were compressed for seven days followed by MPMT testing at the end of each stage. Upon completion of MPMT testing, the net normal stress was released and the chamber was disassembled. The soil bed was then dissected for water content (w) and dry unit weight (γ_d) determination; in Fig. 3 typical results are shown. It is observed that both the w and γ_d are reasonably consistent throughout the depth of the soil beds. However, when comparing the γ_d of one soil bed to another it is observed that the γ_d of the soil beds with lower matric suction (ψ) tend to be higher as observed in Fig. 4. This did not occur in Tan's (2000) study with the bench scale soil beds. This is because in the bench scale study the sample former used was relatively more rigid and there was also better control over the force applied during the static compaction. Therefore the variation in γ_d needs to be taken into account when analyzing the PMT results.

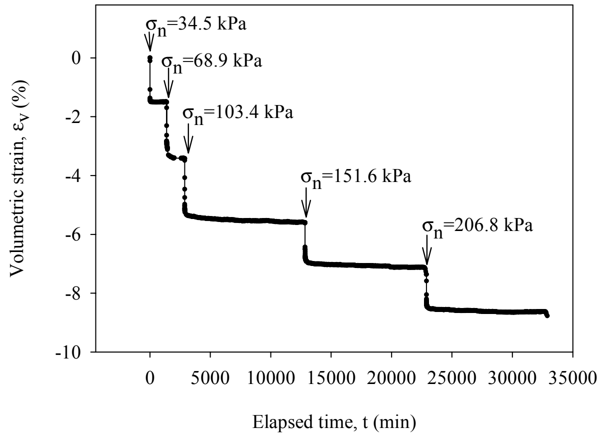

Figure 2. Volumetric strain during compression from test bed CCT27

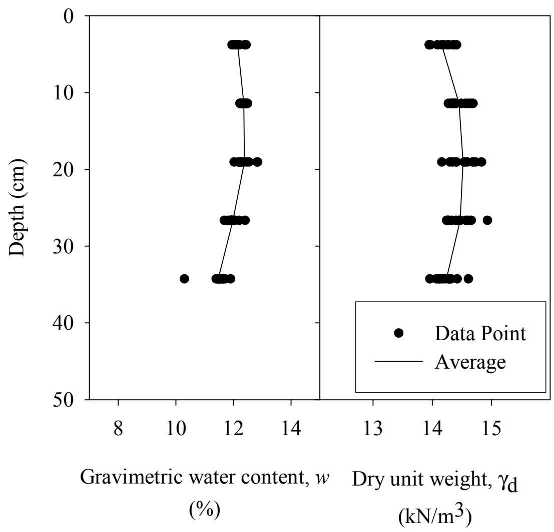

Figure 3. Gravimetric water content and dry unit weight sampling results from test bed CCT27

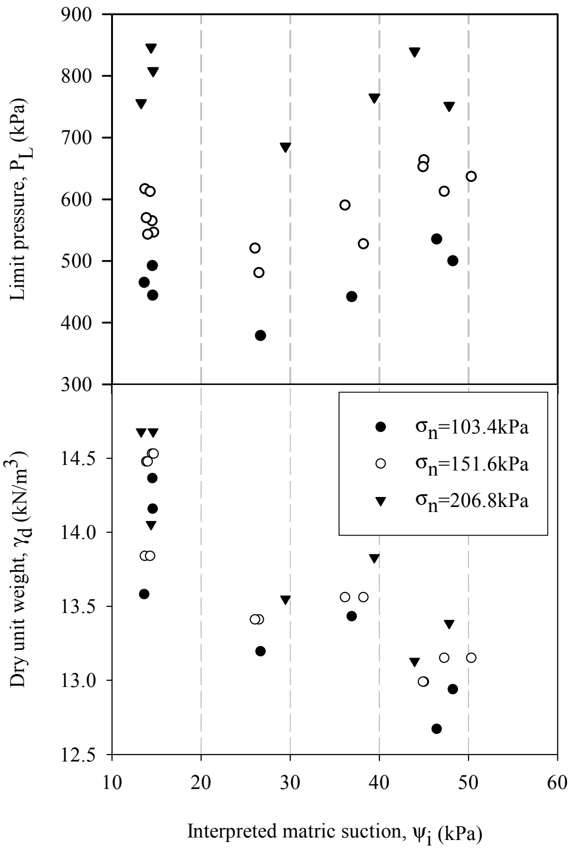

Figure 4. Summary of PMT results with corresponding test bed γ_d

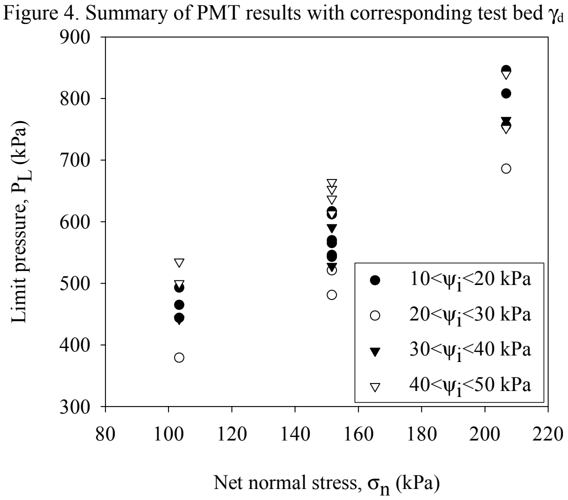

Figure 5. Limit pressure vs. Net normal stress

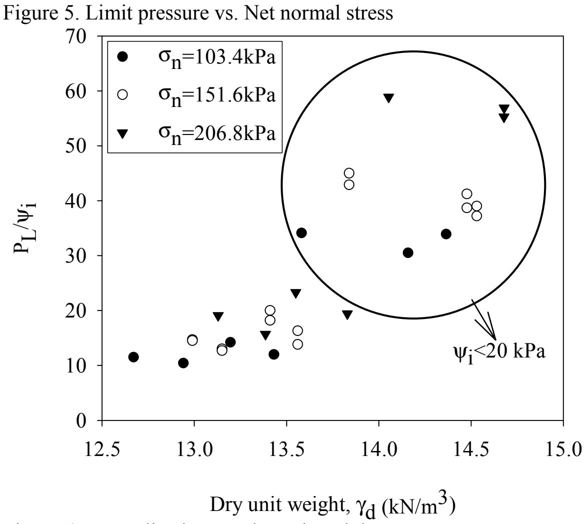

Figure 6. Normalized P_L vs. dry unit weight

The PMT results as a function of matric suction are shown in Figs. 4 and 5. Interpreted matric suction (ψ_i) is determined by using the average water content of soil samples around the test location and the soil water characteristic curve. It is observed that limit pressure, P_L increases with net normal stress, σ_n as shown in Figs. 4 and 5. However, at each σ_n the trend for P_L vs. matric suction is inconclusive when considering data with ψ_i less than 20 kPa. This might be due to the compensating effect of variations in γ_d where the γ_d for soil beds with ψ_i less than 20 kPa tends to be relatively higher. The γ_d for soil beds with ψ_i greater than 20 kPa are relatively close to each other, 13.0±0.5 kN/m^3. Thus, it is reasonable to look at the data separately. For PMTs in soil beds with ψ_i greater than 20 kPa, it is evident that matric suction has a strong influence on P_L. It is observed that P_L increases with ψ_i. In Fig. 4 it is apparent that γ_d has a strong influence on P_L. In order to take variation of γ_d into consideration, P_L is normalized by ψ_i and plotted against γ_d. as shown in Fig. 6. It is observed that generally P_L/ψ_i increases with γ_d for a given net normal stress. The influence of γ_d on P_L/ψ_i is more significant at γ_d greater than 13.5 kN/m^3. However, considering only the data set with ψ_i less than 20 kPa it is observed that the P_L/ψ_i is almost constant (P_L/ψ_I=15±5).

4 MODELLING LIMIT PRESSURE (P_L) VIA CAVITY EXPANSION EQUATION

There are many methods of interpretation for the pressuremeter. However, most of the methods do not incorporate the effects of unsaturated soil. In this paper, the cavity expansion theory is proposed as a possible framework for interpretation of PMT data in unsaturated soil. The cylindrical cavity expansion equation for unsaturated soil developed by Muraleetharan et al. (1998) is used for this preliminary study. The ultimate goal is to be able to predict the influence of ψ on P_L.

By extending Vesic's (1972) original cavity expansion theory and incorporating unsaturated soil theory, Muraleetharan et al. (1998) derived the cylindrical cavity expansion equation in unsaturated soil as shown below.

$$p_u = F_q'\left[p - u_a - \frac{E\Delta(u_a - u_w)}{H(1-2v)}\right] + F_c'c + u_a = P_L \qquad (1)$$

where:
p_u = ultimate cylindrical cavity pressure
p = mean net normal stress
u_a = pore air pressure
u_w = pore water pressure
E = Young's modulus
H = elastic modulus with respect to matric suction
v = Poisson's ratio
c = cohesion intercept = $c'+(u_a-u_w)\tan\phi^b$
c' = effective cohesion
ϕ^b = angle of internal friction associated with the net matric suction
ϕ' = angle of internal friction associated with the net normal stress
F_q, F_c = dimensionless cylindrical cavity expansion factors

$$F_q = (1+\sin\phi')I_{rr}'^{\sin\phi'/(1+\sin\phi')} \qquad (2)$$

$$F_c = (F_q' - 1)\cot\phi' \qquad (3)$$

I_{rr} = reduced rigidity index

$$I_{rr} = \frac{1+\varepsilon_v}{\frac{f_2}{I_r} - \frac{2(1+v)\Delta(u_a-u_w)}{H(1-2v)} + \frac{2(1+v)\Delta u_a \sin\phi'}{E} + \varepsilon_v} \qquad (4)$$

I_r = rigidity index

$$I_r = \frac{E}{2(1+v)(p\tan\phi' + c)} \quad (5)$$

f_2 = $\cos\phi'$ (6)

ε_v = volumetric strain in the plastic zone

Muraleetharan et al. (1998) assumed that beyond the plastic zone the soil behaves as a linear elastic solid and soil within this zone behaves as a compressible plastic solid. Thus, when the internal pressure of the cylindrical cavity reaches its ultimate value p_u, the radius of the cavity and plastic zone are R_u and R_p respectively. Muraleetharan et al. (1998) derived the equation below to relate the R_u and R_p.

$$\frac{R_p}{R_u} = \sqrt{I'_{rr}} \quad (7)$$

Examining Equations 1 to 7, several parameters need to be known in order to predict the ultimate pressure (p_u) of the cavity. Parameters can be obtained from the Mohr-Coulomb envelope for unsaturated soil or can be fairly well estimated along with several assumptions. The modulus E was taken as the PMT modulus, and H was assumed equal to 5E based on values of some typical soils (Miller and Muraleetharan, 2000). Ananthanathan (2002) conducted a series of laboratory triaxial tests, which give an estimate of the soil ϕ', ϕ^b, c′ and c. However, the volumetric strain (ε_v) in the plastic zone surrounding the cylindrical cavity is a parameter that is unknown and is not easily obtained from laboratory tests. Thus, it is back calculated here using the laboratory data, the cylindrical cavity expansion equation, and assuming the limit pressure of the PMT is equal to the ultimate cylindrical cavity pressure (i.e. $P_L=p_u$). It is also assumed that during cavity expansion: 1) Poisson's ratio v=1/3; 2) pore air pressure (u_a) remains zero; and 3) gravimetric water content (w), and matric suction (ψ) stay constant. Ananthanathan (2002) has also developed a series of soil-water characteristic curves for the Minco silt compacted statically with dry unit weight ranging from 12.6 kN/m^3 to 15.7 kN/m^3 as shown in Fig. 7. It is observed that the curve is unique and independent of dry unit weight; therefore, assumption 3) is reasonable since the soil in the plastic zone is assumed to be in a closed system.

In Fig. 8 the back calculated results are shown. It is observed that generally ε_v decreases with suction except at low suction (<20kPa). Again, this inconsistency might be due to variation in the dry unit weight of the soil beds. Considering only the results with ψ_i greater than 20 kPa, it is observed that ε_v decreases with ψ_i. The results overall seem reasonable since at higher suction the soil tends to be more rigid. However the influence of σ_n on ε_v is not as clear as the influence of ψ_i on ε_v. It is envisioned that this research will eventually generate a series of typical curves that relate ε_v and ψ_i for various soil types. Thus, by using Equation 1 along with the generated curves it will be possible to predict the influence of matric suction on P_L. With this, it will be possible for geotechnical engineers to conduct PMT in the field and predict how P_L might change with changes in moisture content and suction over the seasons.

5 SUMMARY AND CONCULSIONS

Miniature pressuremeter tests (MPMT) have been conducted in a calibration chamber with unsaturated Minco silt at the University of Oklahoma. The results shows that matric suction, net normal stress and dry unit weight have a strong influence on the limit pressure where limit pressure increases with suction, net normal stress and dry unit weight. In the preliminary analysis of the PMT data the cylindrical cavity expansion equations for unsaturated soil have been utilized. The results obtained from the analysis seem promising for the future development of a method to interpret PMT results in unsaturated soil.

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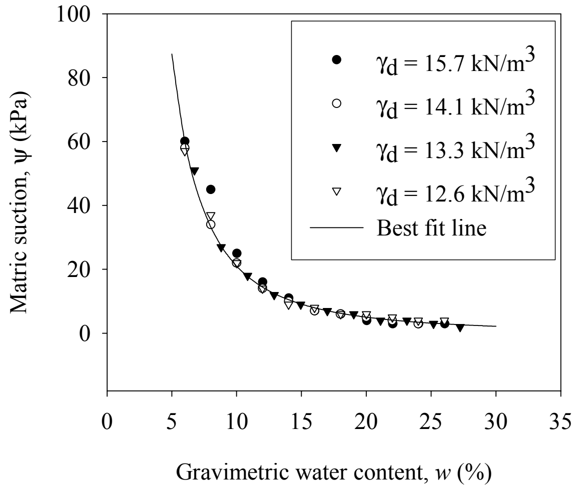

Figure 7. Soil-water characteristic curve for Minco silt (wetting curve)

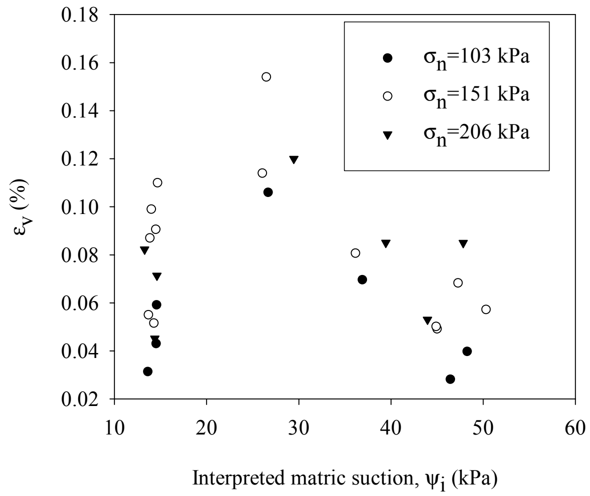

Figure 8. Matric suction versus volumetric strain in plastic zone

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