Interpreting CPT results in unsaturated sands

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ABSTRACT: This paper presents the interpretation of cone penetration test results conducted in unsaturated and saturated sands to determine the contribution of suction to the initial effective stress. The method used is based on similarities between the cavity expansion and cone penetration problems, in particular, the power law proportionalities between initial effective stress and cavity expansion pressure or cone penetration resistance. The effects of suction cause the initial effective stress of the sand to increase and also cause both the cone penetration resistance and cavity expansion pressure to increase. It is highlighted that suction has a profound influence and failure to account for this may lead to misrepresentations in soil properties estimated using cone penetration tests.

1 INTRODUCTION

Soils which have both air and water present in the pore space are referred to as unsaturated soils. They are widely spread across the world, and their engineering behavior is influenced by many factors including externally applied stresses, soil type, structure, density, and particularly suction arising from surface tension across the air-water interface within pores. Most notably, suction increases the shear strength and stiffens the soil skeletal response. Upon wetting, however, this increase in stiffness is lost and may be associated with large and non-reversible volumetric collapse. These behavioral characteristics need to be dealt with in many engineering problems including foundations, pavements, dams and slopes.

The characterization of unsaturated soils requires expensive and time consuming site investigations. This typically involves soil borings, careful undisturbed sampling and laboratory testing using specialized equipment permitting suction control.

Performing the cone penetration test (CPT) in unsaturated soils, a commonly used in situ test, may enable less costly and more rapid characterization. However, a small number of published studies provide evidence that suction may significantly influence cone penetration resistance in sands. Hryciw & Dowding (1987) and Lehane et al. (2004), through experimental and field work, respectively, have shown that the cone penetration resistance in unsaturated sands can be more than double the saturated or dry values under certain conditions. In a theoretical study of cavity expansion in unsaturated soils, Russell & Khalili (2006a) found that the asymptotic cone penetration resistance significantly increases due to the presence of suction. From these studies it seems that failure to account for suction when interpreting CPT results, particularly penetration resistance, has the potential to lead to significant and non-conservative misrepresentations in estimated soil properties.

This paper considers results of CPTs conducted in unsaturated sands in a newly developed calibration chamber and compares the trends observed with other results from the literature. Details of the chamber are contained in a companion paper (Pournaghiazar et al. 2010). Similarities between cavity pressure and cone penetration resistance are also highlighted. The effects of suction cause both the cone penetration resistance and cavity pressure to increase significantly. Steps are taken towards developing a systematic approach for back-calculating the magnitude of suction in a soil in which a CPT has been performed.

2 SUCTION AND THE EFFECTIVE STRESS IN UNSATURATED SOILS

Recent years have seen major advances in unsaturated soil mechanics (Alonso et al., 1990; Kogho et al., 1993; Wheeler & Sivakumar, 1995; Bolzon et al., 1996; Loret & Khalili, 2002; Gallipoli et al., 2003; Russell & Khalili, 2006b; and Khalili et al., 2008; among others). Suction causes the particle contact forces of an unsaturated soil to increase above their saturated or dry values. It is usually assumed that suction is an isotropic phenomenon and the potential macroscopic effects of this are an increase in the stiffness of the soil skeletal response and the mean effective stress p'. Following the work of Bishop (1959), the mean effective stress may be defined in a simple way:

$$p' = p_n + \chi s \tag{1}$$

where p_n is mean net stress or mean total stress in excess of pore air pressure u_a; s is the difference between pore air and pore water pressure ($u_a - u_w$) also referred to as suction; and χ is the effective stress parameter and has a value of 1 for saturated soils and 0 for dry soils. One of the most appealing features of the effective stress approach in unsaturated soil mechanics is that many behavioral characteristics may be described using properties and relationships well established for saturated soils. For example, the shear strength at the critical state may be defined as:

$$q_{cs} = M_{cs} p'_{cs} \tag{2}$$

where M_{cs} is the usual function of the critical state friction angle and is a material constant relevant to both saturated and unsaturated conditions. Furthermore, the complex phenomena of suction hardening and volumetric collapse upon wetting can be explained using the effective stress (Loret & Khalili, 2002).

Khalili et al. (2004) and Russell & Khalili (2006b) found that χ may be expressed in the non-dimensional form:

$$\chi = \begin{cases} 1 & \text{for} \quad \dfrac{s}{s_e} \leq 1 \\ \left(\dfrac{s}{s_e}\right)^{-0.55} & \text{for} \quad 1 < \dfrac{s}{s_e} \leq 25 \\ 25^{0.45}\left(\dfrac{s}{s_e}\right)^{-1} & \text{for} \quad 25 < \dfrac{s}{s_e} \end{cases} \tag{3}$$

where s_e is the suction value separating saturated from unsaturated states. This relationship was determined following consideration of laboratory strength and volume change data for a quartz sand containing no fines and values of s/s_e less than 70 as well as fine grained soils having values of s/s_e less than 12. A lack of experimental data has prevented it being tested for fine grained soils with s/s_e larger than 12.

In many engineering problems p_n can be readily quantified as it is related to the externally applied stresses on a soil element and therefore overburden pressure. However, the χs term requires careful determination of s_e and the suction in the ground. This usually involves suction determination tests conducted on representative samples of the soil in the laboratory or measuring the moisture content in the ground and indirectly obtaining suction from the soil-water characteristic curve.

These methods are time consuming and expensive. There is need is for a more rapid estimation of χs, for example using the CPT.

3 CONE PENETRATION TEST RESULTS

3.1 *Calibration chamber investigations*

New results of CPTs conducted in saturated and unsaturated specimens of Sydney sand in a recently developed calibration chamber are presented in Pournaghiazar et al. (2010). The chamber accommodates cylindrical specimens that that are 460 mm in diameter and 800 mm in height. A cone penetrometer of 16 mm diameter was pushed into the specimens at a constant rate of 2 cm/s. The chamber allowed lateral and vertical pressures to be applied independently to an unsaturated soil specimen. Horizontal pressure was applied by cell water pressure pushing on a rubber membrane enclosing the specimen, vertical pressure was maintained by a hydraulic loading ram placed under a chamber piston at the specimen base. Suction was controlled in a specimen using the axis translation technique.

Sydney sand, a predominantly quartz sand, is classified as SP with a D_{50} of 0.3 mm. The relative densities of the formed specimens were about 61%. The saturated specimen (S1) was subjected to an isotropic effective stress of 100 kPa (lateral, vertical and pore water pressures of 350 kPa, 350 kPa and 250 kPa, respectively). The first unsaturated specimen (U1) was subjected to an isotropic net confining stress of 100 kPa and controlled suction of 50 kPa (lateral, vertical, pore water and pore air pressures of 200 kPa, 200 kPa, 50 kPa and 100 kPa respectively). The second unsaturated specimen (U2) was subjected to an isotropic net confining stress of 100 kPa and controlled suction of 200 kPa (lateral, vertical, pore water and pore air pressures of

350 kPa, 350 kPa, 50 kPa and 250 kPa respectively). The cone tip resistances averaged about 10.7 MPa, 11.7 MPa and 13.6 MPa for S1 (saturated), U1 (unsaturated, s = 50 kPa) and U2 (unsaturated, s = 200 kPa) specimens, respectively.

The results are presented again here as hollow symbols in Figure 1. For the constant initial net confining stress p_{n0} = 100 kPa, the cone resistances have been normalized against the saturated value and plotted against degree of saturation S_r. The normalized quantity is denoted as $q_{c\chi s}/q_{c0}$, where $q_{c\chi s}$ is the cone resistance measured in an unsaturated test and q_{c0} is the cone resistance measured in a saturated test. The results indicate that suction induced in the samples causes $q_{c\chi s}/q_{c0}$ to rise above unity.

Hryciw & Dowding (1987) have also conducted an experimental investigation where CPTs were performed in Ottawa (quartz) sand in a much smaller and less sophisticated calibration chamber. Samples were prepared to a relative density D_r = 0.5 and a range of S_r values. The samples in the chamber were not subjected to external confining stresses during the tests. Cone penetration resistance at the 0.3 m depth was measured (where p_{n0} = 5kPa for a unit weight of about 16kN/m^3 and isotropic stress conditions), and normalized against its value for saturated conditions and plotted against S_r. The results are also presented here in Figure 1 as solid symbols.

The results indicate that suction induced in the samples for S_r values larger than about 0.65 has negligible effect on the cone resistance. However, for S_r less than about 0.1 there is an increase in $q_{c\chi s}$. In general, when S_r is less than about 0.1, suction is large enough to have a significant effect on CPT results.

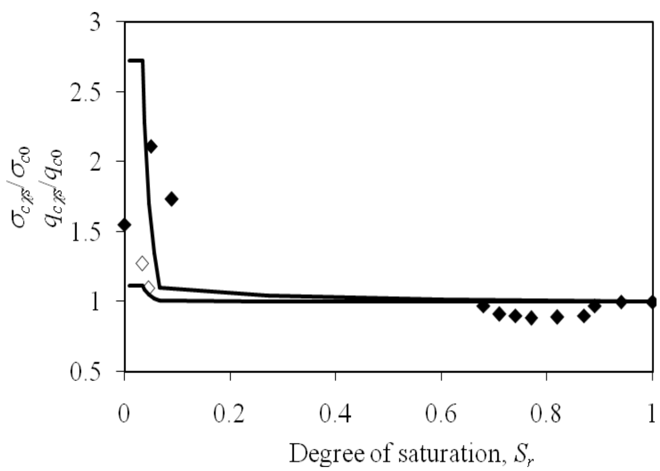

Figure 1. Normalized cone penetration resistances (symbols) and cavity expansion pressures (continuous lines) plotted against degree of saturation, for mean net stresses of 5 kPa and 100 kPa.

Figure 1 also presents drained spherical cavity expansion results for Kurnell sand (Russell & Khalili, 2006a), a quartz sand that has almost identical properties to Sydney sand as they were sourced from sand dunes near each other. The cavity expansion results are presented as two lines. One is for p_{n0} = 100kPa, D_r = 0.6 and a range of S_r values, the other is for p_{n0} = 5kPa, D_r = 0.5 and a range of S_r values, to permit comparisons with the cone penetration test results from the two experimental studies. More specifically, the net radial stress required to expand a cavity (denoted as σ_c) is normalised against its value for saturated conditions and plotted against S_r. The normalised quantity is denoted as $\sigma_{c\chi s}/\sigma_{c0}$, where subscripts χs and 0 indicate correspondence to an unsaturated expansion and a saturated (or dry) expansion, respectively.

3.2 *A field investigation*

Lehane et al. (2004) present a series of CPT results for a site comprising Perth sand, a predominantly quartz sand containing less than 5% fines and of relative density $D_r = 0.45 \pm 0.1$. The tests were performed at different times corresponding to the end of a wet season and end of a dry season. Some tests were performed on parts of the site near large tress, while other tests were performed in an open area. Near the trees it was found that, at the end of the dry season, q_c was significantly higher than the corresponding values at the end of the wet season. Also, in the open area, the seasonal change had a very minor influence, if any at all, on the test results. Figure 2 summarises the results of tests. The main conclusion drawn in the Lehane et al. (2004) investigation was that when S_r is less than about 0.1 suction is large enough to have a significant effect on q_c, although the presence of tree roots was required to cause S_r to drop below 0.1 and therefore increase s significantly. This latter point was evidenced by the results in the open area which were virtually indistinguishable at the ends of the wet and dry seasons.

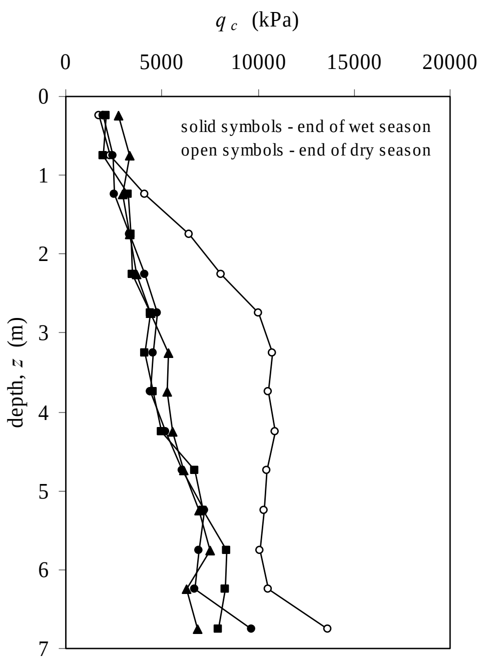

Figure 2. Cone penetration resistance for Perth sand in a treed area at the ends of wet and dry seasons (after Lehane et al., 2004).

4 INTERPRETATION OF RESULTS

Suction has a certain influence on cone penetration resistance and cavity expansion pressure. The influence increases in significance as the initial mean net stress reduces.

For sands cone penetration resistance (or cavity expansion pressure) is proportional to initial mean effective stress in the ground. Cone penetration or cavity expansion occurs under drained conditions in saturated sands. In unsaturated sands, although perfect drainage is less likely as unsaturated sands have a much lower permeability than saturated sands, the cavity expansion analysis of Russell & Khalili (2006a) has shown that drained and undrained expansions give almost identical results unless the initial degree of saturation is slightly less than unity. The assumption that drained conditions prevail around a cone penetrometer in unsaturated sands is therefore applied here.

Cavity expansion pressure may be related to initial mean effective stress p'_0 according to a power law (Russell, 2004):

$$\sigma'_c = (16.3 - 18.6 \ln D_r)\exp(2.1 D_r) p_0'^{0.7} \tag{4}$$

Slightly different and more accurate relationships may be observed for small ranges of p'_0, but Equation 4 is more general and places no restriction on the ranges of p'_0 values to which it applies. The advantage of having this type of proportionality is that the following equation also applies:

$$\frac{\sigma'_{c2}}{\sigma'_{c1}} = \left(\frac{p'_{02}}{p'_{01}}\right)^{0.7} \tag{5}$$

where σ'_{c1} and σ'_{c2} are the cavity expansion pressures determined for initial stress conditions p'_{01} and p'_{02}, respectively, when the initial density of the sand is the same for each. It follows that if a cavity is expanded in a sand when saturated or dry (such that $p'_0 = p_{n0} - u_w$, u_w is the pore water pressure and is zero when the sand is dry) and again in the same sand when unsaturated (such that $p'_0 = p_{n0} + \chi s$), the ratio between the cavity limit pressures is:

$$\frac{\sigma'_{c\chi s}}{\sigma'_{c0}} = \left(\frac{p_{n0} + \chi s}{p_{n0} - u_w}\right)^{0.7} \tag{6}$$

There are similarities between cavity expansion results and CPT results. Cone resistance is also proportional to p'_0 according to a power law (for example Baldi et al. 1986; Houlsby & Hitchman, 1988). Reported magnitudes of the power vary between 0.5 and 0.8 for a range of sands so a value of 0.7 is assumed here. A relationship similar to Equation 6 therefore also applies to cone penetration resistance:

$$\frac{q'_{c2}}{q'_{c1}} = \left(\frac{p'_{02}}{p'_{01}}\right)^{0.7} \tag{7}$$

It follows that if a CPT is performed in a saturated or dry sand and again in the same sand when unsaturated, the ratio between the total cone resistances q_c in the unsaturated state $q_{c\chi s}$ and the saturated or dry state q_{c0} is:

$$\frac{q_{c_{\chi s}}}{q_{c0}} = \left(1 - \frac{u_w}{q_{c0}}\right)\left(\frac{p_{n0} + \chi s}{p_{n0} - u_w}\right)^{0.7} - \frac{\chi s}{q_{c0}} \tag{8}$$

Realizing that $q_{c0} >> |u_w|$ and $|\chi s|$, Equation 8 may be simplified to:

$$\frac{q_{c_{\chi s}}}{q_{c0}} = \left(\frac{p_{n0} + \chi s}{p_{n0} - u_w}\right)^{0.7} \tag{9}$$

Applying Equation 9 to the CPT results of Pournaghiazar et al (2010) enables values of χs = 14 kPa and χs = 41 kPa to be determined for U1 and U2 specimens, respectively. Alternatively, as suction values were known to be 50 kPa and 200 kPa immediately prior to testing, Equation 1 can be applied, along with s_e = 7 kPa for the sand tested, to obtain χs = 17 kPa and χs = 30 kPa for U1 and U2 specimens, respectively. The two methods for evaluating χs give broadly similar results. It seems as though the power law of Equation 9 is an appropriate and simple tool for back calculation of χs, with errors being less than 11 kPa.

Equation 9 will now be used to back calculate χs values from the data of Lehane et al. (2004). The following expression was used to evaluate p'_0 with depth z at the end of the wet season by assuming $\chi s = 0$, $p'_0 = (1 + 2K_0)\gamma z/3$, in which the horizontal earth pressure coefficient (K_0) and bulk density (γ) take values of 0.5 and 16.7 kN/m^3 (as reported in Lehane et al., 2004). The determined values of χs are plotted with depth in Figure 3. χs has an upper limit of 90 kPa at 3.25 m depth.

Equation 9 may be used to convert a CPT profile in an unsaturated sand at a site to an equivalent profile in a saturated/dry sand at the same site as long as the variation of χs and with depth is known (assuming of course that the u_w profile for saturated conditions is known). Alternatively, if CPT profiles at a particular site are available for saturated/dry and unsaturated conditions then the χs profile can be back-calculated for the unsaturated condition. A similar procedure was followed by Russell and Khalili (2006c), using a localized linear proportionality in place of a power law.

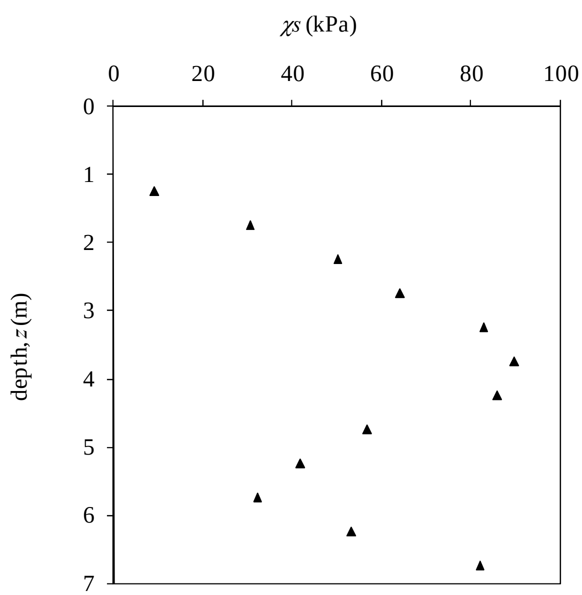

Figure 3. χs back-calculated from cone penetration resistance using Equation 9.

5 CONCLUSIONS

Similar power law proportionalities between initial mean effective stress and cavity expansion pressure or cone penetration resistance exist. From these, a simple equation was developed enabling the contribution of suction to the effective stress - χs - in an unsaturated soil to be estimated. Values of χs determined were in broad agreement with those prevailing in controlled calibration chamber tests. When a profile of cone penetration resistance at a particular site is available for saturated/dry and unsaturated conditions then the χs profile can be back-calculated. Furthermore, failing to account for χs in the mean effective stress may result in significant and non-conservative misrepresentations of estimated sand parameters.

6 ACKNOWLEDGMENTS

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