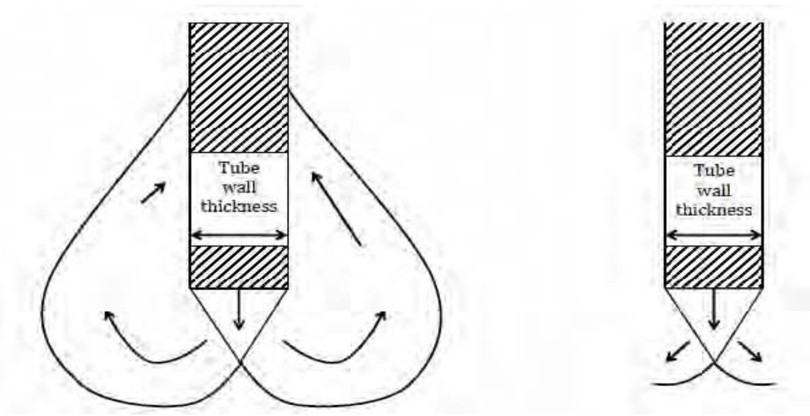

(a) (b)

Figure 7. General shear (a), Local/punching shear (b).

response was observed. To account for sampling disturbance, Houston and Houston (1997) recommended that in the interpretation of 1- D oedometer response to wetting tests on collapsible soils, the field collapse strain for full wetting conditions be taken as the strain from the origin to the wetted curve (corresponding to an essentially flat dry loading curve in Figure 8). This interpretation is supported by the fact that cemented collapsible soils, in their dry in-situ state, exhibit only negligible strain in response to typical structural loading (Houston et al. 1988; Peck et al. 1974). The effect of sampling disturbance on collapsible soils is to break bonds which otherwise would be weakened and therefore lost during wetting, the net result of which is higher dry loading strains as a result of sample disturbance. The overall dry plus wetted strain, however, has been shown to be quite stable (Houston and El-Ehwany, 1991; Feda, 1988; Jasmer and Ore, 1987; Basma and Tuncer, 1992; Munoz-Castelblanco et al. 2011; Delage et al. 2005).

Studies on compacted fills by McCook and Shanklin (2000) showed essentially no difference between drive tube sample dry density and sand cone dry density for compacted fill soils with no reported gravel. Noorany et al. (2000) and Houston et al. (2002) showed that dry density is slightly lower for tube sampling compared to sand cone density determination when gravel content of the soil is 10% to 20%. Houston, et al (2002) attributed the difference in dry density of gravelly soils primarily to the fact that the gravel content of tube samples is, on average, less than the gravel content of field sand cone samples. Houston et al. (2002) compared gravel content between sand cone and drive tube samples, showing average sand cone gravel content of 21.9% compared to a tube-sampled gravel content average of 18.6%. In addition, it is likely that a certain number of rock fragments are hit by the edge of the tube, causing these fragments to rotate and loosen the soil to some extent as it enters the tube. Nonetheless, the tube samples of unsaturated soil containing 10 to 20% gravel have been found to have dry densities within 2 to 8% of companion sand cone specimens (Noorany, et al, 2000; Houston et al, 2002). It is unlikely that the void ratio of the soil matrix and the general structure of the unsaturated soil are significantly altered by tube sampling, even when gravel up to 20% is present in the soil.

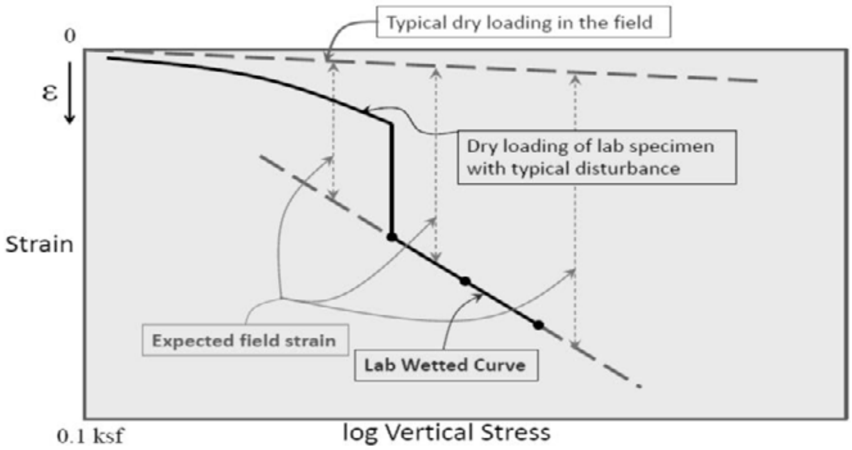

Figure 8. 1-D Response to Wetting on Collapsible Soils- Effect of Disturbance

In a study on unsaturated expansive clays, Singhal (2010) reports that intentional sample disturbance by remolding leads to some reduction in soil suction, and associated reduction in swell pressure and percent swell. However, partial remolding resulted in much less suction change than thorough remolding, and matric suction did not change appreciably upon remolding for the soils having PI values higher than approximately 45. Figure 10 shows that for higher PI and lower void ratio soils, there is less reduction of matric suction upon remolding. Higher PI soils seem to require higher disturbance effort (breaking up of particles) to fully remold the sample. This, together with the local shear failure issues discussed above, makes it unlikely that tube sampling would have a significant impact on suction of unsaturated clay soils. Further, when unsaturated clay soils are recompressed in the laboratory back to their field net normal stress conditions, effects of sampling disturbance are believed to be largely ameliorated. In support of this position, Singhal et al. (2011) report that swell pressures of tube-sampled expansive soils, first loaded to field stress level, were found to be, on average, the same as swell pressures obtained on companion specimens where sampling disturbance correction methods proposed by Nelson and Miller (1992) and Fredlund et al. (1980) were applied. Singhal et al. (2011) express the opinion that most of what is perceived as sampling disturbance effects is embodied in the release of stored energy when a sample is removed from the field, and that reapplication of overburden stress before wetting in an oedometer swell test restores most or all of the stored energy lost by sampling.

In a study by Douthitt et al. (1998), direct shear test cohesion intercept, c, and angle of friction, ϕ, parameters on block samples of unsaturated soils were compared to direct shear parameters for companion thoroughly remolded/disturbed specimens prepared to the same dry density and water content of the block specimens. The results of these direct shear tests are shown in Table 1. Complete and intentional disturbance, well beyond what would be expected during tube sampling, resulted in a reduction of the cohesion intercept, but had little impact on the friction angle of the specimens. Houston et al. (1997) also reported the relative insensitivity of ϕ values to sampling disturbance, as shown in Figure

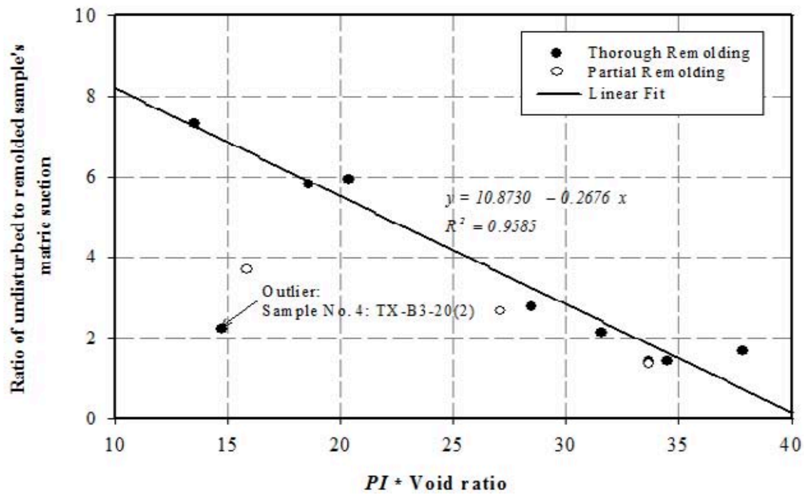

Figure 9. Effect of Remolding on Matric Suction (Singhal, 2010)

10 (a) comparing ϕ values for undisturbed specimens to ϕ values for specimens remolded to in-situ dry density and water content. Figure 10 (b), also from Houston et al. (1997), shows that the cohesion intercept, c, is reduced by remolding, but not nearly to the extent of specimen submergence-induced reduction in c. The impact of thorough remolding on shear strength is small compared to the impact of submergence, as shown in Figure 10. The impact of rather thorough remolding of unsaturated soils results in essentially no change in friction angle, ϕ, but some reduction of cohesion intercept, c. Because tube-sampling of unsaturated soils results in considerably less disturbance compared to the intentionally remolding of specimens, shear strength parameters obtained on tube-sampled unsaturated soils would be expected to typically be slightly conservative compared to those of block-sampled specimens or in-situ undisturbed soils. Tube sampling of unsaturated soil shear strength test specimens is considered appropriate for engineering design purposes.

In summary, although studies by the author and others have shown, as expected, some sample disturbance when tube samples are used to collect specimens, overall, research findings support the use of tube sampling in unsaturated soils for geotechnical investigation and estimation of response to wetting and shear strength properties. Given the great inconvenience and/or impracticality of obtaining block specimens, it is recommended for sampling of unsaturated soils that tube samples may be driven, if convenient, and that the wall thickness of the tube be as small as practical, but large enough to successfully sample the soils at the site. It is expected that sampling disturbance of unsaturated soils will, in general, lead to conservative estimates of strength parameters due to an underestimate of cohesion intercept resulting from some bond breaking and some minor reduction in soil suction. Sampling disturbance for response to wetting tests on collapsible soils can be conservatively (but only slightly conservatively) accounted for by taking the full wetting collapse strain for field conditions the strain from the origin to the

Table 1. Direct Shear Tests on Unsaturated SM Soils (from Douthitt et al. 1998)

Sample Description	Site A c (kPa)/ϕ	Site B c (kPa)/ϕ	Site B c (kPa)/ϕ
Dry Block	34/14.5	62/20.5	120/23.4
Remolded at In-Situ Dry Density and wc	14/15.0	27/20.5	45/21.0
Block, Submerged	8/14.0	0/19.0	5/22.0

wetted curve (dry strain plus strain upon wetting), as suggested by Houston and Houston (1997). For expansive clays, the response to wetting appears to be conservatively estimated by first loading the specimen back to field overburden stress level, and then re-zeroing the LVDT reading before wetting (Singhal, 2010; Singhal et al. 2011).

When representative specimens of new compacted fill soils are required, the best that can be done is to prepare the specimens according to field compaction specifications. Of course it is quite challenging, if not impossible, to match laboratory gradation precisely to field gradation, and the difficulties are exacerbated when soils are clayey and tend to develop clods and clumps in the field compaction process. Nonetheless, it is advisable in assessment of appropriate field compaction specifications with respect to compacted fill response to wetting that specimens be prepared as close as possible to that which will be compacted in the field.

RESPONSE TO WETTING TESTS

What is most important in the characterization of unsaturated soils is to obtain the best quality undisturbed specimen possible and to subject this specimen to wetting in the laboratory to assess the unsaturated soil response to wetting. A response to wetting test normally refers to subjecting to full wetting a test specimen initially prepared at in-situ moisture conditions and net normal stress conditions. Relatively simple full wetting laboratory response tests, such as those performed in 1-D oedometers and direct shear devices, can provide considerable insight into field behavior of unsaturated soils.

The effects of wetting include loss of apparent cementation, volume change, and loss of shear strength. Volume change upon wetting is either swell (if the material is plastic, initially dry, and lightly confined) or collapse (if the material is non-plastic or slightly plastic, initially dry, and heavily confined). When the matric suction is reduced the soil shear strength is reduced. In general, testing should include both volume change and shear strength. Shear strength testing should appropriately model field pore water pressure and pore air pressure dissipation conditions. If soils have some significant PI, even if the soils are unsaturated it is unlikely that pore air pressures will dissipate immediately during in slope stability, evaluation of short-term factor of safety requires that the undrained properties be determined – even when the soil is unsaturated. Soil strength parameters should be reduced to account for any post-development wetting of the soils. Testing of

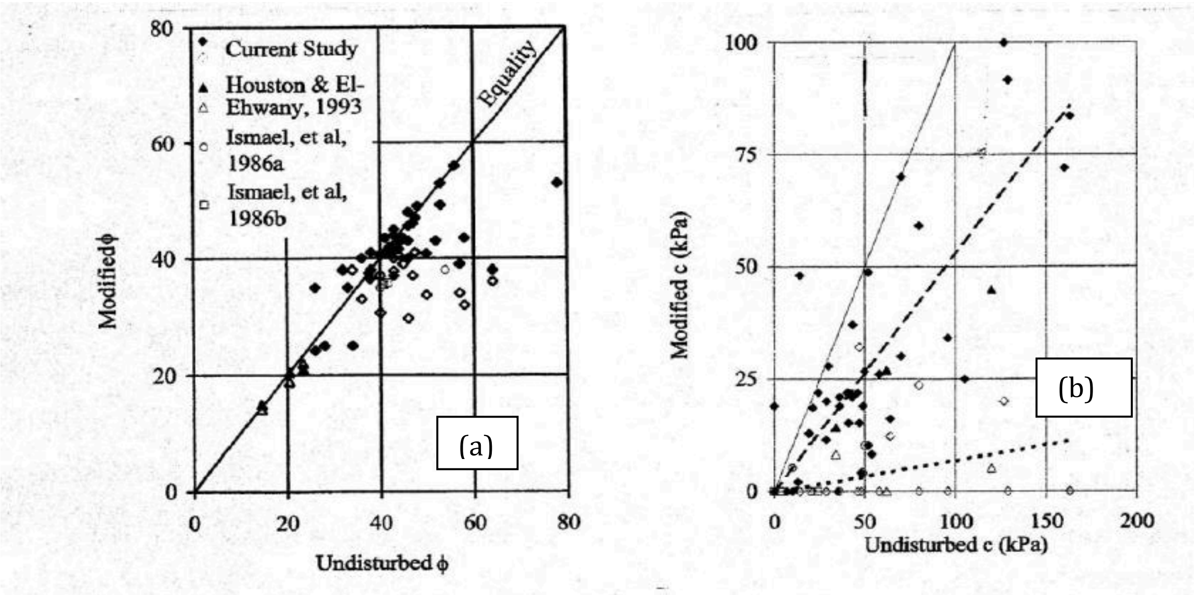

Figure 10. Disturbance and Submergence Effects on (a) ϕ and (b) c (Houston et al. 1997).

wetted soils, to assess response to wetting, should be considered if water contents are expected to increase because shear strength values obtained for initial moisture state would be unconservative.

While simple test boundary conditions, such as 1-D, cannot be expected to be fully representative of all field conditions of interest, results from such tests are extremely useful in the identification of moisture sensitive unsaturated soils and in making appropriate mitigation decisions. If moisture sensitive soils are found at a site through performance of full wetting tests, the engineer then has the opportunity to refine the estimated unsaturated soil response for conditions of partial wetting and/or for more complex boundary conditions, in general. Knowledge of moisture sensitive soils also provides the engineer with the opportunity to recommend extra precautions against wetting (or drying) of subsurface soils through implementation of various measure to control and minimize impact of surface and subsurface water sources.

Of course, the greatest challenge in characterization of an unsaturated soil site is the estimation of the degree and extent of wetting that will occur over the life of the structure. However, often conservative estimates of partial wetting, coupled with empirical methods for estimating partial wetting response, can lead to substantial cost savings compared to ignoring partial wetting in favor of use of full wetting response directly in the estimation of unsaturated soil field behavior.

ESTIMATION OF PARTIAL WETTING EFFECTS

The performance of response to wetting tests is perhaps the most important step in the characterization of unsaturated soil profiles. It is the response to wetting test that alerts the geotechnical engineer to the presence of any moisture sensitive soils. However, the most common response to wetting tests involve full submergence/full wetting of the test specimen, and therefore provides only the full wetting soil behavior. Complete characterization of an unsaturated soil site requires the estimation of the degree and extent of wetting of an unsaturated profile over the life of the structure. The extent of wetting refers to the depth and lateral extent of the zone that experiences any wetting, and the degree of wetting refers to the increase in degree of saturation (reduction in soil suction) that occurs at a point within the wetted zone.

Estimation of degree and extent of wetting is, of course, the most challenging aspect of unsaturated soil site characterization. Nonetheless, in current practice, such estimates are routinely made, although not often explicitly stated by the geotechnical engineer. The two most common assumptions are: (1) the soil will not become wetted or change its water content relative to its state at the time of the site investigation, or (2) the soil will become fully wetted (i.e. to 100% saturation). Rarely is either of these assumptions valid, although with extraordinary attention to control of site water it is possible to dramatically limit changes in subsurface moisture conditions. When full wetting assumptions are invoked, the assumed depth of full wetting is commonly limited by regional practices due in part to cost of mitigation. For example, it is commonly assumed that depth of wetting is limited to 5 to 15 ft. Houston and Nelson (2012) provide considerable discussion on depth and degree of wetting for expansive soils profiles, and state that the effect of partial wetting should be accounted for in the estimation of wetting induced volume change of expansive or collapsible soils profiles. There has been considerable debate and difference of opinion regarding the estimation of degree and extent of wetting (Walsh et al. 2009; Houston and Nelson, 2012). Therefore, the estimation of degree and extent of wetting will not be explicitly addressed here. However, for the vast majority of projects, only partial wetting of the unsaturated soils will occur. Following are some relatively simplified approaches for estimation of unsaturated soil response for partial wetting conditions. Where estimates of soil wetting have been made on the basis of water content or degree of saturation, it may be necessary to estimate soil suction or change in soil suction for assessment of unsaturated soil properties or response for partial wetting conditions.

A few example procedures for estimating unsaturated soil properties and/or partial wetting response are presented below. In all cases it is required that response to wetting data, for fully wetted conditions, be available.

Shear Strength: Fredlund and Rahardjo (1993) postulated an unsaturated soil shear strength equation that takes the form of an extended Mohr Coulomb failure criterion. The term $(u_a-u_w)\tan\phi^b$ was used to account for the increase in shear strength due to suction.

$$\tau_f = c' + (\sigma_n - u_a)tan\emptyset' + (u_a - u_w)tan\emptyset^b \qquad (3)$$

where ϕ^b is the angle for the increase of shear strength with matric suction, c' and ϕ' are effective stress parameters obtained from saturated soil tests, (u_a-u_w) is matric suction, and (σ_n-u_a) is the net normal stress on the plane of shear. It has been demonstrated that the increase of shear strength due to suction becomes non-linear when the range of suction is extended to large values (Escario and Juca, 1986; Fredlund et al., 1987; Miao et al., 2002). Thus, ϕ^b is not a constant but varies as a function of soil suction. Garven and Vanapalli (2006) report that at least 19 models have been proposed to predict or estimate the unsaturated shear strength as a function of soil suction and net normal stress. Most procedures use the saturated soil properties, together with the soil suction and SWCC, to arrive at estimated unsaturated soil shear strength.

Houston et al. (2008) found that at matric suction values below the air entry value (AEV), ϕ^b was found to be close to ϕ'. The equation for the prediction of ϕ^b when suction is larger than the air entry value (estimated from the SWCC) can be presented as a hyperbola:

$$a + b\Psi^* = \frac{\Psi^*}{\phi' - \phi^b} \qquad (4)$$

$$\Psi^* = \Psi - \text{AEV} \qquad (5)$$

Figure 11 shows the correlation for the parameter *a* with percentage of sand, D_{30} (mm) and D_{60} (mm). The correlation for *a* has an R^2 of 0.84. Also shown in Figure 11 is that the correlation of the inverse of *b* with ϕ' is good. The advantage of correlating *b* with ϕ' is that this correlation makes use of a soil property having physical significance.

Vanapalli et al (1996) present the follow equation for estimation of unsaturated soil shear strength:

$$\tau = c' + (\sigma - u_a)tan\phi' + (u_a - u_w)\left(\frac{\theta_w - \theta_r}{\theta_s - \theta_r}\right)(tan\phi') \qquad (6)$$

where c' and ϕ' are the saturated soil effective stress parameters, (u_a-u_w) is the soil suction, and θ_w is the volumetric water content, θ_r is the volumetric water content at residual suction (estimated from the SWCC), and θ_s is the volumetric water content at saturation.

<u>Expansive Soils</u>: The most accurate method for assessment of partial wetting expansion is to perform suction controlled tests that encompass the range of suction for the field application, thereby directly measuring the suction compression index. The matric suction compression index, γ_h, is normally defined as the heave strain, ε, that occurs in response to a 1-log cycle change in suction (Lytton et al., 2005). The partial wetting strain is:

$$\varepsilon = \gamma_h\left[\log(u_a - u_w)_o - \log(u_a - u_w)_f\right] \qquad (7)$$

At this time, suction-control testing equipment is not used in routine geotechnical practice. The most common method for determination of full wetting swell potential is to perform 1-D response to wetting tests, such as ASTM D4546. The full-wetting swell potential can be adjusted to account for partial wetting. Coduto (2005) proposes one simple method where the full wetting swell strains are modified by a multiplier, α :

$$\alpha = \frac{S - S_o}{1 - S_o} \qquad (8)$$

While the α value is not well behaved as initial degree of saturation, S_o, approaches 1, this correction represents a simple and reasonable approach to accounting for partial wetting heave. Note that the α values from Eq. 8 are precisely correct at the "end points" where $S = S_o$ (no change in degree of saturation) and where $S = 1$ (full wetting).

Collapsible Soils: The full wetting collapse strain is most commonly obtained by running a 1-D response to wetting test on an undisturbed specimen, as discussed previously, and as depicted schematically in Figure 8. Houston and Houston (1997) and Singhal et al. (2003) have presented typical partial wetting collapse curves for silty collapsible soils, as shown in Figure 12. The best method for assessment of partial wetting collapse strain is to perform tests at intermediate values of wetting (suction), which requires suction-control laboratory testing equipment that is not commonly available to practitioners at this time. However, typical curves such as the "average" curve A presented in Figure 12 can be used to estimated partial wetting collapse. An alternative approximate method has been proposed by Coduto (2005) wherein the full wetting collapse strain is multiplied by an adjustment factor intended to account for partial wetting that is typical of field situations. Coduto suggests that partial wetting adjustment factor for collapsible soils typically varies from 0.3 to 0.8, decreasing with depth within the wetted zone. However, the α factor suggested for use by Coduto for expansive soils (Eq. 8) could also be applied to full wetting collapse strains and is reasonably appropriate given its accuracy at the "end points".

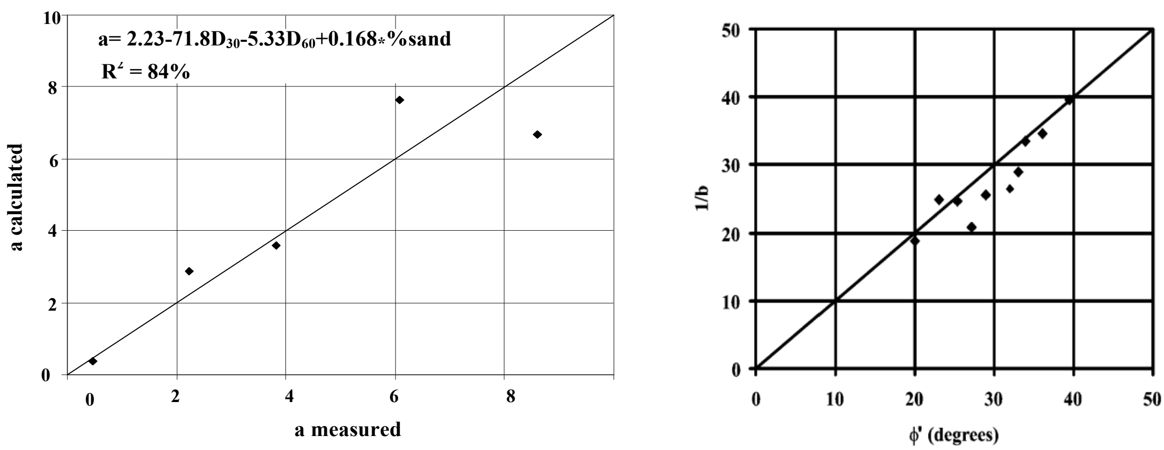

Figure 11. Best-Fit Equation for Parameters a and b (from Houston et al. 2008)

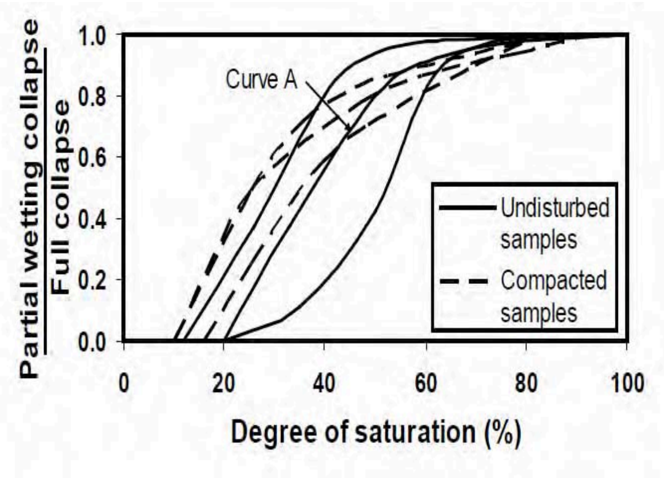

Figure 12. Silt Partial Wetting Collapse (Houston and Houston, 1997; Singhal et al. 2003).

SUMMARY

The general approach to characterization of an unsaturated soil site must take into consideration both stress state variables of net normal stress and matric suction. Successful characterization of an unsaturated soil site can be summarized by:

1. Drill and sample to appropriate depth. Selection of appropriate depth for sampling takes into consideration both structural (mechanical) load and depth of wetting.
2. Obtain the best quality undisturbed specimen possible, and maintain the unsaturated soil sample at the field moisture state.
3. Apply appropriate net normal stress, corresponding to probable field conditions (overburden plus applied loads).
4. Perform a response to wetting test. Fully wet the undisturbed specimen under field net normal stress conditions and observe/measure the response and properties.
5. Make adjustments/allowances for partial wetting in estimating field unsaturated soil response and in selection of foundation design and mitigation alternatives.

Relative simple, low cost modifications to routine geotechnical investigations, including in particular performance of response to wetting tests, lead to better and more cost-effective geotechnical engineering solutions. It is not absolutely necessary to directly measure soil suction as a part of routine characterization of an unsaturated soil profile. However, in planning and executing an unsaturated soil geotechnical investigation, it is necessary to be mindful of soil suction as a key stress state variable controlling soil behavior.

REFERENCES

Basma, A. and Tuncer, E. (1992). Evaluation and Control of Collapsible Soils. J. of Geot. Eng., ASCE, V. 118. No. 10, 1491 – 1504.
Delage, P., Cui, Y., and Antoine, P. (2005). Geotechnical Problems Related with Loess Deposits in Northern France. Proc. of the Int'l Conf. on Problematic Soils, 24 pp.
Douthitt, B., Houston, W., Walsh, K., and Houston, S. (1998). Effect of Wetting on Pile Skin Friction Resistance, 2nd Int'l Conf. on Unsat. Soils, Beijing, Aug., 219-224.
Coduto, D. (2005). Foundation Design: Principles and Practices, 2nd ed., Prentice Hall.
Escario, V. and Juca, J.F.T. (1986). The shear strength of partly saturated soils. Geotechnique, 36(3), 453-456.
Feda, J. (1988). Collapse of Loess Upon Wetting. Engr. Geology, V. 25, 263 - 269.
Fredlund, D.G., Hassan, J.U. and Gilson, H. (1980). The prediction of total heave, In Proc. 4th Int'l Conference on Expansive Soils, Denver, Colorado, 1-17.
Fredlund, D.G., Rahardjo, H., and Gan, J.K.M. (1987). "Nonlinearity of strength envelope for unsaturated soils." Proc. Sixth Int. Conf. Expansive Soils, New Delhi, 49-54.
Fredlund, D. and Houston, S. (2009). "A Protocol for Assessment of Unsaturated Soils Properties for Geotechnical Practice," Can. Geotech. J. **46**(6): 694–707.
Fredlund, D. G., and Xing, A. (1994). Equations for the Soil-Water Characteristic Curve. Canadian Geotechnical Journal, 31(4), 521-532.
Garven, E. and Vanapalli, S. (2006). Evaluation of empirical procedures for predicting the shear strength of unsaturated soils. *ASCE, GSP* No. 147, Vol. 2, pp. 2570-2581.
Houston, S., Houston, W. and Spadola, D. (1988). Prediction of Field Collapse of Soils Due to Wetting, J. of Geotechnical Engr. Div., ASCE,Vol. 1, 1988, 40 - 58.
Houston, S. and El-Ehwany, M. (1991). Sample Disturbance of Cemented Collapsible Soils, J. of Geotechnical Div., ASCE, Vol. 117, No. 5, 731 - 752.
Houston, S. Houston, W., and Anderson, T. (1995). Moisture and Strength Variability in Some Arizona Subgrades, TRB Record No. 1481, 1995, 35 - 46.
Houston, S. and W. Houston (1997). Collapsible Soil Engineering, by S., Unsaturated Soil Engineering Practice, GSP No. 68, ASCE, 199 – 232.
Houston, S., Walsh, K., and Houston, W. (1997). Soil Strength Contribution of Soil *S*uction in Cemented Soil. Proceedings, Solos Não Saturados, Vol.1, April, 25-34.
Houston, S.L. (2002), Applied Unsaturated Soil Mechanics, State of the Art Report, Proc. UNSAT 2002. Recife, Brazil, Balkema, Vol. 3, pp 1127 – 1134.
Houston, S., Perez-Garcia, N., and Houston, W. (2008). Shear Strength and Shear-Induced Volume Change of Unsaturated Soils from a Triaxial Testing Program, J. of Geot. and Geoenvironmental Engr/, ASCE, Vol. 134, No. 11, 1619- 1632.
Houston, W. and Nelson, J. (2012). The State of the Practice in Foundation Engineering on Expansive and Collapsible Soils. Proc. GeoCongress 2012, San Diego, pp. 608-642.
Houston, W., Dye, H., Zapata, C., Perera, Y. and Haraz, A. (2006). Determination of SWCC using One Point Suction Measurement and Standard Curves. Proc. UNSAT2006, ASCE, Carefree, AZ.
Jasmar, R. and Ore, H. (1987). Hydrocompaction Hazards due to Collapsible Loess in Southeastern Idaho. Proc. 23rd Symp. On Engr. Geology and Soils Engr., 461 – 474.