A soil suction surrogate and its use in the suction-oedometer method for computation of volume change of expansive soils

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ABSTRACT: The experience base of practitioners and the vast supply of field data on expansive soils are largely devoid of directly measured soil suction. Since engineers' experiences are so important to practice, this historical lack of suction measurement represents an impediment to adoption of modern unsaturated soil engineering to problems of expansive soils. Herein, a substitute or surrogate for soil suction is presented, such that the surrogate mimics observed field soil suction patterns, allowing interpretation of past experiences in terms of soil suction. This surrogate for natural field soils is a function of water content, routinely measured index properties, and TMI. It is possible to proceed from the beginning to the end of the Suction-Oedometer soil heave/shrinkage analysis without directly measuring soil suction. However, where suction measurements are available, direct use of measured soil suction in the Suction-Oedometer method for computation of heave/shrinkage is recommended. The soil suction surrogate is somewhat less accurate than directly measured suction, containing inherent errors associated with hysteresis, for example. The suction surrogate-based approach is an intermediate step towards the adoption of unsaturated soil engineering in expansive soils analyses, wherein a complete-stress-state approach, considering both net normal stress and soil suction, is applied.

1 INTRODUCTION

The geotechnical literature is replete with expansive soil studies. Methods of estimating field heave range from index property correlation, to oedometer methods, to suction-based methods, to water content-based methods. Despite these efforts, no agreement on the best approach to estimating expansive soil movements or approaches to mitigation has emerged, and the issue of expansive soils and their remediation is widely debated and disputed.

It is a generally accepted opinion among researchers that expansive soil must be understood within the context of unsaturated soil mechanics. Most research or forensic investigations on expansive soils use soil suction-based methods of heave computation, with direct measurement of soil suction. However, values of the suction compression/swell index (volume change in response to one log-cycle change in suction) can vary widely depending on whether field appropriate confining stress has been used in direct suction-controlled measurement, or depending on the empirical method of estimation selected, as investigated by Olaiz (2017). Oedometer methods for computation of heave, based on full wetting swell tests under field-appropriate stress level (e.g. ASTM D-4546) are also very popular. However, oedometer-based methods often assume full wetting in the field and generally do not appropriately consider impacts of partial wetting (i.e., computation of heave in going from initial to final soil suction).

Herein, the writers present an extension of the Suction-Oedometer method, presented by Houston and Houston (2017), using a soil suction surrogate as a substitute for measured soil suction. The Suction-Oedometer method is anchored on the conventional 1-D overburden swell test but is also a suction-based method in that initial and final soil suction profiles must be measured or estimated. In the Suction-Oedometer method, interpolation between the initial suction profile and the full wetting condition is accomplished with the Surrogate Path Method, presented by Singhal (2010), to account for partial wetting from the initial to the final soil suction condition. The Suction-Oedometer method can also be used for shrinkage and for estimation of partial wetting collapse strains, but this paper focuses on heave computation. The introduction of the soil suction surrogate allows use of the Suction-Oedometer method where soil suction measurements/estimates are not available – and allows for use of historical data/experience in judging reasonableness of design soil suction profiles. The soil suction surrogate was developed from a set of 476 field data points from various climatic regions where soil suction and soil index properties were directly measured, and a statistical analysis was made of the data fit.

2 SOIL SUCTION SURROGATE

The relationship between soil suction and what are termed here "soil suction surrogates" have been utilized by numerous researchers in the past and consist of such things as relationships between water content and index properties, including plasticity index (PI), plastic limit (PL), liquid limit (LL), percent clay, percent passing #200 sieve (P_{200}), activity, thornthwaite moisture index (TMI), and others. Many of these past efforts have been focused on development of correlations between index properties and soil-water characteristic curves, where specimens are allowed to achieve equilibrium with imposed soil suction conditions in the laboratory. In contrast, equilibrium conditions are rarely the case for the field, except at substantial depth (e.g., below seasonal fluctuation depth) where near-equilibrium soil suction is established. Field suction values below the moisture active zone are commonly estimated from climatic measures such as TMI, rather than water content and soil index properties.

As the focus of the soil suction surrogate search was for estimation of field suction profiles, a search for a surrogate that included water content and soil index properties alone was undertaken, as well as a search that included water content, soil index properties, and TMI. A total of 476 data points has been obtained for soils from Denver, Colorado; Hobart, Oklahoma; Phoenix, Arizona; and San Antonio, Texas. For each sample, moisture content, Atterberg Limits, and the percent passing the #200 sieve were measured to depths of 10 m. Additionally, the total suction was measured using a WP4-C device. Using the entire data set, a soil suction surrogate dependent only on water content and liquid limit was found to be the best-fit, and is illustrated in Figure 1 and described in Equation 1:

$$\psi = 3.2117\left(\frac{w}{LL}\right)^{-0.2177} \quad ; \quad 0.05 \leq \frac{w}{LL} \leq 1.0 \qquad (1)$$

where, ψ = Total Suction (pF); w = Moisture Content (%); LL = Liquid Limit (%). This regression model was derived using the Minitab program. The program uses iterative Gauss-Newton algorithms to obtain the best-fit coefficients for a given form of equation by minimizing the sum of squared errors. A meaningful metric from Minitab is the Standard Error of Regression (S), which is a measure of the accuracy of the predictions. An optimized fit will minimize S. S is the square root of the MSE (Mean Square Error) and has the same units as the response parameter. For the Figure 1 dataset, S is 0.275 pF.

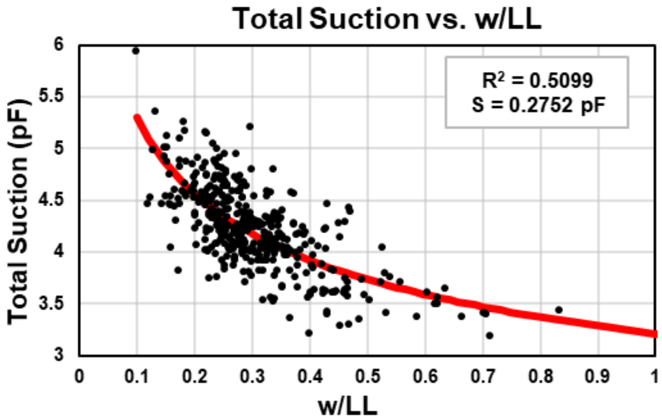

Figure 1. Fit of the measured total suction and relationship to water content divided by liquid limit.

Further statistical analyses revealed a strong R^2 correlation with the form of Equation 2 (below) for the suction surrogate to a depth of 3.66 m (12 ft); below a depth of 3.66 m, the R^2 value decreased significantly with using the form of Equation 2 for the surrogate, with the reduction in R^2 becoming quite significant below about 5.79 m. Therefore, a TMI component was introduced into the equation for the data below 3.66 m to improve the fit of the data with respect to R^2 and S. The Equation 4 form of the suction surrogate, which includes an additional TMI term, was found to provide the strongest correlation below a depth of 5.79 m (19 ft), predicated on the optimization of the statistical parameters. The Witczak et al. (2006) form of the TMI equation was used in the model due to simplicity of calculation and its close correlation to the original Thornthwaite (1948) equation, as observed by Olaiz et al. (2017). A depth-weighted function for suction surrogate (Equation 3) was used to estimate soil suction between depths of 3.66 m and 5.79 m, creating a depth dependent set of suction surrogate equations expressed as:

$$\psi_I = a\left(\frac{w}{LL}\right)^{b} \quad ; \quad z \leq 3.66 \qquad (2)$$

$$\psi_{II} = \psi_I + \left(\frac{z-3.66}{2.13}\right)\left(\psi_{III} - \psi_I\right) \quad ; \quad 3.66 < z < 5.79 \qquad (3)$$

$$\psi_{III} = c\left(\frac{w}{LL}\right)^{d} + eTMI \quad ; \quad z \geq 5.79 \qquad (4)$$

where, a = 3.0524; b = -0.2663; c = 3.3655; d = -0.2006; e = 0.0068; z = depth in meters. The overall R^2 using Equations 2, 3, and 4 to predict soil suction for the entire 476-point data set increased to 0.57, compared to R^2 of 0.51 using Equation 1 (Figure 1). Also, S significantly decreased for ψ_{II}, ψ_{III}, and for the data set as whole, and S increased for ψ_I, as shown in Table 1. Although wetting/drying hysteresis is reduced for field situations compared to typical laboratory SWCC testing conditions, field hysteresis is unavoidable and would be expected to be greatest in shallower soil depths where variations in soil suction due to changes in surface flux conditions (e.g. seasonal variation) are most pronounced. Therefore, the greatest scatter in soil suction data would be expected to be above the depth of near-equilibrium suction, as the Table 1 statistics support given the higher S value for shallower soil suction data. The Table 1 statistics also suggest that the "equilibrium" depth would be between about 3.66 m and 5.79 m for the data set considered. The optimum surrogate function is part of an on-going study, and future refinements to the surrogate function may emerge with added data.

Table 1. Depth-dependent surrogate statistics

Surrogate Equation	Depth Range (m)	S (pF)
ψ_I	$z \leq 3.66$	0.3219
ψ_{II}	$3.66 < z < 5.79$	0.2541
ψ_{III}	$z \geq 5.79$	0.1562
ψ_I, ψ_{II} & ψ_{III}	*All*	0.2596

3 SUCTION-OEDOMETER METHOD FOR COMPUTATION OF HEAVE

3.1 *Overview of Suction-Oedometer Method*

The Suction-Oedometer Method requires that soil suction be measured and/or estimated and is described in considerable detail by Houston and Houston (2017). Of course, it is possible to simply substitute the soil suction surrogate for directly measured/estimated soil suction values, giving rise to the Soil Suction Surrogate-Based Suction-Oedometer Method. The Suction-Oedometer Method, whether using soil suction or the soil suction surrogate, requires establishment of initial and final soil suction profiles, both dependent on boundary conditions, as discussed by Houston and Houston (2017). Determination of the soil suction below the zone of moisture fluctuation is particularly helpful in establishment of the initial and final soil suction profiles at a given site. In application of the Suction-Oedometer Method, evaluation of partial wetting strains for each sublayer requires performance of conventional overburden swell tests, estimation of swell pressure, and a method, such as the Surrogate Path Method (SPM), to estimate partial wetting strains.

The surrogate path method (SPM) for partial wetting strain estimation requires site-specific measurements of the fully-wetted swell potential that are performed at field-appropriate stress level on undisturbed (or, for fills, compacted to field-specification) specimens. The SPM, as defined by Singhal (2010), is conceptually similar to procedures put forth by Fredlund and Rahardjo (1993) and subsequently by Nelson et al. (2012) wherein the actual stress path in the volume change-suction-net stress space is mapped onto the net stress plane where matric suction is zero. Hence, where total soil suction is used, adjustments for osmotic suction are required to obtain matric suction for use in the SPM.

The SPM is illustrated in Figure 2 in terms of soil suction. However, a soil suction surrogate (Section 2) could be used as a substitute for measured soil suction when suction values are unavailable. In Figure 2, the suction (u_a-u_w) and vertical strain (ε) axes are arithmetic and the net total stress (σ-u_a) axis is logarithmic.

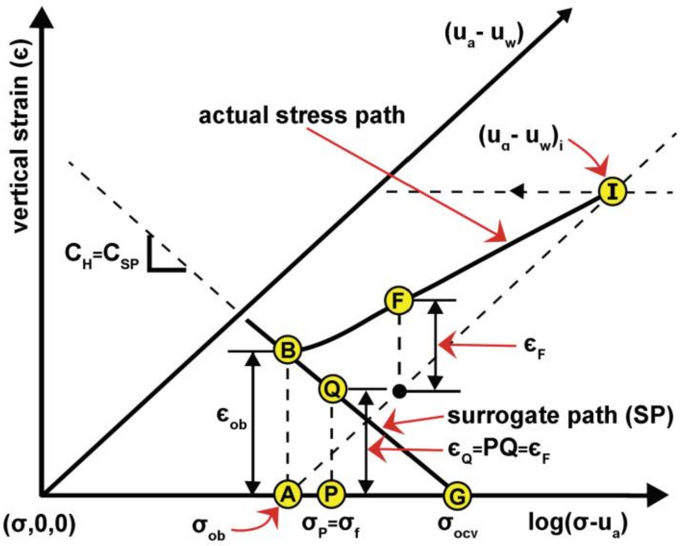

Figure 2. The SPM from Houston and Houston (2017).

In Figure 2, Point I is depicted as the initial or beginning point for the wetting process, where the suction is $(u_a\text{-}u_w)_i$. The plane IBA is parallel to the suction axis and perpendicular to the net stress axis. Point B lies in the net total stress plane where the suction is zero. The path (curve) IFB is the suction path for full wetting and produces a full wetting strain, $\varepsilon_{ob} = \varepsilon_{fw}$ (i.e. the strain corresponding to the distance AB in Figure 2). The path IFB is labelled as the Actual Stress Path and is curved, not a straight line. IFB would be somewhat non-linear if suction were plotted on a log scale, and it is even more non-linear given that suction is plotted arithmetically. For partial wetting, the matric suction does not go all the way to zero but stops at a final condition depicted by Point F where the partial wetting strain is $\varepsilon_{pw} = \varepsilon_F$.

Now wetting path IFB mapped as path GQB in the σ plane is considered, where $(u_a\text{-}u_w) = 0$. The path GQB is the path for wetting to zero matric suction at Point B. The path BQG is established as follows:

i) A test specimen with initial suction $(u_a\text{-}u_w)_i$ and field overburden stress of σ_{ob} is loaded in the laboratory oedometer to σ_{ob} and then submerged. When swelling ceases, the strain is ε_{ob}, which plots as AB in Figure 2. Note that where structural loads are significant, the applied stress (referred to here as σ_{ob}) should be overburden plus structural load.

ii) A second specimen, as nearly identical as possible to the first specimen, is loaded to a higher stress (preferably 2 to 3 times σ_{ob}, or more), then flooded, and the resultant strain is plotted versus the applied stress. Extrapolation (or interpolation) through points B and the second specimen point on the stress axis is used to approximate the swell pressure, σ_{ocv}, at zero strain (point G). This technique has been widely used to approximate σ_{ocv}. The subscript "ocv" refers to the swelling pressure for a specimen first loaded to overburden and then subjected to a constant-volume swell pressure measurement. Alternatively, the load-back procedure, with correction, can be used to approximate the constant volume swell pressure, σ_{ocv}, from Nelson et al. (2006) and Olaiz (2017).

With σ_{ocv} established at point G, the line GB serves as a surrogate path (SP) for the Actual Stress Path. Note that the actual path IFB generates a full wetting strain of ε_{ob} = AB, and the surrogate path (SP) generates the same strain, ε_{ob}, in going from G to B. The objective of the interpolation method is to find an intermediate stress between σ_{ob} and σ_{ocv}, call it σ_p, that produces a strain PQ that is equal to ε_F, the partial wetting strain at Point F. This interpolation is accomplished by using the proportion of suction dissipated by wetting from I to F as a proportionality factor in estimating the final net stress, σ_p, at point P. In other words, R_w is defined as $R_w = (u_a-u_w)_f /(u_a-u_w)_i$ where $(u_a-u_w)_i$ is the initial suction and $(u_a-u_w)_f$ is the final suction. Thus $R_w = 1$ for no wetting and $R_w = 0$ for full wetting, and $(1-R_w)$ = degree of wetting. Then, $\sigma_p = \sigma_{ob} + R_w (\sigma_{ocv} - \sigma_{ob})$. The actual path, I to F, in Figure 1 is replaced with the surrogate path, GQ.

The SPM requires that initial and final suction values in the field be measured or estimated; the SPM does not require that suction-controlled oedometer testing be performed, but rather employs the very familiar oedometer procedure and apparatus. The SPM does not require that the slope of the strain-log suction curve, γ_h, be measured or estimated and problems with the nonlinearity of this curve in the low and high suction range are greatly reduced or eliminated. However, it is noted that the data needed to estimate the suction compression index is readily available from the SPM without measuring or controlling suction.

The Modified Oedometer Method (MOM) presented below, represents a simple alternative to the SPM for estimating partial wetting strains. It entails the evaluation of the slope of the volumetric strain-log total suction curve, γ_{hm}, with the m in the subscript added for "modified". The value of γ_{hm} is obtained from the results of a conventional oedometer swell test (ASTM D-4546) performed on an undisturbed sample with overburden confining stress applied and held constant during wetting. The result from the swell test is the fully-wetted overburden swell strain, ε_{ob}. The value of γ_{hm} can be computed from:

$$\gamma_{hm} = \frac{\varepsilon_{ob}}{\psi_i - \psi_f} \tag{5}$$

where the initial total suction (ψ_i) and final total suction (ψ_f) are directly measured, by filter paper or WP4-C, e.g., and expressed as pF values – thus the denominator is the number of log cycles change in total suction during the ASTM D-4546 test. Note that, the final total suction in the ASTM D-4546 test is the osmotic suction because the matric suction has been driven to zero by submergence. The osmotic suction can be ascertained by measurement, but with a probable error of about ±50 kPa when using the WP4-C device. Houston and Houston (2017) evaluated field data from various locations throughout the USA and concluded that a good average value of osmotic suction is about 175 kPa (3.24 pF). Thus, where direct osmotic measurements are not available, γ_{hm} can be estimated from:

$$\gamma_{hm} = \frac{\varepsilon_{ob}}{\psi_i - 3.24\,pF} \tag{6}$$

The implementation of γ_{hm} to compute partial wetting strains is to simply employ:

$$\varepsilon_{pw} = \gamma_{hm}\left(\psi_i - \psi_f\right) \tag{7}$$

where, ψ is in pF. The value of ε_{pw} from Equation 7 is specific to the depth from which the ASTM D-4546 sample was obtained. The initial and final suction values correspond to the field conditions and are likewise specific to the same depth. The initial and final suctions depend on numerous factors including climate, drainage, and landscaping which combine to characterize the boundary conditions. Houston and Houston (2017) discuss procedures for measuring or estimating these values of suction. To avoid problems with the non-linearity of the strain-log suction curve, this γ_{hm} should be used only for final suction values in the field which are greater than 3.44 pF. It should also be noted that, despite apparent similarities, the value of the Equation 5 γ_{hm} differs from the γ_h provided by PTI (2004) in that the PTI value corresponds to an overburden stress of only 40 cm. By contrast for γ_{hm}, the full effect of overburden stress is reflected in the measured ε_{ob}, which is thus depth specific, as is the initial total suction. Thus the γ_{hm} is depth specific and should be used to obtain ε_{pw} for this depth, which is then multiplied times the thickness of the corresponding sublayer to obtain an increment of heave.

3.2 *Comparison of Directly Measured Partial Wetting Swell Strain to Suction Surrogate- and Suction-Based SPM and MOM Estimates*

Undisturbed samples of expansive clay were tested for partial wetting strains using an oedometer pressure plate device (OPPD) which allowed for control of both net normal stress and soil matric suction (Olaiz 2017). A full suite of soil index properties was run on the soil specimens, and initial soil suction values were directly measured using either the OPPD (Fredlund SWCC Device, GCTS, Inc.) or the WP4-C device (Meter, Inc.). The OPPD strains observed in response to various changes in soil suction were then compared to those estimated by the SPM procedure using measured soil suction, and then again using soil suction values computed from Equations 2, 3, and 4. Comparisons of OPPD measured strains to MOM strains were also made.

The full wetting oedometer test (ASTM D-4546) is typically used in the SPM to determine the slope of the surrogate path (C_H) and to estimate swell pressure. However, even though from the same sample tube, several of the "companion" ASTM D-4546 and OPPD specimens tested in this study did not show good agreement in strain when fully wetted, likely due to field sample variability. Therefore, the procedure of using companion specimens was not employed in this this study and the conventional swell tests (ASTM D-4546) were used only to estimate swell pressure in the calculations of the partial wetting strains. The OPPD specimens were, in general, taken to low matric suction values of 0 to 100 kPa, where matric suction was reduced below 100 kPa negligible additional swell was observed. Therefore, when specimens were not fully wetted in the OPPD to zero matric suction, the largest value of swell strain (e.g., swell strain at 50 kPa matric suction), corresponding to the lowest matric suction used in the test, was used in lieu of the full wetting strain to avoid errors associated with sample variability. The constant volume swell pressures (σ_{OCV}) were estimated using the average ASTM D-4546 C_H slope of the surrogate path, provided by Olaiz (2017). The initial soil matric suction for each specimen was either directly measured with the OPPD or calculated from WP4-C (Meter, Inc.) total suction measurements using the average determined osmotic suction for each site.

Comparison of the suction-based SPM partial wetting swell strains, the suction surrogate-based SPM partial wetting strains, and MOM strains (using directly measured suction) to the OPPD directly measured partial wetting swell strains are summarized in Table 2. Initial suction values corresponded to field conditions, and final suction values for the partial wetting tests ranged from 1400 kPa to 200 kPa for the results in Table 2. For each partial wetting result shown in Table 2, the soil matric suction was decreased from the initial field value to some lower suction (e.g. 800 kPa). The Sample ID in Table 2 indicates the location where the specimen was obtained, D for Denver and SA for San Antonio.

The SPM partial wetting strains obtained from measured initial and final suction values showed very good agreement, on average, with the directly measured OPPD partial wetting strains. The soil suction surrogate-based SPM partial wetting strains also provide reasonable estimates of measured strains on average, with only a few exceptions of very good match shown for individual tests in the Table 2 data. Similarly, the MOM predictions of partial wetting strains are typically a good match to measured OPPD strains, with a few notable exceptions shown in Table 2.

Where measured suction values are available better estimates of partial wetting strains are expected, in general. This is a result, in part, of inherent error associated with use of a suction surrogate (e.g. errors due to hysteresis and soil structure/density, use of estimated osmotic suction in computation of matric suction). In addition, the final water content values used here to obtain the final soil suction surrogate were not directly measured for the Table 2 comparisons, but rather the water contents were inferred from OPPD tube out-flow readings. The out-flow tube water content determinations have some error associated with use of estimated evaporation losses in computation of water content. Such OPPD water content error increases with test duration, and long equilibration times were required for the clays of this study. However, for application to the field, these uncertainties associated with long term laboratory testing do not negatively affect quality of surrogate estimates, and better agreement, in general, would be expected between field partial wetting strains and surrogate-based SPM estimates of partial wetting strains.

Nonetheless, because a soil suction surrogate is subject to errors from hysteresis, for example, use of directly measured soil suction values is recommended, where possible. Initial soil suction profiles can generally be obtained by direct measurement, for example by using the WP4-C device to get total suction, together with measured or estimated osmotic suction for estimation of matric suction profiles. Final suction profiles for design are best obtained from regional experience where a data base of post-construction directly measured soil suction profiles have been collected for application-specific boundary conditions. An example of such a database is that collected over years of study by the Colorado Association of Geotechnical Engineers (CAGE), and which was used by Walsh et al. (2009), in a study of depth of wetting for residential construction in the Denver front range.

Table 2. Comparison of measured and predicted partial wetting strain.

Sample ID	ε_{OPPD} MEASURED	ε_{SPM}	ε_{SPM} SURROGATE	ε_{MOM}
D-1	0.32	0.41	0.32	0.21
D-3	0.94	1.03	0.98	0.65
D-7	0.10	0.16	0.10	0.10
SA-1	0.21	0.26	0.21	0.21
SA-6	0.21	0.24	0.17	0.19
SA-9	0.61	0.53	0.50	0.36
D-8	0.41	0.46	0.04*	0.30
SA-10	0.32	0.39	0.31	0.31
SA-2	0.10	0.12	0.11	0.19
SA-4	0.21	0.26	0.21	0.19
SA-7	0.47	0.36	0.18	0.29
D-9	0.10	0.34	0.28	0.19
SA-11	0.32	0.35	0.28	0.26
SA-3	0.52	0.57	0.50	0.44
SA-5	0.21	0.19	0.18	0.14
SA-8	0.21	0.26	0.23	0.18
D-5	0.21	0.32	0.25	0.19
D-10	0.63	0.51	0.43	0.12
Mean	***0.34***	***0.38***	***0.29***	***0.25***
σ	***0.217***	***0.201***	***0.207***	***0.128***

*An error in calculated water content from OPPD manometer is suspected but not verified.

4 CONCLUSIONS

In this study, a dual approach (based measured soil suction or estimated soil suction) was taken to the development of methods for estimation of expansive soil movements, wherein the Suction-Oedometer Method was linked to a Soil Suction Surrogate-Oedometer Method to develop a consistent analysis of heave whether a suction-based or surrogate-based approach is taken. Here, it was shown that the soil suction surrogate can be used – in lieu of measured soil suction – to evaluate expansive soil heave for the general case of partial wetting. The soil suction-based approach represents the benchmark result, but both soil suction and soil suction surrogate approaches use a complete-stress-state analysis, taking into consideration both net normal stress and soil suction, in making the estimate of field heave (or shrinkage). A simple suction-oedometer based alternative to the SPM method (MOM method) was also shown to provide reasonable estimates of partial wetting strain for the data considered in this study.

The soil suction surrogate provides engineers with a sound basis, derived from site-specific measurements, to use past experiences and data in estimating initial and final moisture conditions for design. A soil suction surrogate, such as that proposed in this study, will also allow practitioners and researchers to use the existing extensive database of water content profiles, along with soil index property profiles, to enhance their database for estimating initial and final moisture state conditions. While the soil suction surrogate proposed herein is not perfect, it was demonstrated that the soil suction surrogate can be used to obtain quite reasonable estimates of partial wetting swell strain that are quite likely to be sufficiently accurate for engineering purposes. It is possible that the contribution of additional field data (where measured soil suction, climatic data, and soil index properties are available) will lead to a more robust soil suction surrogate, with less scatter. Meanwhile, the writers propose that the soil suction surrogate presented herein as Equations 2, 3, ad 4 be considered for use in estimation of field total suction where soil suction cannot be measured or estimated reliably.

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