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Application of in situ tests in unsaturated soils to analysis of spread footings

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Article

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Unsaturated clay
Spread footing
Bearing capacity

Abstract

Spread footings are often supported in the upper zone of the soil profile, which is frequently unsaturated. It is common in geotechnical practice to use in situ testing to assess soil properties throughout the zone of influence for footings. These tests regularly include the Standard Penetration Test (SPT), and sometimes the Cone Penetration Test (CPT), and Pre-bored Pressuremeter Test (PMT). Yet degree of saturation is often not considered in the analysis of the test results. To investigate the importance of partial saturation, SPTs, CPTs, and PMTs were conducted at two test sites over two years covering dry and wet periods. Water content and suction profiles were established for each test date to assess their impact on the in situ tests. Results from this study revealed that changes in moisture content and suction had an important influence on the results of in situ tests and the soil parameters derived from these tests. Specifically, undrained shear strengths estimated from SPT penetration resistance and CPT tip resistance using empirical and semi-empirical equations, respectively, were significantly lower during wet periods compared to dry periods. Consequently, estimated bearing capacities for a shallow foundation varied considerably from dry to wet periods. Similarly, PMT limit pressures were significantly impacted by increases in moisture content. Associated reductions in limit pressures resulted in large reductions in predicted allowable bearing capacity. While PMT modulus did appear to decrease with increasing moisture, its impact on settlement was offset by the decrease in allowable bearing pressure under wet conditions.

1. Introduction

In situ tests are commonly used as part of geotechnical investigations. Basic parameters obtained from these tests are used to predict soil properties and in turn to estimate bearing capacity and settlement of foundations. Researchers at the University of Oklahoma conducted in situ tests over a two-year period at two unsaturated soil test sites and collected water content and suction data in parallel. Results of this work revealed that basic test parameters and derived properties can vary significantly depending on seasonal variations in moisture conditions. Results from the Standard Penetration Test (SPT), Cone Penetration Test (CPT), and Pressuremeter Test (PMT), demonstrating these seasonal variations at the two clayey test sites are presented in this paper. In addition, variations in the predicted bearing capacity and settlement of a spread footing are presented and discussed in light of these seasonal variations in test parameters.

2. Background: predicting spread footing behavior using results of in-situ tests

2.1 Overview

Soil properties interpreted from in-situ tests are many, including drained and undrained shear strength parameters and elastic modulus for settlement analysis. Using the interpreted parameters, bearing capacity and elastic settlement of footings can be estimated using a drained or undrained analysis as appropriate. In the following sections two equations for estimating the undrained shear strength from SPT and CPT are presented, for use in a total stress analysis of spread footing bearing capacity at the clay test sites. In addition, for the PMT, equations for predicting bearing capacity and settlement based on the pressuremeter limit pressure and modulus, respectively, are also presented. Equations presented are provided as examples and their inclusion is not intended to

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be an endorsement of their use over others that are available. The goal is to illustrate how the predicted soil properties from these equations can vary due to varying moisture conditions in an unsaturated profile; and consequently, how this impacts predicted bearing capacity and settlement of footings. The reader should keep in mind that the applicability of equations presented in this section may be questioned on the basis of actual drainage conditions during field testing, and because in the development of these equations, generally saturated drained or undrained conditions were assumed to prevail. In the case of unsaturated soils, the drainage conditions are vastly more complicated because of the presence of the air phase and the fact that excess pore pressures are governed by factors that extend beyond temporal volume change tendencies in the soil. Nevertheless, in practice the degree of saturation is not widely addressed in developing foundation recommendations, although it should be.

In the last decade researchers have been working on the problem of shallow foundations on unsaturated soils (Le et al., 2013; Oh & Vanapalli, 2013a, b, 2018; Vanapalli & Mohamed, 2013; Mohamed & Vanapalli, 2015; Tang et al., 2017a, b; Akbari Garakani et al., 2020) and various approaches for modeling and analysis have been presented. In this paper, the use of in situ testing to obtain parameters for estimating bearing capacity and settlement in unsaturated soils is explored. Of particular interest is how the in situ test results vary seasonally, and what impact this has on estimated bearing capacity and settlement if partially saturated conditions are not considered in the estimation of soil properties.

This paper demonstrates the possible consequences of not considering the moisture content at the time of in situ testing, relative to predicted soil properties, bearing capacity and settlement. The results highlight the necessity of developing methods for practitioners to address the influence of moisture content and suction on in situ test results for application to bearing capacity and settlement analysis. Preliminary recommendations for addressing these issues are provided.

2.2 Bearing capacity

For the purpose of this paper, the Terzaghi (1943) equation for ultimate bearing capacity of a square footing under general shear failure will be used. Ultimate bearing pressure, q_u, is given by Equation 1.

$$q_u = 1.3cN_c + \gamma_1 D_f N_q + 0.4\gamma_2 B N_\gamma \tag{1}$$

For a total stress analysis of clays, the total stress friction angle, ϕ_t, is assumed equal to zero with c equal to the undrained shear strength, c_u, N_c equal to 5.7, N_q equal to one, N_γ equal to zero, and γ_1 equal to the total unit weight above the bearing level. For effective stress analysis of sand, c is equal to zero, N_q and N_γ depend on the effective stress friction angle ϕ', and, γ_1 and γ_2 are equal to the weighted average effective unit weights considering the position of the water table.

Fredlund et al. (2012) offer suggestions for predicting bearing capacity of unsaturated soils where the contribution of matric suction is captured via the cohesion, c, for a drained analysis. They also discuss a total stress approach based on strengths obtained from unconfined compression tests. For the purpose of this paper, Equation 1 was evaluated using a total stress approach for clays, with the governing strength parameters predicted from SPT and CPT results. In this way, the influence of seasonal variability in saturation and suction on the predictions will be revealed through the variation in interpreted soil parameters. This approach is indicative of the state of practice in areas where unsaturated soil mechanics has not been incorporated into the analysis of bearing capacity and settlement.

2.3 Standard Penetration Test (SPT)

The SPT is among the most widely used in situ test in geotechnical practice. It offers the advantage of providing a sample simultaneously while conducting the test. There are numerous correlations for estimating properties of sands and clays based on the SPT N-value. Equation 2 is but one example for estimating undrained shear strength, c_u (Hara et al., 1974), of clay.

$$c_u\left(\text{kPa}\right) = 29N^{0.72} \tag{2}$$

Correlations between N and c_u are known to be unreliable; however, the authors have found that Equation 2 is reasonable compared to other methods of determining c_u. While not desirable, sometimes the SPT along with soil index properties provide the only means of estimating mechanical properties of soils for a given project.

2.4 Cone Penetration Test (CPT)

A CPT uses a friction cone and is a rapid profiling tool that provides near continuous records of tip resistance, q_c, and sleeve friction, f_s. The CPT can be used to estimate soil types and various soil properties. The cone can be equipped with a sensor to detect pore water pressure during penetration; however, since the research discussed in this paper involved unsaturated soils, reliable measurements of pore water pressures during penetration could not be obtained. As with the SPT, the undrained shear strength of clay can be estimated from the CPT using available correlations such as that represented by Equation 3 (Kulhawy & Mayne, 1990).

$$c_u = \frac{q_c - \sigma_o}{N_k} \tag{3}$$

Unlike Equation 2, Equation 3 is semi-empirical with its theoretical basis in bearing capacity theory; however, the determination of the bearing capacity factor N_K is based on empirical data. Factor N_k reported by Drnevich et al. (1988)

varies between about 5 and 25 for a wide range of clays; a value around 15 appears to be a reasonable first order approximation (Drnevich et al., 1988) for a wide range of clays. A value of N_k equal 20 was conservatively selected by the authors, in part because it seems to provide more reasonable values for the overconsolidated residual clays we have worked with.

2.5 Pressuremeter test (PMT)

The pressuremeter can be used to directly estimate the ultimate bearing pressure of a shallow foundation via Equation 4 (Briaud, 1992).

$$q_u = kp^*_{Le} + \gamma D_f \quad (4)$$

For D_f/B of 0.5, the recommended bearing capacity factor for clay is about 0.9 (Briaud, 1992). The pressuremeter is an in situ test that provides a stress-stress curve that can be used to directly determine the modulus of elasticity. The pressuremeter modulus can be used to predict settlement, S, using Equation 5 (Ménard & Rousseau, 1962; Briaud, 1992).

$$S = \frac{2}{9E_d} q_{net} B_o \left(\lambda_d \frac{B}{B_o} \right)^{\alpha} + \frac{\alpha}{E_c} q_{net} \lambda_c B \quad (5)$$

If the pressuremeter modulus, E_p, is constant with depth, Equation 5 reduces to Equation 6, where the constant C depends on the soil type and ratio B/B_o.

$$S = C \frac{q_{net} B}{E_p} \quad (6)$$

For a square footing, the shape factors are both about 1.1 and the rheological factor is 1 for overconsolidated clay. Thus, for a square footing on overconsolidated clay having a uniform E_p with depth, the constant C is about 1.3.

3. Results of in situ testing and foundation analysis in unsaturated soil

3.1 Standard penetration and cone penetration testing at two clay sites

Results of SPT and CPT testing at two different test sites on two different days are shown in Figures 1 and 2. On each testing date, one SPT and three CPT profiles were conducted and moisture content samples were collected. As discussed by Collins (2016) and Miller et al. (2018), the matric suction was estimated from gravimetric water content data using a soil-water characteristic curve (SWCC) developed for the test soils at each site using total suction measurements, pressure plate data and empirical curve fitting

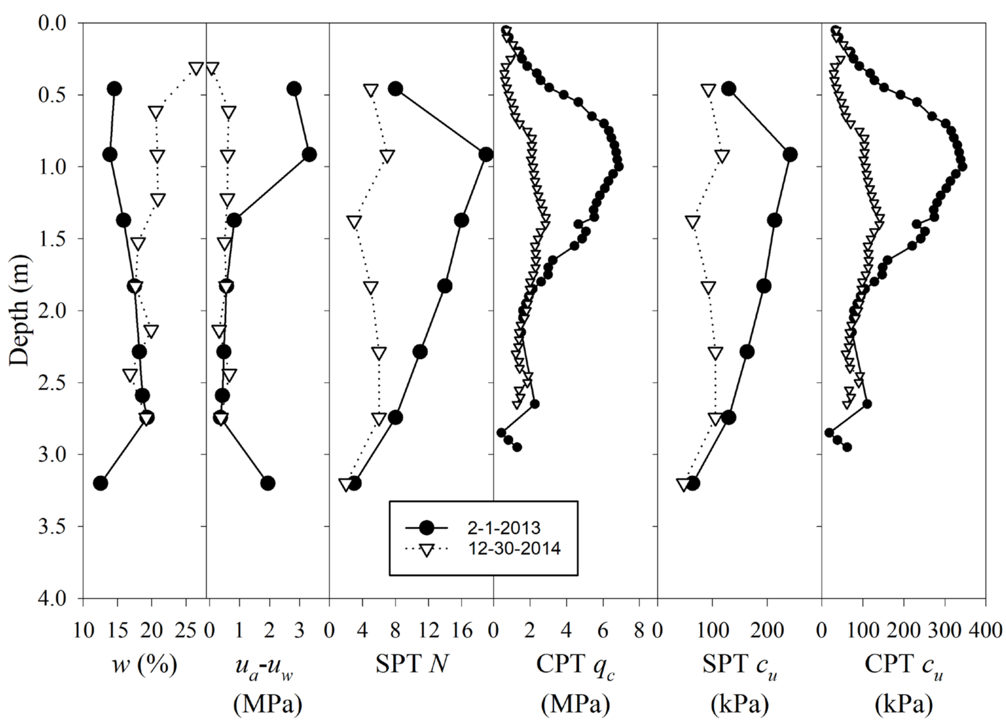

Figure 1. Results of SPT and CPT at North Base Test Site on two different test dates.

Table 1. Average soil properties for layers at North Base and Goldsby.

Depths (m)	Test Soil Site Name	UCSC Classification	LL	PI	%F*	%S#	n+	G_s^
0.3-0.9	North Base-Layer 1	CL, Lean clay	47	29	91	9	0.414	2.72
0.9-3	North Base-Layer 2	CL, Lean clay	35	19	89	11	0.364	
0-1.5	Goldsby-Layer 1	CL, Lean clay	32	11	92	8	0.439	2.71
1.5-3	Goldsby-Layer 2	CL, Lean clay with sand	30	9	80	20	0.417	

*% fines; #% sand; +porosity; ^specific gravity of solids.

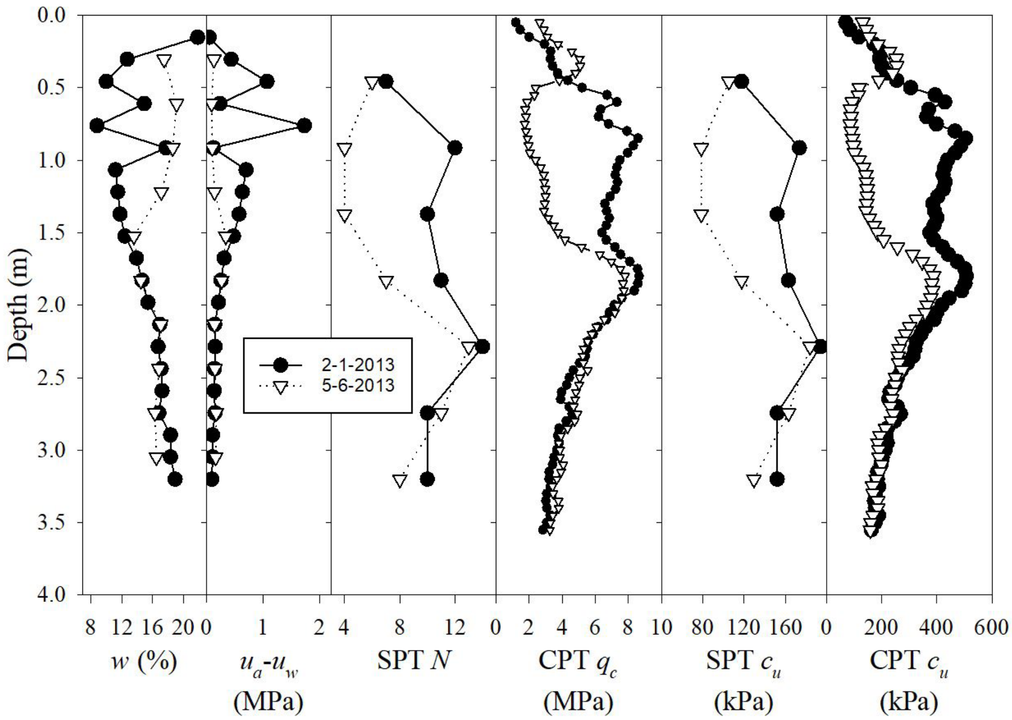

Figure 2. Results of SPT and CPT at Goldsby Test Site on two different test dates.

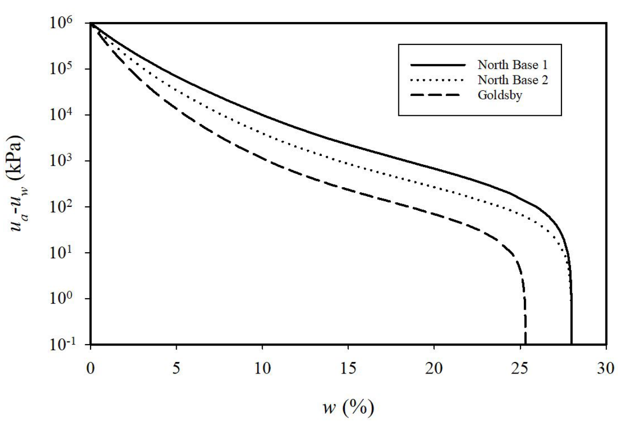

Figure 3. Soil Water Characteristic Curves used to estimate matric suction from gravimetric water content.

using the method of Zapata et al. (2000). The soil layering and average properties at each site are listed in Table 1, while the SWCCs used to estimate matric suction from the gravimetric water content are provided in Figure 3. Measurements of total suction revealed significant osmotic suction when the soil was near saturation; however, changes in matric suction are generally more meaningful relative to mechanical behavior (e.g. Fredlund et al., 2012) and therefore, matric suction was used in the analysis.

The impact of the change in water content and suction is clearly revealed in the trends of the SPT *N* values and CPT q_c values with depth in Figures 1 and 2. Interestingly, at both sites the SPT *N* values on the two dates below about 2.0 m continued to show some differences even though it appeared that water content and suction below 2.0 m was quite similar. On the other hand, the CPT q_c values on the two dates tended to converge at a lesser depth, closer to where the moisture content differences became minimal. Two possible contributors to this observation include, first, the fact that the SPT starts 0.3 m above the plotted test depth and so is influenced by soil above the actual point where the *N* value is plotted. Second, matric suction during wetting may be lower than predicted from a single SWCC that does not account for hysteresis. Because of hysteresis, for a given water content during a period of wetting, the matric suction would be less than during drying, but using a single SWCC does not account for this. Thus, actual values of matric suction in Figures 1 and 2, would be lower for the inverted triangles, corresponding to the wetting event, relative to the solid circles at the same water content.

Predicted undrained shear strengths using Equation 2 with SPT *N* values and Equation 3 with CPT q_c values are shown side by side in Figures 1 and 2. The average undrained shear strengths from SPT and CPT in a layer extending from 0.5 to 2 m for each site and each date are summarized in Table 2 along with average water content, suction, *N* value and q_c. Also, shown in Table 2 are the predicted bearing capacities for each case, assuming a 1 m square footing is embedded 0.5 m, and using the average undrained strengths in a total stress analysis with Equation 1 and total unit weight, γ_1, of 18 kN/m^3. In the last two columns of Table 2 are the factors of safety (FS) for the dry season date (assumed to be 3) and the wet season date calculated due to the change in q_u from dry to wet seasons. These FS values indicate that if the SPT or CPT are conducted in a dry season and used for footing design, the wet season *FS* could be about half of the original *FS*. This suggests great caution is needed in the interpretation of SPT and CPT results in unsaturated soils, particularly during drying seasons. What is needed is a practical method for interpreting SPT and CPT with consideration of moisture content changes from dry to wet seasons. The SPT and CPT values of undrained shear strength agree reasonably well for the higher *PI* North Base soil compared to the lower *PI* Goldsby soil. This highlights the uncertainty in empirical correlations and the importance of using more than one approach for estimating important soil mechanical properties. It is noted that c_u estimated based on SPT was lower in both cases, probably due to the significant conservatism built into SPT correlations. Also, these correlations are fundamentally more applicable to saturated than unsaturated clay soils.

The data in Table 2 indicate that on average the moisture content in the zone of interest for this footing increased about 4% at both sites and the average decrease in undrained shear strength and ultimate bearing capacity was about 50% considering both the q_c and *N* values at both sites.

3.2 Pressuremeter testing at two clay sites

Results of pressuremeter tests at the North Base and Goldsby test sites on different dates over a nearly 2-year period are shown in Figures 4 and 5, respectively. These figures summarize the interpreted limit pressures, P_L, and pressuremeter moduli, E_p, for tests at three different depths, along with the natural moisture content and daily rainfall from a nearby weather station (Mesonet, 2021, Norman Station). The Mesonet weather station is less than 0.2 km from the North Base site and about 9.0 km north of the Goldsby site. The pressuremeter testing began in a relatively dry period in the beginning of 2013 when soil moisture contents were low. Then, rainfall events increased in frequency and magnitude until mid-November of 2013. There was an increase in soil moisture content at the test sites during this time and consequently, there is a noticeable decrease in the trend of pressuremeter limit pressures. The pressuremeter moduli also appear to generally decrease over this period, being more noticeable at the North Base site. During this period of wetting there was a total of 118 cm of rainfall. Following this period of wetting there was a dry spell between mid-November 2013 and mid-March 2014 during which only about 4 cm of rainfall occurred. Interestingly, the natural water contents did not decrease much during this period, which was over the colder winter months, but did show a steady decrease throughout the rest of 2014. 2014 was much drier with a total rainfall of 57 cm compared to 120 cm in 2013.

The influence of the changing water contents on the pressuremeter parameters at both North Base and Goldsby test sites is revealed in Figures 6 and 7, respectively. In these figures, the limit pressure and modulus, normalized by the vertical total stress, are plotted against the natural water content and corresponding matric suction estimated from the SWCC. The parameters were normalized by vertical overburden pressure to account for the differences in total stress state, which reflects the initial net normal stress state, at the three

Table 2. Average properties and bearing capacity.

Test Site	Avg. *w*	Avg. u_a-u_w	Avg. N	Avg. q_c	SPT Avg. c_u	CPT Avg. c_u	SPT q_u	CPT q_u	SPT	CPT
	(%)	(kPa)		(kPa)	(kPa)	(kPa)	(kPa)	(kPa)	*FS*	*FS*
North Base										
2/1/2013	15.5	1883	14.3	4809	194	231	1447	1721	3	3
12/30/2014	19.6	579	5.0	2068	91	102	683	765	1.4	1.3
Goldsby										
2/1/2013	12.9	569	9.7	7301	148	428	1106	3180	3	3
5/6/2013	16.5	180	4.7	3893	88	194	661	1447	1.8	1.4

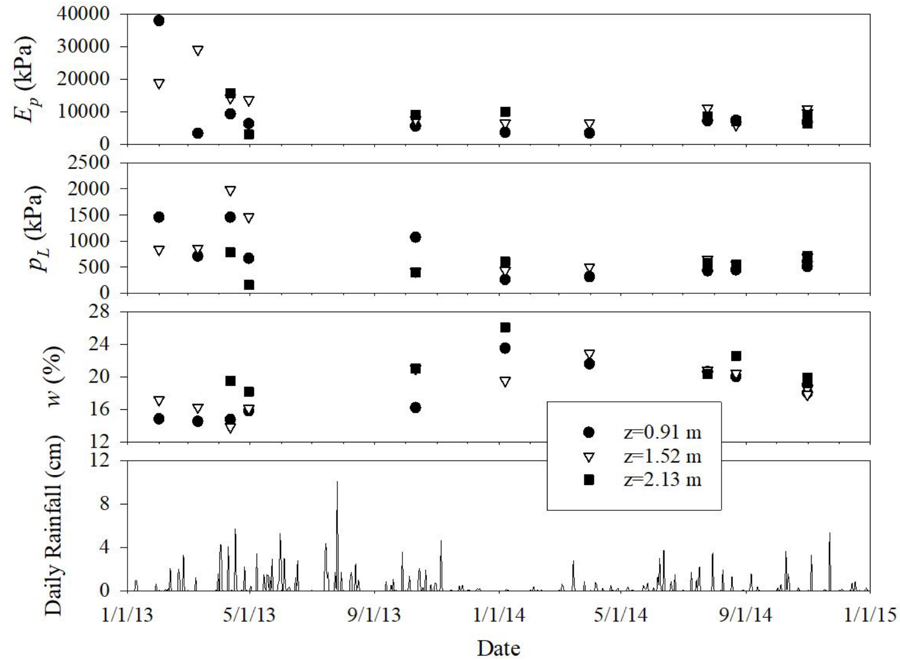

Figure 4. Pressuremeter limit pressure and modulus, and corresponding water content for the North Base test site for three test depths on different dates. Rainfall data obtained from a nearby weather station (Norman station, Mesonet 2021).

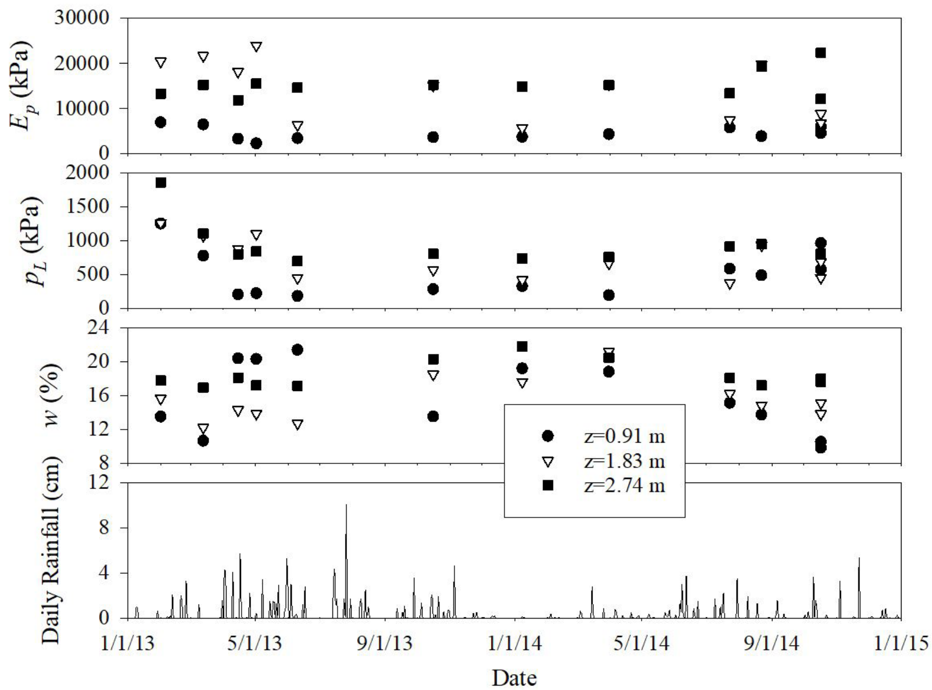

Figure 5. Pressuremeter limit pressure and modulus, and corresponding water content for the Goldsby test site for three test depths on different dates. Rainfall data obtained from a nearby weather station (Norman station, Mesonet 2021).

test depths. There is a fair amount of scatter in the data, which is largely attributed to the natural variations in soil properties at these sites. Nevertheless, there appears to be rather strong trends in the variation of normalized limit pressure with water content and suction. The trends in normalized modulus are not as statistically robust as the limit pressures; however, they do show expected decreasing trends with increasing moisture content. The scatter in the pressuremeter modulus data is due in part to the subjectivity in selecting the near linear portion of the pressuremeter curve to interpret the modulus; a small

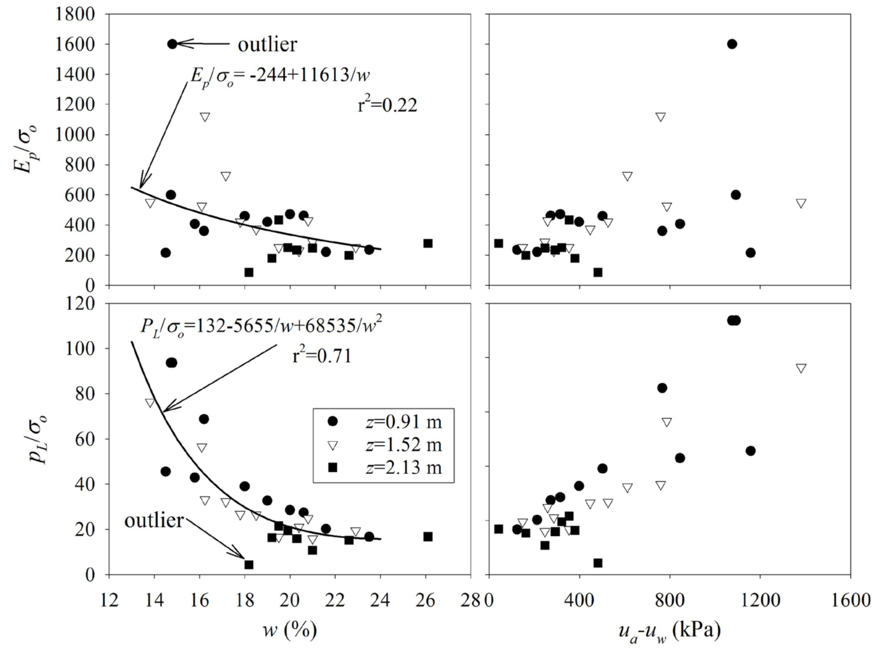

Figure 6. Normalized pressuremeter limit pressure and modulus versus water content and matric suction for North Base.

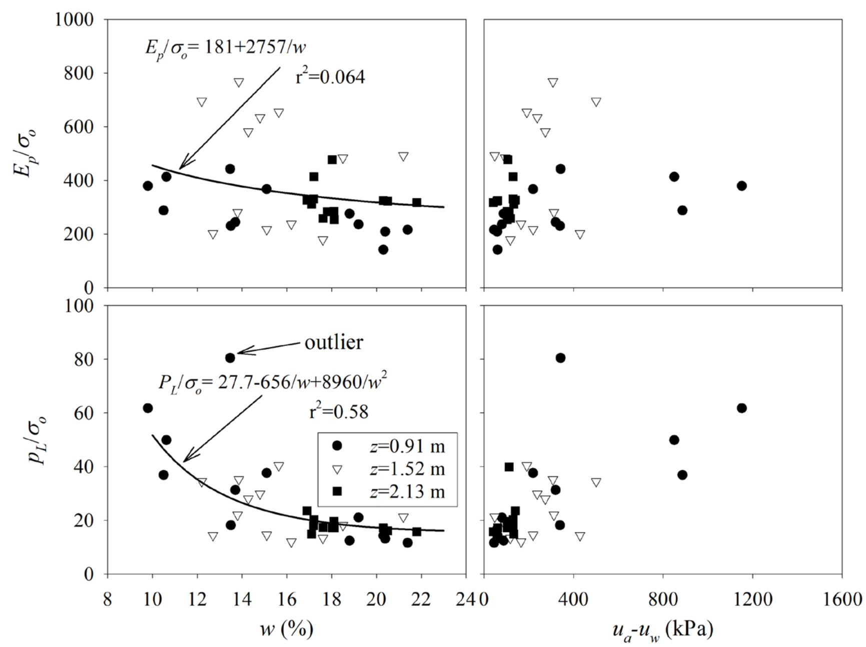

Figure 7. Normalized pressuremeter limit pressure and modulus versus water content and matric suction for Goldsby.

difference in the slope makes a large difference in the calculated modulus. Also, the pressuremeter modulus is more sensitive to disturbance around the borehole.

In Figures 8 and 9, the variation in predicted allowable bearing capacity and settlement using Equations 4 and 6 due to variations in water content during the testing period are presented. The water contents for the upper two test depths were averaged to represent the moisture content in the zone of influence for bearing capacity (1-m wide square footing) while the moisture contents for all three test depths were averaged to represent the zone on influence for settlement. Pressuremeter limit pressures and moduli used in Equations 4 and 6 were calculated using the regression equations shown in Figures 6 and 7.

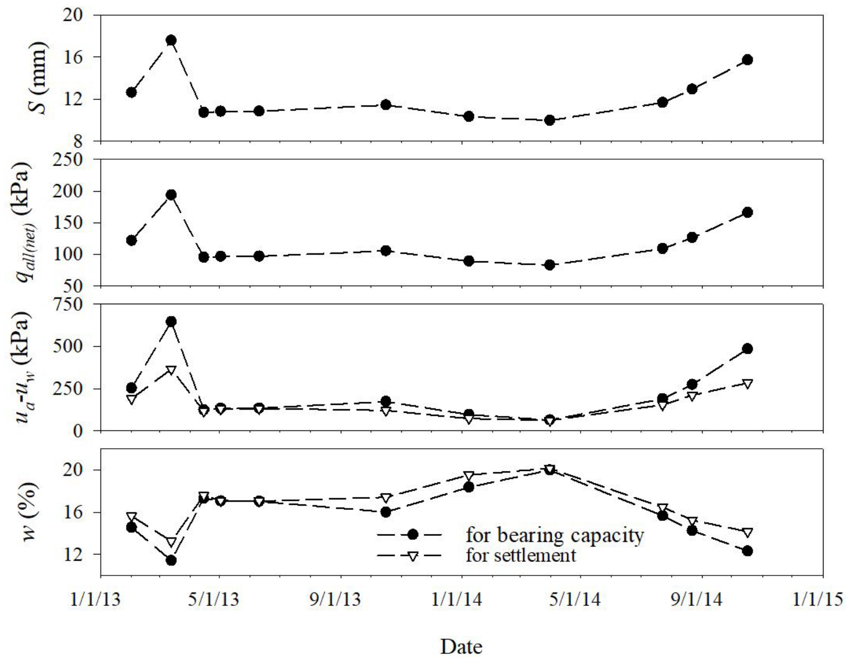

Figure 9. Predicted allowable bearing capacity and settlement in relation to variations in average moisture contents and matric suction within the zone of influence for bearing capacity and settlement during the testing period at Goldsby.

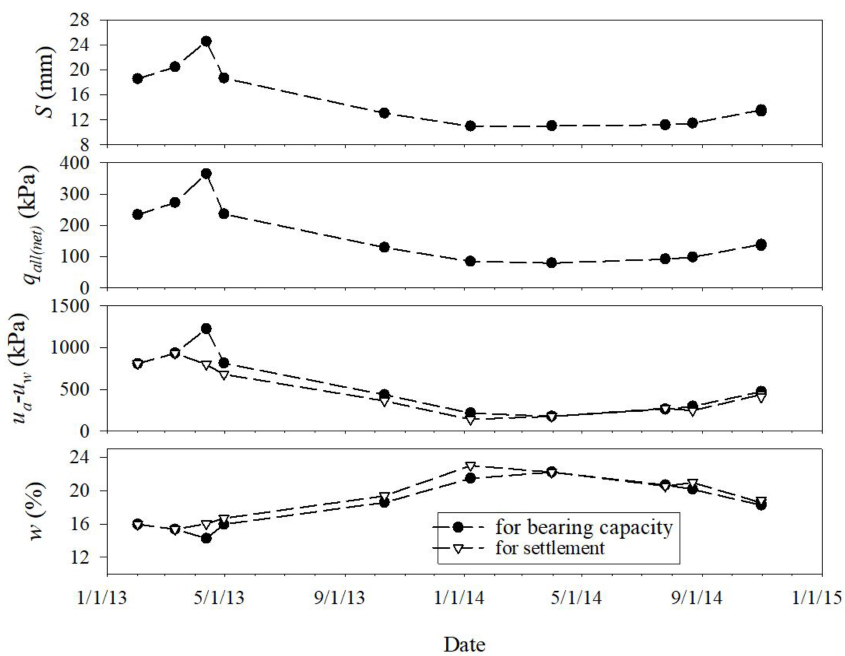

Figure 8. Predicted allowable bearing capacity and settlement in relation to variations in average moisture contents and matric suction within the zone of influence for bearing capacity and settlement during the testing period at North Base.

Figure 8 reveals that during the test period the predicted net allowable bearing pressure, assuming a factor of safety of three, varied between 80 and 366 kPa with corresponding settlement of 11 mm to 25 mm for the North Base site. For Goldsby in Figure 9, the predicted allowable bearing capacity and settlement ranged from 83 to 194 kPa and 10 to 18 mm, respectively. While the predicted range of settlements is not overly concerning, the change in allowable bearing capacity is alarming at both sites. Even though the modulus decreased with increasing moisture content, predicted settlements also decreased due to the decrease in allowable bearing pressures. The maximum predicted allowable bearing pressure corresponding to dry conditions at North Base is 4.6 time greater than the minimum obtained during wet conditions. This implies that the allowable bearing pressure for dry conditions is greater than the ultimate bearing pressure for wet conditions. Or in other words, the factor of safety can drop below one if the footing is designed for dry conditions. The results of these pressuremeter tests emphasize the need for caution when interpreting PMT results in partially saturated clays, particularly during a dry period.

4. Discussion

Results of in situ testing during dry and wet periods discussed in previous sections highlight the need to account for the influence of partial saturation on test parameters and resulting foundation analysis. To properly account for unsaturated soil mechanics in the analysis of foundation bearing capacity and settlement requires estimation of unsaturated soil parameters and soil water characteristic behavior. However, unsaturated soil mechanics in this regard has not yet been widely implemented in practice. Some advancements in the analysis of foundations on partially saturated soil have also been made as noted previously, but are not yet widely employed in practice. Furthermore, the state of knowledge regarding interpretation of in situ tests in unsaturated soils is still rather limited, in spite of some recent significant advancements in research (e.g. Mohamed & Vanapalli, 2015; Yang & Russell, 2015; Miller et al., 2018). Nevertheless, in situ tests are being conducted every day in unsaturated soil profiles and used in developing shallow foundation recommendations, especially the SPT. Practitioners need some interim, practical suggestions for addressing the impacts of partial saturation on their foundation recommendations, and other geotechnical problems where derived soil properties depend on in situ test results.

To assess the moisture conditions and potential impact on results of in situ tests in unsaturated soils, geotechnical engineers can employ a number of strategies. For example, the usual field and laboratory testing activities could be supplemented with the following:

1) Examining historical weather records for a site can help to determine whether the current conditions may be more dry or wet. Some states like Oklahoma also provide drought monitoring which contributes greatly to this assessment;
2) At a minimum, on the day of testing, collect frequent moisture content samples in the unsaturated zone, and if possible determine or estimate matric suction at the same depths. Matric suction can be estimated from the SWCC, which can also be estimated using the method of Zapata et al. (2000), for example;
3) If the soil is drier than the wettest condition expected for the site, which could be near saturation, the in situ test parameters corresponding to wet conditions could be estimated for use in geotechnical analysis. This step has a great deal of uncertainty associated with it because of the lack of published data and procedures needed to make such predictions. However, not considering the consequences of wetter conditions is not an acceptable alternative. For soil profiles that are somewhat uniform in character with depth, it is possible that plotting the moisture content, even from a single day, versus the test parameters or normalized test parameters obtained at different depths may provide some insight. Otherwise, published data such as the normalized pressuremeter data in Figures 6 and 7 could be used to gain some insight into expected changes in the test results due to wetter conditions. Similar plots are shown in Figures 10, 11, 12 and 13, for SPT and CPT parameters from the North Base and Goldsby test sites. While there is significant scatter in these plots, there are reasonable trends exhibited and in some cases coefficients of determination are significant.

Figures 10 and 11 present SPT data obtained on different dates at the North Base and Goldsby sites, respectively, and representing lean clay layers with different plasticity and sand content as indicated in Table 1. The data are limited but do show some fairly substantial trends with moisture content and estimated matric suction, most notably for the North Base site. In Figures 10 and 11, the field SPT N values are presented along with N values corrected to standard energy and overburden pressure denoted as $(N_1)_{60}$. For calculating $(N_1)_{60}$, a hammer efficiency of 80% was assumed for the automatic hammer, borehole correction factor was 1.0, sampler correction factor was 1.0, rod length factor was 0.95, and the correction for overburden pressure (C_N) was that of Liao & Whitman (1986), where $C_N = (1/\sigma_o)^{0.5}$. By correcting for overburden pressure the influence of net normal stress is to some extent accounted for, and use of $(N_1)_{60}$ makes the use of the correlations more universal.

In Figures 12 and 13, CPT q_c data are presented with respect to moisture content and estimated suction. Plots are shown with q_c and q_c normalized by vertical total stress. Expressions for q_c and normalized q_c are presented as a function of water content and matric suction. Significant trends are evident and can be exploited for estimating changes in q_c due to wetting. Additional data from the literature and a method for interpreting CPT q_c data from unsaturated soils are presented in the paper by Miller et al. (2018).

For the purpose of estimating bearing capacity and settlement of foundations based on properties derived from in situ tests in unsaturated soils, it would seem most logical to predict the test parameters at moisture contents corresponding to the wettest states, near saturation. Then these parameters could be used to predict the soil properties, bearing capacity and settlement using the equations presented previously (e.g. Equations 1-5). The correlation equations for clay soil properties, such as those for undrained strength, are likely most applicable to clayey soils in the saturated state where

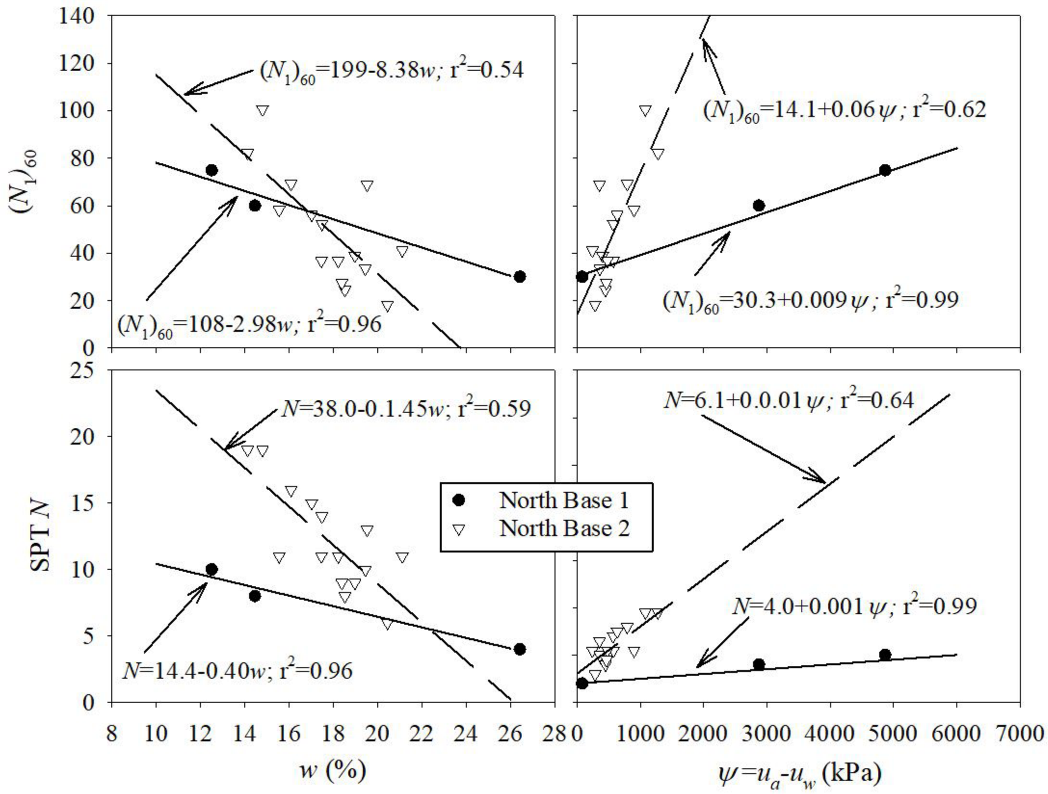

Figure 10. SPT N and $(N_1)_{60}$ versus water content and matric suction for North Base site.

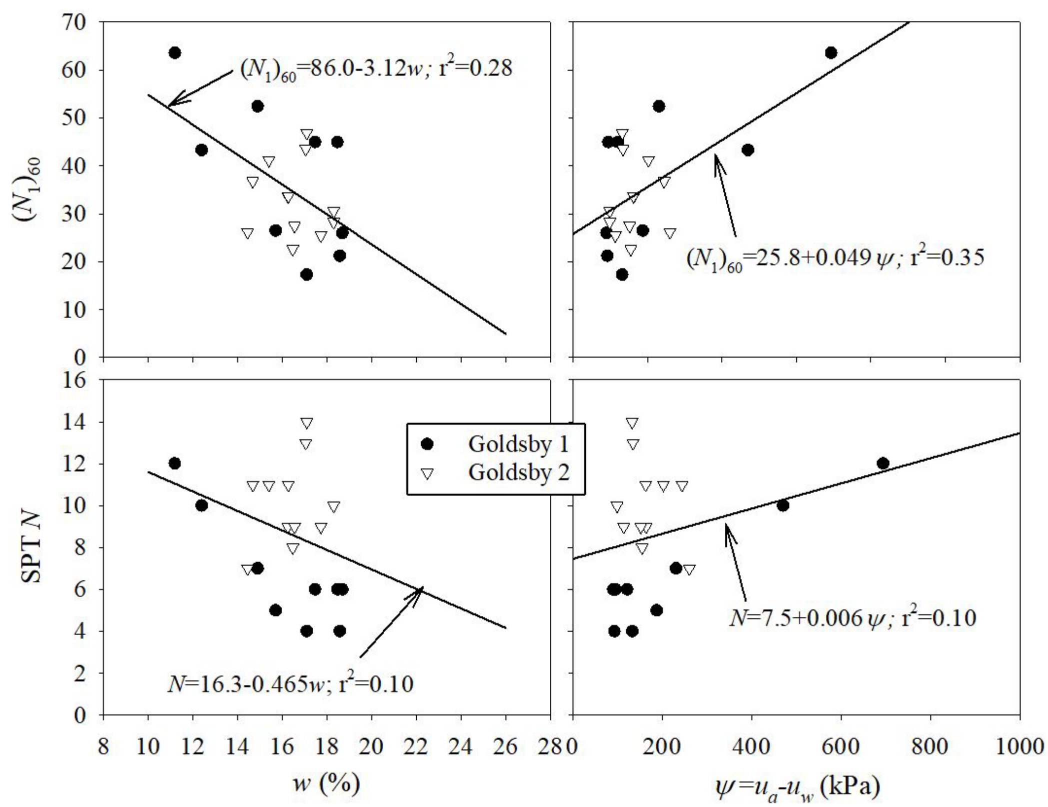

Figure 11. SPT N and $(N_1)_{60}$ versus water content and matric suction for Goldsby site.

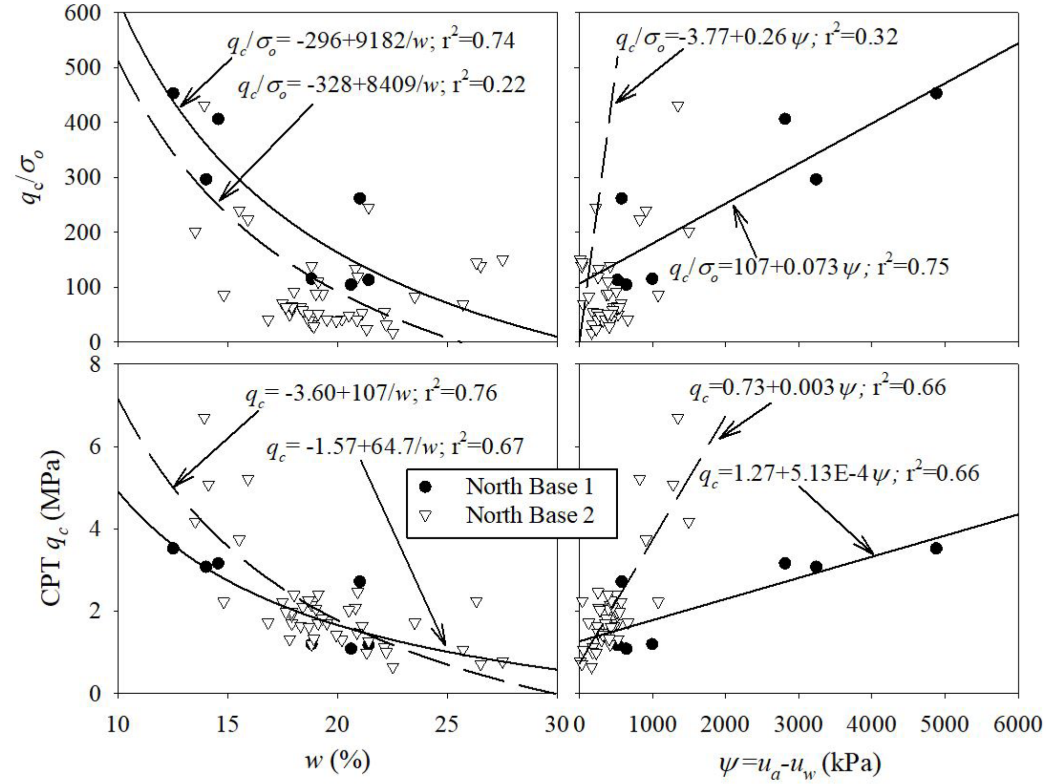

Figure 12. CPT q_c and q_c/σ_o versus water content and matric suction for North Base site.

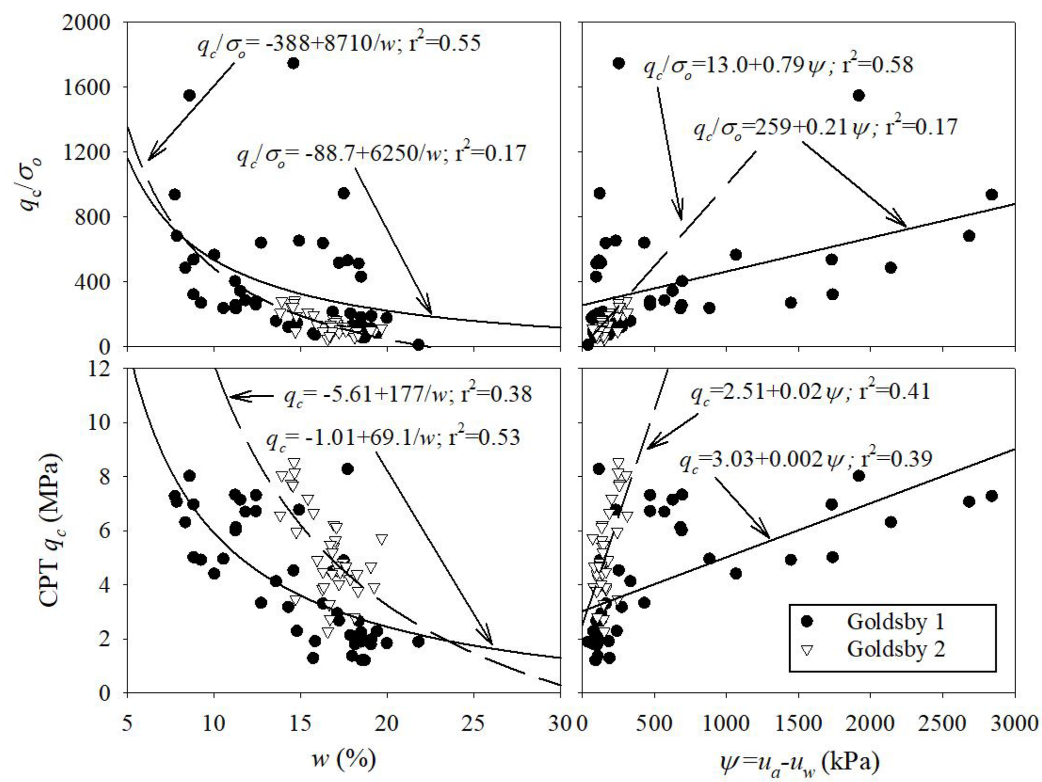

Figure 13. CPT q_c and q_c/σ_o versus water content and matric suction for Goldsby site.

undrained conditions may prevail during testing. For unsaturated states, the use of such correlations is questionable because of the likelihood of partial drainage during the tests. This is a topic in need of a great deal of additional research.

5. Conclusions

In situ tests were conducted at two clay test sites over a period of two years, encompassing dry and wet soil conditions. Companion moisture contents were obtained throughout the depth of testing on test dates and matric suction was estimated based on soil water characteristic curves. SPT N values and CPT q_c values corresponding to different moisture conditions were used to estimate undrained shear strength using empirical equations and bearing capacity of a footing was estimated using a total stress analysis. Pressuremeter limit pressures and moduli were determined from tests under different moisture conditions and also used to predict bearing capacity and settlement of a footing. The following conclusions are based on this work.

1) Substantial reductions in SPT N values and CPT q_c values occurred due to increases in moisture content. Values of SPT N and corrected $(N_1)_{60}$ plotted against moisture content and matric suction exhibit trends that can be exploited for predicting changes in these parameters. Similarly, values of q_c and normalized q_c plotted against moisture content and matric suction exhibited useful trends;
2) Undrained shear strengths calculated using empirical correlations for q_c and N values obtained on dry and wet days were substantially different. Corresponding allowable bearing capacities for wet days were substantially lower than for dry days;
3) Pressuremeter limit pressure was significantly affected by decreasing moisture contents. Significant trends were found between normalized limit pressure and moisture content and suction for the clayey soils tested. Pressuremeter moduli also exhibited decreasing trends with increasing moisture, but exhibited more scatter and appeared less sensitive to moisture changes compared to limit pressures. Predicted allowable bearing capacity based on the pressuremeter limit pressure for wet conditions was significantly lower compared to dry conditions. Predicted settlements were less concerning and more sensitive to the decrease in applied allowable bearing pressure than the change in modulus due to increased moisture content.

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Declaration of interest

There were no competing interests or conflicts of interest associated with the conduct of this research or the development of this paper.

Authors' contributions

Gerald A. Miller: conceptualization (equal), funding acquisition, formal analysis (equal), supervision (lead), writing-original draft. Rodney W. Collins: conceptualization (equal), formal analysis (equal), investigation, data curation, writing-review and editing (equal). Kanthasamy K. Muraleetharan: supervision (supporting), writing-review and editing (equal). Tareq Z. Abuawad: writing-review and editing (equal).

List of symbols

q_u	ultimate bearing pressure of a square footing
c	cohesion term in ultimate bearing pressure equation
N_c, N_q, N_γ	bearing capacity factors dependent on the friction angle, ϕ
ϕ	friction angle of soil
γ_1 and γ_2	the soil unit weight above and below the bearing level, respectively
D_f	depth to bearing level
B	footing width
c_u	undrained shear strength
ϕ_t	total stress friction angle
ϕ'	effective stress friction angle
N	field value of penetration resistance from the Standard Penetration Test (SPT)
q_c	tip resistance from the Cone Penetration Test (CPT)
f_s	skin friction from the CPT
σ_o	in situ vertical total stress
N_k	empirical parameter for estimating c_u from the Cone Penetration Test
k	a bearing capacity factor,
p^*_{Le}	geometric mean of net limit pressure from the Pressuremeter Test (PMT)
p_L	limit pressure from the PMT
γ	total unit weight above the bearing level
S	settlement predicted using elastic modulus obtained from the PMT
E_p	elastic modulus obtained from PMT results
E_d	PMT modulus within a zone of about 8B thick below the footing
E_c	PMT modulus within a zone of about B/2 thick below the footing

q_{net} net bearing pressure below a footing
B_o reference footing width equal to 60 cm
α rheological factor
λ_d shape factor for the deviatoric term
λ_c shape factor for the spherical term
C constant for predicting settlement of a square footing from PMT results
LL liquid limit
PI plasticity index
$\%F$ percent of fines by weight
$\%S$ percent of sand by weight
w soil gravimetric water content
ψ u_a-u_w=soil matric suction
FS factor of safety for bearing capacity
r^2 coefficient of determination
$(N_1)_{60}$ SPT N corrected to standard energy and effective overburden pressure
C_N correction factor accounting for overburden pressure

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