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Estimation of Bearing Capacity of Saturated and Unsaturated Sands from the SPT and CPT Correlations

*Fathi M. O. Mohamed[1)] and Sai K. Vanapalli[2)]

[1), 2)] *Department of Civil Engineering, University of Ottawa, K2C 3N5, Ottawa, ON, Canada*
[1)] fmoha035@uottawa.ca

ABSTRACT

The in-situ bearing capacity of sandy soils is conventionally determined or estimated using the plate load tests (PLTs), cone penetration tests (CPTs) or standard penetration tests (SPTs). The contribution of matric suction towards the bearing capacity of unsaturated sands is, however, not estimated from these tests. In this paper, several SPTs and PLTs were conducted on sand in Ottawa, Canada under saturated and unsaturated conditions to demonstrate the contribution of matric suction on the bearing capacity results. In addition, relationships have been proposed to estimate the bearing capacity of sands under both saturated and unsaturated conditions from the SPT and CPT results. Comparisons are provided between the measured and estimated bearing capacity values for three different sands using the PLTs, footing load tests (FLTs), CPTs and SPTs data from the literature using the proposed relationships. The results of the studies suggest that the proposed simple relationships are reliable and can be used in the estimation of the bearing capacity of both saturated and unsaturated sands.

1. INTRODUCTION

The bearing capacity is one of the key parameters required in the design of shallow foundations in sandy soils. The plate load tests (PLTs); standard penetration tests (SPTs) and cone penetration tests (CPTs) are used in geotechnical engineering practice for the determination or estimation of the bearing capacity of soils. The SPTs are more widely used in comparison to other methods to estimate the shear strength, settlement and also the bearing capacity of sands. There are several well-established SPT-based design techniques available in the literature for estimating the bearing capacity of shallow foundations in sands (Meyerhof 1956, Burland and Burbidge 1985 and Bowles 1996). However, the influence of capillary stresses (i.e., matric suction) above the ground water table (GWT) is typically ignored in the estimation of the bearing capacity of sands in conventional engineering practice. Ignoring the contribution of matric suction towards the bearing capacity leads to conservative shallow footing designs in sands, particularly in semi-arid and arid regions, where the natural GWT is

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[1)] PhD candidate
[2)] Professor & Chair

typically at a greater depth. Steensen-Bach et al. (1987) commented that ignoring the influence of capillary stresses in the bearing capacity of unsaturated sands would be equivalent to disregarding the influence of reinforcement in the design of reinforced concrete.

In the present study, in-situ PLTs and SPTs were conducted in sand under both saturated (i.e., matric suction, $(u_a - u_w) = 0$ kPa) and unsaturated (i.e., $(u_a - u_w) > 0$ kPa) conditions in Ottawa, Canada to highlight the differences in the bearing capacity results and the N_{SPT} values. The bearing capacity of the sand at a matric suction value of 8 kPa was approximately 3.5 times greater in comparison to saturated conditions. The N_{SPT} values from the SPTs conducted in unsaturated condition (with no rain for 3 continuous days in May 2012) was 3 times higher than the N_{SPT} values obtained from the SPT conducted in saturated condition at the same site. Simple relationships are suggested to estimate the bearing capacity of sands under both saturated and unsaturated conditions from the conventional SPT and CPT results.

The simple methodology presented in this paper should encourage the geotechnical engineers to consider the influence of matric suction in the design of shallow foundations for sands and use them in practice, particularly in arid and semi-arid regions where the sands are typically in a state of unsaturated condition.

2. BACKGROUND

The bearing capacity of shallow foundations has received the attention of several investigators over the last century. Prandtl (1921) was one of the earliest investigators who studied the bearing capacity of soils by loading a strip footing until it penetrated into the soil. The applied stress at which stability failure occurs was defined as the ultimate bearing capacity of the soil. Several techniques and empirical procedures that followed Prandtl's research were valuable to provide a comprehensive understanding of the bearing capacity of soils (Terzaghi 1943, Terzaghi and Peck 1948, Meyerhof 1951, Meyerhof 1956, Lawrence 1968, Vesić 1973, and Bolton and Lau 1993). These studies were useful in the estimation of the bearing capacity based on the saturated shear strength parameters of the soil, dimensions of the footing and its shape, depth and inclination factors and the ground water table depth.

The in-situ bearing capacity of soils can be reliably determined using the PLT results; however, they are difficult, time consuming and expensive. A number of studies are reported in the literature for evaluating the bearing capacity of soils from the CPTs results using empirical equations (for example, Meyerhof 1956, Robertson et al. 1983, Eslaamizaad and Robertson 1996, Lee and Salgado 2006, Eslami and Gholami 2006, CFEM 2006). Samples cannot be collected from CPTs along the depth of penetration for visual examination of the soil. This limitation makes it difficult in some scenarios to reliably interpret the variation of bearing capacity with respect to depth. The CPTs are more commonly used for estimating the bearing capacity of fine-grained soils.

Several SPT-based methods can be used to estimate the variation of bearing capacity with respect to depth (Meyerhof 1956, Burland and Burbidge 1985, Bowles 1996). Some investigators highlighted the possible uncertainties associated with the N_{SPT} values obtained from the SPTs as they are operator dependent (Seed et al. 1985). The reliability of interpreting the bearing capacity of sandy soils from in-situ SPTs has significantly increased over a period of time due to the developments in the SPT equipment and the standards used in conducting them (Mitchell, 2000). The SPTs can be performed quickly and are economical in comparison to other field or laboratory tests. ASTM D6066-96 provides details of the SPT that can be followed for sandy soils. These procedures are widely used in practice in many regions of the world.

The SPT results are dependent on the water content (i.e., degree of saturation or capillary stresses) of sandy soils. Extending the relationships of SPTs, which are linked to saturated soil properties such as the shear strength parameters, may not be reliable when they are used for unsaturated sandy soils. The bearing capacity of sands is significantly influenced by capillary stresses or matric suction within the unsaturated zone above the GWT. Terzaghi (1943) studies show that the bearing capacity of a footing on sand below the ground water table is about one-half to that of dry sand. More recent experimental studies show that even low matric suction values of 2 to 6 kPa can increase the bearing capacity of sands by 4 to 6 times in comparison to saturated conditions (Mohamed and Vanapalli 2006). Vanapalli and Mohamed (2007) proposed a semi-empirical relationship that can be used to estimate the variation of bearing capacity of sands with respect to matric suction using model footing tests. The shear strength parameters (c' and ϕ') and the soil-water characteristic curve (SWCC) are required for estimating the bearing capacity of a sandy soil. These studies were valuable to better understand the bearing capacity of unsaturated soils.

Meyerhof (1956) stated more than five decades ago that there were limited studies reported in the literature with respect to the bearing capacity of unsaturated coarse-grained soils from field studies. This statement is still valid to-date as there are only few field studies to understand the influence of matric suction on the bearing capacity of unsaturated soils based on the PLTs, CPTs and SPTs (for example, Gidden and Briaud 1994, Schnaid et al. 1995, Costa et al. 2003, Rojas et al. 2007).

There is a need to conduct more field studies to better understand the behavior of foundations in sands both in saturated and unsaturated conditions. Based on such studies, empirical relationships can be developed and used in the design of foundations.

3. DETAILS OF THE TEST SITE AND SOIL PROPERTIES

3.1. Description of the test site

The test site is located at Carp Region in Ottawa, Ontario, Canada as shown in the map in Fig. 1.

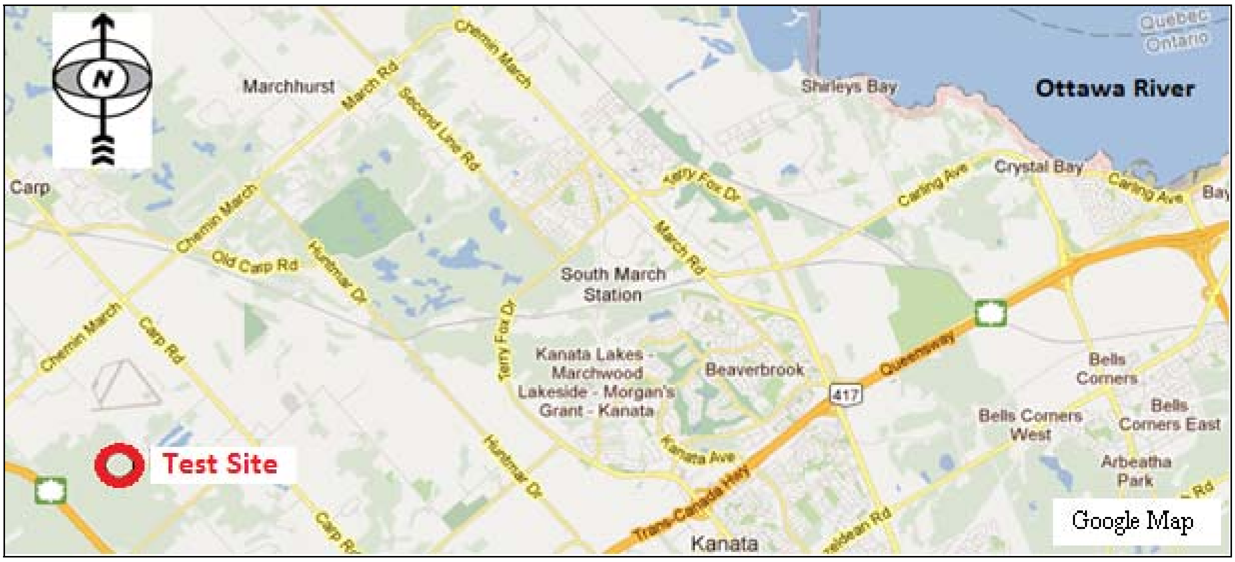

Fig. 1. Location of the test site, Carp Region of Ottawa in Canada.

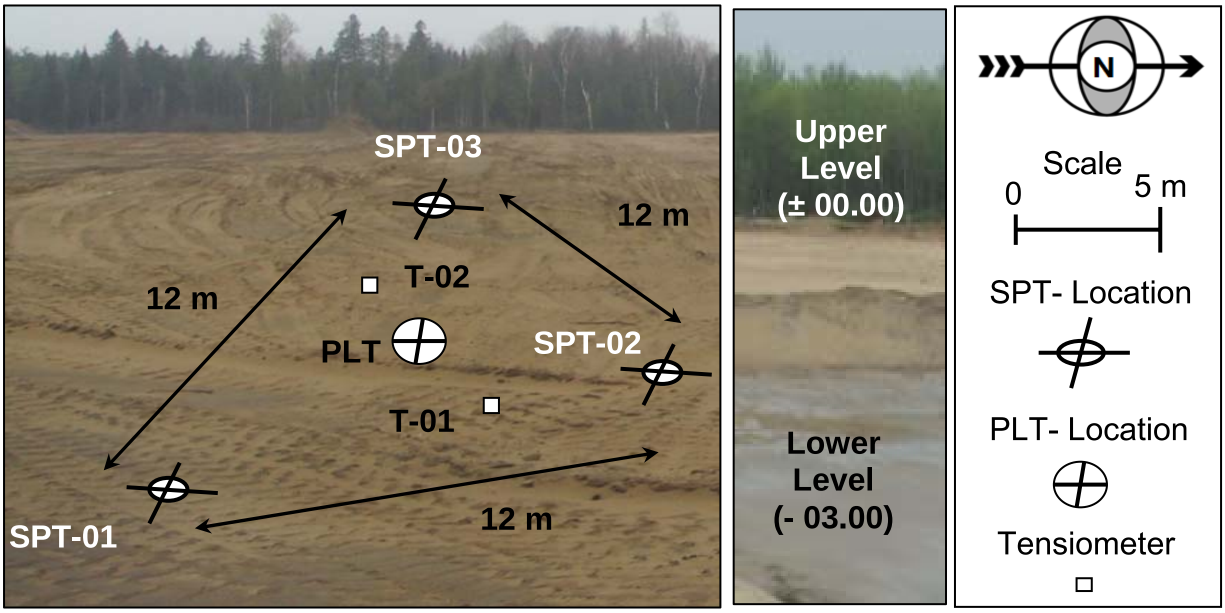

Fig. 2. Location of the SPTs, PLTs and tensiometers on the test site.

The water table level is at - 2.8 m below the natural ground level. The site has a sloping terrain as shown in Fig. 3 with two different levels which are referred to hereafter as the upper level (± 0.0 m) and the lower level (- 2.4 m) in the remainder of the paper (refer to Fig. 3).

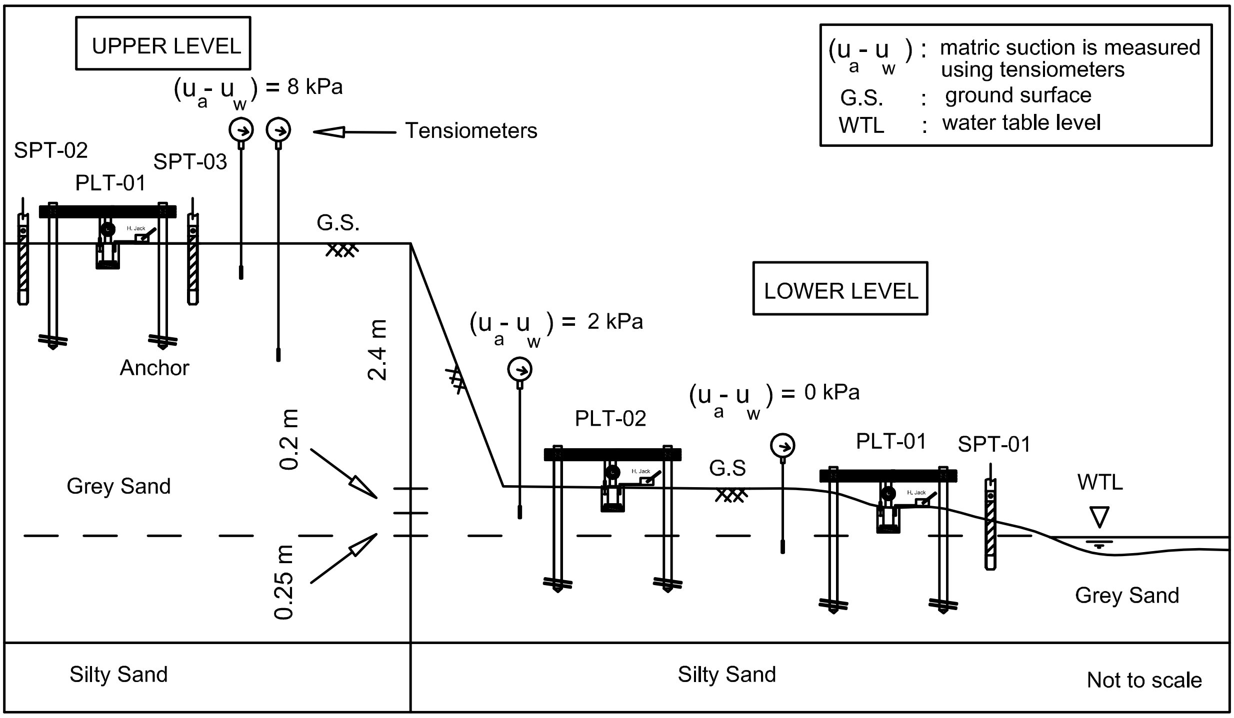

Fig. 3. Sectional view of the test site with details of SPTs and PLTs locations.

3.2. Properties of the tested soil

Samples were collected at locations close to where the SPTs and PLTs were conducted to determine the soil properties. Grey sandy soil with some dark silt (i.e., known locally as septic sand) was available for a depth of 4.7 m below the ground surface (from the upper level). Dark-grey silty sand was located underneath the septic sand. The soil can be classified as poorly-graded sand, SP according to the USCS. The bulk density and the specific gravity of the sand were equal to 17.5 kN/m^3 and 2.65, respectively. The angle of internal friction, ϕ' was estimated using Hatanaka and Uchida (1996) equation as a function of the N_{SPT}-values of the SPTs was estimated to be 40°. The SPTs were conducted at regular intervals up to a depth of 3.5 m below the ground surface.

4. IN-SITU STANDARD PENETRATION TESTS (SPTs)

4.1. Equipment details

The SPTs were conducted at the test location under both saturated and unsaturated conditions following the ASTM D1586-11. The SPT equipment used in this research program is shown in Fig. 4 (a). A hammer (of weight 623 N) was used to drive the sampler vertically. The SPTs were conducted up to a depth - 3.5 m from the natural ground surface. The split-spoon sampler (with an inside and outside diameter of 34.93 mm and 50.8 mm, respectively) with a spring core catcher was used for collecting soil samples. After the split-spoon sampler was withdrawn, the soil sample from within was removed, stored in labeled zipped plastic bags and used for determining the water content, grain-size distribution, specific gravity and soil classification from laboratory tests.

4.2. Summary of SPT and matric suction measurement results

SPT-01 was conducted at the lower level which is close to natural ground water table (at the water basin; see the lower level in Fig. 2). This test can be assumed to be conducted in a state of saturated condition in the field. Three other SPTs (i.e., SPT-02, SPT-03, SPT-04) were conducted at the upper level in a triangular grid separated by approximately 12 m spacing as shown in the upper level in Fig. 2. The three PLTs (using a 0.2 m × 0.2 m steel plate) were performed under both saturated and unsaturated conditions. Soil samples were collected to determine the variation of water content with respect to depth.

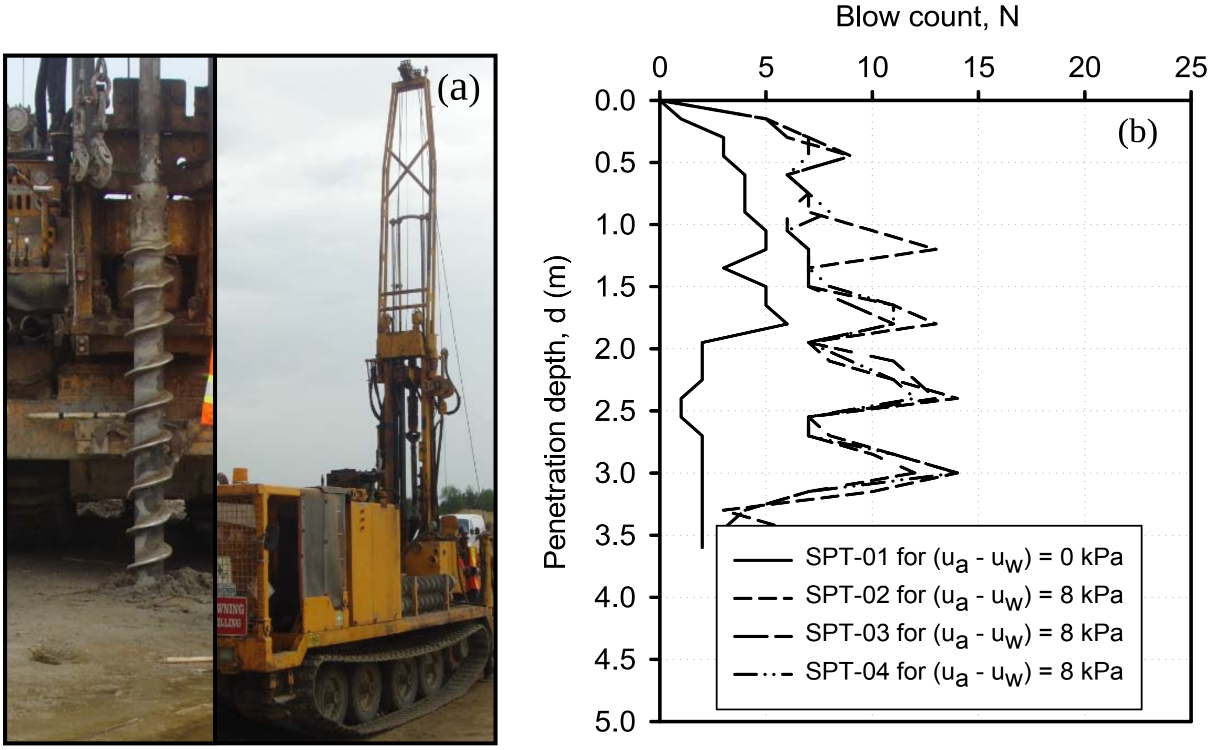

Fig. 4. (a) SPT equipment; (b) Variation of blow count, N_{SPT} versus depth for the sand tested under saturated and unsaturated conditions.

The SPT tests were performed using a Falling Model truck mounted with a rotary drilling rig following the procedures summarized in ASTM D1586-11. The length of each of the drill rods (i.e., standard *N* rods) is 3.0 m with 1.5 m length extension rods that were used as needed. The blow counts over 450 mm of penetration were recorded in three intervals (e.g., 150 mm per interval). The N_{SPT}-value is noted as the summation of the blows for the last two 150 mm penetrations. Briaud and Gibbens (1994) measured the SPT/W energy in sandy soil using a pair of Piezoresistive Accelerometers and foil resistive strain gauges. They reported that the blow counts were measured with an energy efficiency averaging 53%. In the present study, SPT/W energy was not estimated; however, an energy efficiency of 60% as recommended by Das (2007) was used in the present study.

The SPT results are summarized in Fig. 4(b). SPT-01 results summarize the blow counts of N_{SPT} with respect depth conducted at the site under saturated condition (i.e., at the lower level of the site as illustrated in Fig. 2). The other three (i.e., SPT-02, SPT-03 and SPT-04) tests also show the blow counts of N_{SPT} with depth for unsaturated sand at the upper level of the site (see Fig. 2). There is a significant increase in N_{SPT} values due to the contribution of matric suction in unsaturated sand.

Two tensiometers (i.e., referred to as T-01 and T-02; see Fig. 2 and Fig. 3) were embedded at different locations in the upper level of the site and depths close to the PLT of 0.15 m and 1.2 m respectively. The in-situ matric suction was measured using tensiometers while the SPTs and PLTs were being conducted. Two more tensiometers installed in the lower level (see Fig. 3).

5. IN-SITU PLATE LOAD TESTS (PLTs)

The results of the average matric suction values measured in the vicinity of the stress bulb zone (i.e., influence zone) which is equal to depth 1.5B (i.e. 1.5 times the width of the plate used for testing) are summarized in Table 1.

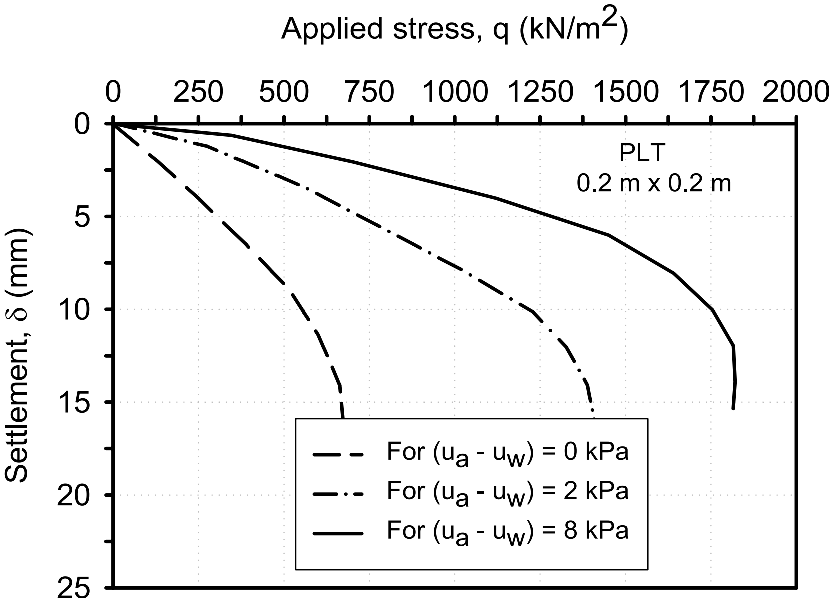

Fig. 5. The relationship between the applied stress and the settlement of 0.2 m × 0.2 m square plate.

The influence zone is the depth in which stresses are predominant for shallow square footings (Poulos and Davis 1974, Chen 1999). The relationship between the applied stress and the settlement of the in-situ PLTs conducted in this research program is shown in Fig. 5. These relationships demonstrate that there is a significant increase in the applied stress (i.e., bearing capacity) of the PLTs due to the contribution of the matric suction in the tested sand. The matric suction values were measured at half-way of the depth of the stress bulb zone (i.e., 1.5B) using four tensiometers.

Terzaghi and Peck (1948) proposed a relationship for estimating the settlement of a footing from PLTs using a plate of dimensions 0.3 m × 0.3 m as given below:

$$\delta_{B_1} = \delta_{B_2} \left[\frac{B_1 (B_2 + 0.3)}{B_2 (B_1 + 0.3)} \right]^2 \qquad (1)$$

where: δ_{B1} is the settlement of a footing with width B_1; δ_{B2} is the settlement of a footing with width B_2.

Terzaghi and Peck (1948) suggested the permissible settlement for large footing sizes of 2.0 m width as 25.4 mm (i.e., 1 inch). Several foundation codes from various regions of the world recommend a permissible settlement value for shallow foundations in coarse grained soils as 25 mm. However, lower values of settlement values are also used by investigators for estimating the allowable bearing capacity for smaller size footings. Nabil (1985) carried out PLTs (using plate size of 0.5 m × 0.5 m) and estimated the allowable bearing capacity as a value occurring at a settlement of 13 mm. The allowable bearing capacity in the present study was estimated for the tested sand under saturated and unsaturated conditions at a settlement value of 6 mm from the PLTs conducted on 0.2 m × 0.2 m plate. Estimated values of the bearing capacity using the proposed relationships are compared with the allowable bearing capacity values.

6. RELATIONSHIPS USING THE SPTs AND CPTs FOR THE ESTIMATION OF q_{all}

Meyerhof (1956) investigated the relationship between *N* value and static cone resistance q_c for fine and silty sands and suggested that:

$$q_c = 4.4\, N \qquad (2)$$

where: q_c is the cone resistance in kN/m^2 and *N* is the blow count.

Schmertmman (1970) suggested another relationship between the cone resistance of the CPT and the *N*-value from SPTs based on the results of several fine to medium sands and silty sands. Several other researchers also proposed different relationships to correlate the SPTs results to cone resistance, q_c values (De Alencar Velloso 1959, Meigh and Nixon 1961, Robertson et al. 1983, Danziger and de Valleso 1998). More recently, Kara and Gündüz (2010) proposed a simple relationship between the *N*-value from SPTs and the cone resistance, q_c to be used for determining the bearing capacity of sand as in Eq. 3.

$$q_c = 0.533\, N^{0.8019} \tag{3}$$

where: q_c is in MPa and N is the corrected blow count ($(N_1)_{60}$).

6.1 Proposed relationships

Mohamed et al. (2010) proposed relationships to estimate the bearing capacity of both saturated and unsaturated sands. Two equations were proposed based on the CPTs results to estimate the bearing capacity of shallow foundations of surface footings placed on saturated and unsaturated homogenous sand respectively. Eq. (4) was suggested to estimate the ultimate bearing capacity for saturated sands (i.e., $(u_a - u_w) = 0$ kPa) from CPT results:

$$q_{ult\ (sat)} = \Theta(q_{c\ sat}) \tag{4}$$

where: q_{ult} (sat) = ultimate bearing capacity for saturated homogenous sand, $\Theta = 0.15/B^{0.63}$ (i.e., correlation factor), $q_{c\ sat}$ = average cone resistance under saturated sand condition (e.g., within influence zone, IZ equal to 1.5B from the footing base level as illustrated in Fig. 6) and B = footing width.

Eq. (4) is suggested to estimate the ultimate bearing capacity for unsaturated sands (i.e. $(u_a - u_w) > 0$ kPa):

$$q_{ult\ (unsat)} = \Omega(q_{c\ unsat}) \tag{5}$$

where: $q_{ult\ (unsat)}$ = ultimate bearing capacity for unsaturated homogenous sand, $\Omega = 0.19/B^{0.68}$ (i.e., correlation factor), $q_{c\ unsat}$ = average cone resistance under unsaturated conditions (e.g., within influence zone, IZ equal to 1.5B from the footing base level), B = footing width.

Table 1. Summary of the estimated allowable bearing capacity using the SPTs and measured allowable bearing capacity (at settlement, δ = 6 mm) from PLTs data of the research program conducted on sand in Carp, Ottawa, Canada.

Sand condition	Saturated $(u_a - u_w) = 0$ kPa	Unsaturated $(u_a - u_w) = 2$ kPa	Unsaturated $(u_a - u_w) = 8$ kPa
Plate width, B (m)	0.2	0.2	0.2
[1]Corrected N_{SPT}-value	3	5	8
[2]q_c (kN/m^2)	825	1711	2528
[3]q_{all} (kN/m^2) (estimated)	341	971	1435
[4]q_{all} (kN/m^2) (measured)	357	834	1498
Estimated/Measured	0.96	1.16	0.96

[1]Average corrected N_{SPT}-value (i.e., N_{60}) in the influence zone of 1.5B; [2]Cone resistance; [3]Estimated allowable bearing capacity using the proposed relationships; [4]Measured bearing capacity from PLTs.

The two correlation factors, Θ and Ω presented in Eq. (4) and Eq. (5) respectively were derived from regression analysis of the experimental results obtained from model PLTs and CPTs for sand under saturated and unsaturated sand conditions (Mohamed et al., 2010). Table 1 summarizes the results of the estimated bearing capacity values taking into account of the corrected N_{SPT}-value (i.e., N_{60} instead of $(N_1)_{60}$) that was proposed by Kara and Gündüz (2010) and using the modified Eq. (3) (i.e., $q_c = 0.533\,N^{0.8}$) in combination with Eq. (4) and Eq. (5) for sands in saturated and unsaturated conditions, respectively. Cone resistance, q_c values and the ratios between the estimated and the measured allowable bearing capacity values for the tested sand were in the range of 96 to 116 %.

Empirical relationships Eq. (6) and Eq. (7) are derived based on the analyses of the obtained results from the present research program. These relationships can be used to estimate the allowable bearing capacity of shallow foundations in saturated and unsaturated sands. Fig. (7) provides the measured and estimated allowable bearing capacity values of the tested sand in both saturated and unsaturated conditions.

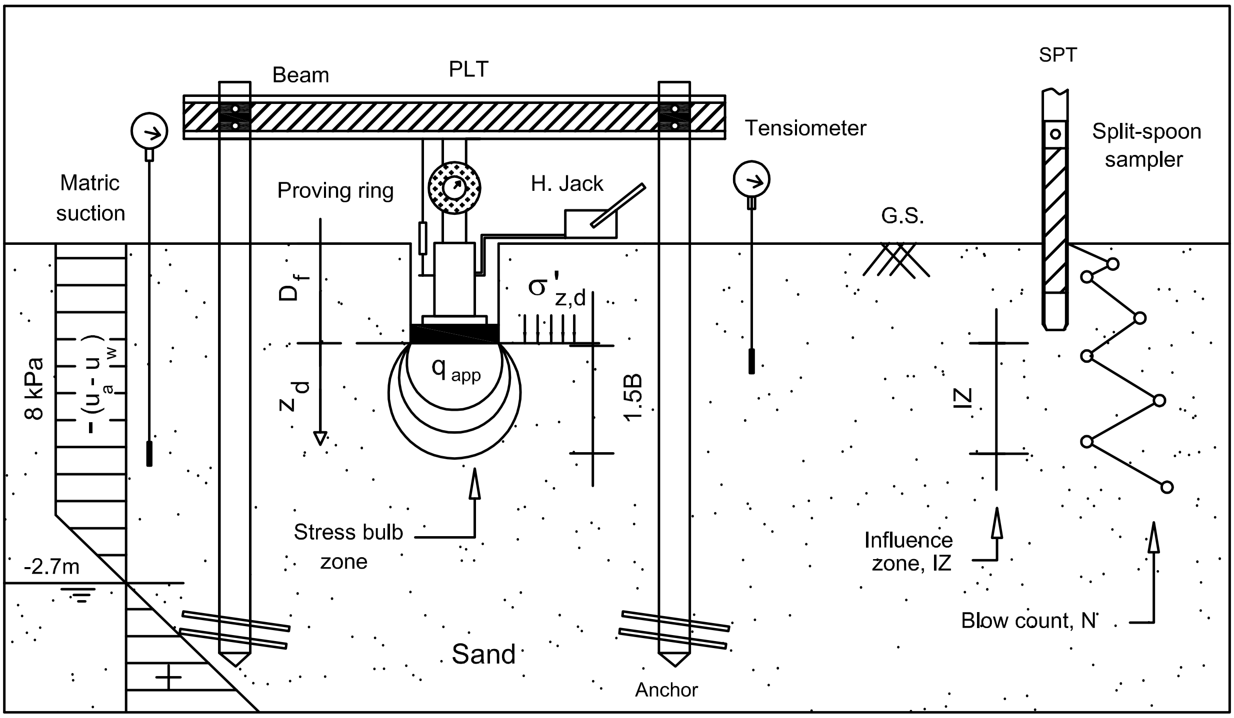

Fig. 6. Schematic showing details of the in-situ PLT and the influence zone, IZ (for the upper level where SPTs and PLTs were conducted in unsaturated sand).

$$q_{all\ (sat.)} = \frac{0.15}{B^{0.63}}\left[\,0.37(N_{SPT\,(sat.)})^{0.73}\right] \times 1000 \qquad (6)$$

$$q_{all\ (unsat.)} = \frac{0.19}{B^{0.68}}\left[0.45\ (N_{SPT(unsat.)})^{0.83}\right] \times 1000 \quad (7)$$

where:
q_{all} = allowable bearing capacity, kN/m^2; B = Footing width, m; N_{SPT} = AVR corrected N_{SPT}-value in the influence zone (i.e., N_{60})

The N_{SPT}-values from Fig. 4 (b) were corrected for the blow count values within the stress bulb zone depth of 1.5B from the base of footing base and used in the analyses of the data.

Details of in-situ footing load tests, FLTs results along with the SPTs published by Briaud and Giddens (1994) and Nabil (1985) are summarized and presented in the next section. These in-situ results (from Briaud and Giddens 1994, and Nabil 1985) are used to check the validity of the proposed procedure (based on SPTs) for estimating the allowable bearing capacity values of other saturated and unsaturated sands.

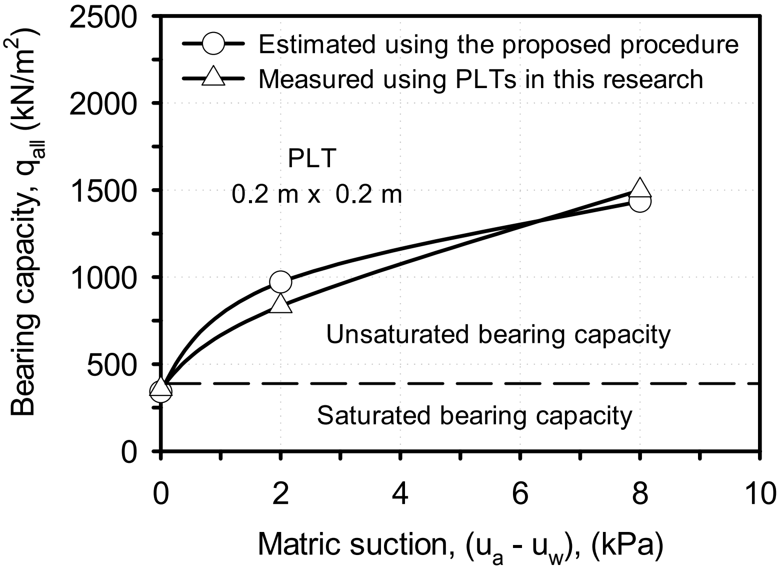

Fig. 7. Comparison between the estimated and the measured bearing capacity values using 0.2 m × 0.2 m square plate.

7. VALIDATION OF THE PROPOSED METHOD

Four large-scale footing load tests (FLTs) results (in a sandy soil with some silt) conducted in-situ by Giddens and Briaud (1994) were used to validate the proposed technique in the present study. The footings were loaded in sand at the Texas A&M University National Geotechnical Experimentation site (i.e., data summarized in Table 2). In addition to these tests, two more footing load tests, FLTs results (performed in a sandy soil at different locations in Kuwait) reported by Nabil (1985) are also analyzed in this study (refer to Table 3).

The average matric suction value for the sand at the Texas site was determined assuming constant matric suction distribution as water content throughout the depth of 4.9 m was the same. The grain size distribution of the sand at Texas site was found to be similar to that of the Sollerod Sand tested by Steensen-Bach et al. (1987). The matric suction value of 10 kPa corresponds to the gravimetric water content value of 5% from the soil water characteristic curve (SWCC) of the Sollerod sand. Therefore, the matric suction value of the Texas site was estimated as 10 kPa and used in the present study.

Table 2. Typical results of the estimated allowable bearing capacity using SPTs and measured allowable bearing capacity of FLTs at a settlement, δ of 25 mm conducted on sand in Texas, USA (from Briaud and Giddens, 1994).

Sand condition	Unsaturated $(u_a - u_w)$ = ~10 kPa	Unsaturated $(u_a - u_w)$ = ~10 kPa	Unsaturated $(u_a - u_w)$ = ~10 kPa	Unsaturated $(u_a - u_w)$ = ~10 kPa
Footing width, B (m)	1.0	1.5	2.5	3.0
[1]Corrected N_{SPT}-value	18	14	18	21
[2]q_c (kN/m^2)	4955	4022	4955	5632
[3]q_{all} (kN/m^2) (estimated)	941	580	504	506
[4]q_{all} (kN/m^2) (measured)	1000	800	630	600
Estimated/Measured	0.94	0.73	0.80	0.84

[1]Average corrected N_{SPT}-value (i.e., N_{60}) in the influence zone of 1.5B; [2]Cone resistance; [3]Estimated allowable bearing capacity using the proposed relationships; [4]Measured bearing allowable capacity from FLTs.

Table 3. Typical results of the estimated allowable bearing capacity using SPTs and measured allowable bearing capacity of FLTs at a settlement, δ of 25 mm from Nabil (1985) conducted on sand in Kuwait.

Sand condition	Unsaturated $(u_a - u_w)$ = ~7 kPa	Unsaturated $(u_a - u_w)$ = ~8 kPa	Unsaturated $(u_a - u_w)$ = ~9 kPa	Unsaturated $(u_a - u_w)$ = ~9 kPa
Plate width, B (m)	0.5	0.5	0.5	1.0
[1]Corrected N_{SPT}-value	7.5	7.5	15	15
[2]q_c (kN/m^2)	2396	2396	4259	4259
[3]q_{all} (kN/m^2) (estimated)	729	729	1296	809
[4]q_{all} (kN/m^2) (measured)	900	800	1200	1100
Estimated/Measured	0.81	0.91	1.08	0.74

[1]Average corrected N_{SPT}-value (i.e., N_{60}) in the influence zone of 1.5B; [2]Cone resistance; [3]Estimated allowable bearing capacity using the proposed relationships; [4]Measured bearing allowable capacity from PLTs.

The groundwater table level at the Kuwait site varied from 2 to 10 m depth depending on the location of the PLT; however the gravimetric water content values reported in the narrow range of 3 to 6%. The matric suction values for these water contents were approximately in the range 7 to 10 kPa. It can be observed that the average N_{SPT}-value required for the proposed technique is a function of the width, B of the footing. The larger the footing width, B the larger would be the influence zone, IZ (see Fig. 6). This relationship leads to the elimination of the scale effect in the estimated allowable bearing capacity values. Table 2 and Table 3 summarize the corrected N_{SPT}-values (i.e., N_{60}), the cone resistance, q_c and the estimated as well as the measured allowable bearing capacity values for Texas and Kuwait sites respectively.

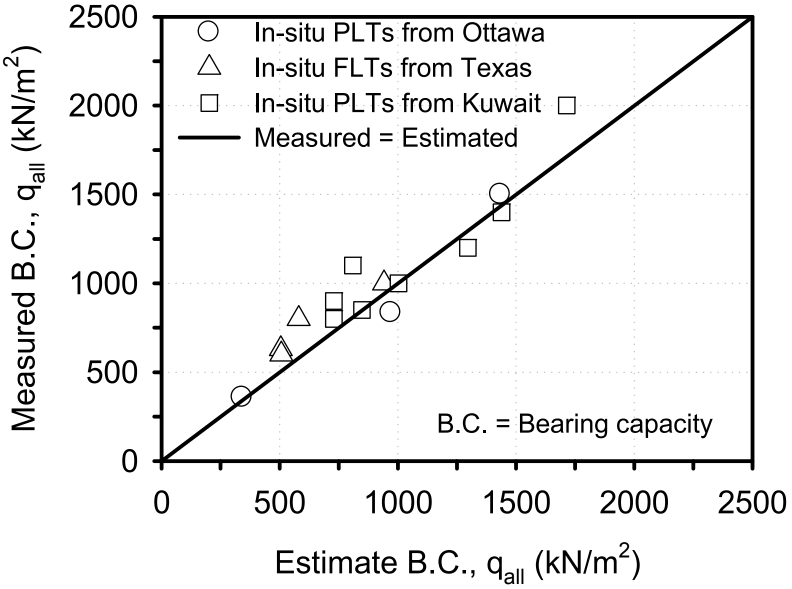

Fig. 8. Comparison between the estimated and the measured allowable bearing capacity values in both saturated and unsaturated sands for seven different footings.

Comparisons are provided in Fig. 8 between the estimated allowable bearing capacity values using the proposed procedure and the measured allowable bearing capacity values for seven different footings (as summarized in Table 1, Table 2 and Table 3) in sandy soils under both saturated and unsaturated conditions.

8. DISCUSSION OF RESULTS

The modified Eq. (3) provides good comparisons between the estimated cone resistance, q_c values and the measured values as presented in Table 2 and Table 3. The ratio between the estimated and measured bearing capacity of the six different footings at different sites is 92%. In some cases, the estimated bearing capacity values are slightly lower than the measured bearing capacity values. However, all results are within acceptable errors from engineering practice point of view.

The contribution of matric suction to the bearing capacity of the tested sand can be clearly seen in Fig. 7. The bearing capacity obtained in-situ from PLTs of 0.2 m × 0.2 m (i.e., conducted for this research) increased linearly in the low matric suction range. The rate of increase is non-linear for matric suction values greater than 2.5 kPa (which is approximately the value of the air-entry value of the sand). This observation is consistent with the behaviour of unsaturated sands as well as the conclusions drawn by Vanapalli et al. (1996) with respect to the shear strength behavior of unsaturated soils. Surface and embedded model footings of 0.1 m × 0.1 m and 0.15 m × 0.15 m tested by Mohamed and Vanapalli (2006) in saturated and unsaturated compacted sand in a controlled laboratory environment have shown similar trends in the bearing capacity behavior.

Fig. 8 provides comparisons between the estimated allowable bearing capacity from the proposed procedure and the measured values from in-situ PLTs and FLTs tested using Eq. (6) for saturated sands and Eq. (7) for unsaturated sand conditions. These two empirical equations are function of the footing, B and the average corrected N_{SPT}-value (i.e., N_{60}) in the influence zone of 1.5B from the footing base level. It is observed that the larger the width, B the larger would be the influence zone, IZ which leads to the elimination of the scale effect on the estimated bearing capacity values. The results (i.e., plotted in Fig. 8) show reasonably good comparison between the estimated and measured allowable bearing capacity values.

SUMMARY AND CONCLUSION

The bearing capacity of shallow foundations is conventionally estimated from in-situ PLTs, CPTs or SPTs. These tests however do not take into account of the contribution of matric suction towards the bearing capacity when the soil is in a state of unsaturated condition. Several PLTs and SPTs were conducted at Carp region in Ottawa, Canada to demonstrate the influence of matric suction on the bearing capacity of sand. Based on the analyses of the results, simple relationships are proposed to estimate the allowable bearing capacity of footings in both saturated and unsaturated sands. The proposed relationships were tested for their validity using the in-situ SPTs, PLTs and FLTs data available in the literature. Reasonable comparisons were observed between the estimated and measured bearing capacity values. The study presented in this paper is of interest for the practicing engineers to implement our present understanding of the mechanics of unsaturated soils in the design of shallow foundations, particularly in arid and semi-arid regions.

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REFERENCES

ASTM, D1586-11. Standard test method for standard penetration test (SPT) and split-barrel sampling of soils, In Annual Book of ASTM Standards, American Society of Testing Material.

ASTM, D6066-96. Standard practice for determination the normalized penetration resistance of sands for evaluation of liquefaction potential, In Annual Book of ASTM Standards, American Society of Testing Material.

Bolton, M. D. and Lau, C. K. (1993). "Vertical bearing capacity factors for circular footings on Mohr-Coulomb soil," Canadian Geotechnical Journal, (30),1024-1033.

Bowles, J. E. (1996). Foundation analysis and design, 5th Edition, The McGraw-Hill Companies, Inc., New York.

Burland, J. B. and Burbidge, M. C. (1985). "Settlement of foundations on sand and gravel", Proceedings of the Institution of Civil Engineers, Part I, Vol. **78**(6), 1325-1381.

Canadian Foundation Engineering Manual (4th Edition). (2006). Canadian Geotechnical Society.

Chen, F. H. (1999). Soil engineering, testing, design and remediation, CRC Press, LCC. N.W. Boca Baton, Florida, USA.

Costa, Y. D., Cintra, J. C. and Zornberg, J. C. (2003). "Influence of matric suction on the results of plate load tests performed on a lateritic soil deposit", Geotechnical Testing journal, Vol. **2**(2), 219-226.

Danziger, F. A. B. and de Valleso. (1998). "CPT-SPT correlations for some Brazilian residual soils", In Robertson & Mayne (eds), Geotechnical Site Characterization, Rotterdam: Balkema, 907-912.

Das, B. M. (2007). Principles of foundation engineering, 6th Edition, Publisher, Chris Carson, USA.

De Alencar Velloso, D. (1959). "O ensaio de diepsondeering e a determinacao da capacidade de cargo do solo", Rodovia, 29.

Eslaamizaad, S., and Robertson, P. K. (1996). "Cone penetration test to evaluate bearing capacity of foundation in sands", Proceedings of the 49th Canadian Geotechnical Conference. St. John's, Newfoundland. September, 429-438.

Eslami, A. and Gholami, M. (2006). "Analytical model for the ultimate bearing capacity of foundations from cone resistance", Scientia Iranica (13), 223-233.

Giddens, R. and Briaud, J. (1994). "Load tests on five large spread footings on sand and evaluation of prediction methods." Federal Highway Administration Department of Civil Engineering, A&M University, TX., USA.

Hatanaka, M. and Uchida, A. (1996). "Empirical correlation between cone resistance and internal friction angle of sandy soils", Soils and Foundations, Vol. **36**(4), 1-10.

Kara, A. and Gündüz (2010). "Correlation between CPT and SPT in Adapazari, Turkey", 2nd International Symposium on Cone Penetration Testing, Huntington Beach, Carlifonia, USA.

Lawrence, A. L. (1968). "Theoretical bearing capacity of very shallow footings", Journal of the Soil Mechanics and Foundations Division, ASCE, Vol. **94**(SM6), 1347-1357.

Lee, J. H. and Salgado, R. (2006). "Application of CPT cone resistance for footing bearing capacity estimation", Proceedings of the Geo-Shanghai International Conference, Shanghai, China.

Meigh, A. C. and Nixon, I. K. (1961). “Comparison of in-situ tests of granular soils”, Proceedings of 5th International Conference on Soil Mechanics and Foundation Engineering. Paris, France, Vol. **1**, pp., 499.

Meyerhof, G. G. (1951). “The ultimate bearing capacity of foundations”, Géotechnique, (2), 301-332.

Meyerhof, G. G. (1956). “Penetration tests and bearing capacity of cohesionless soils”, Proceedings of ASCE, Vol. **82**(SM1), 1-19.

Mitchell, J. K. (2000). “Education in geotechnical engineering: Its evolution, current status and challenges for the 21st century”, XI PCSMGE, Foz do Iguacu, Brazil, Vol. **4**, 167-174.

Mohamed, F. M. O., and Vanapalli, S. K. (2006). “Laboratory investigations for the measurement of the bearing capacity of an unsaturated coarse-grained soil”, In Proceedings of the 59th Canadian Geotechnical Conference, Vancouver, B.C., 1-4 October 2006. Canadian Geotechnical Society, Richmond, B.C., 219-216.

Mohamed, F. M. O., Vanapalli, S. K., and Saatcioglu, M. (2010). “Comparison of bearing capacity of unsaturated sands using cone penetration tests (CPT) and plate load tests (PLT)”, Unsaturated Soils, Edited by Antonio Gens, CRS Press 2010, 1183-1188.

Nabil, I. F. (1985). “Allowable pressure from loading tests on Kuwaiti soils”, Canadian Geotechnical Journal, (22), 151-157.

Poulos, H. G., and Davis, E. H. (1974). Elastic solutions for soil and rock mechanics, John Wiley and Sons, New York.

Prandtl, L. (1921). “Über die Eindringungsfestigkeit (Härte) plastischer Baustoffe und die Festigkeit von Schneiden”, (On the penetrating strengths (hardness) of plastic construction materials and the strength of cutting edges), Zeit. Angew. Math. Mech., Vol. **1**(1), 15-20.

Robertson, P. K., Campanella, R. G. and Wightman, A. (1983). “SPT-CPT correlation”, Journal of Geotechnical Engineering, Vol. **109**(11), 1449-1459.

Rojas, J. C., Salinas, L. M. and Seja, C. (2007). “Plate-load tests on an unsaturated lean clay”, In Proceedings of the 2nd International Conference on Unsaturated Soils, Weimar, 445-452.

Schmertmann, J. H. (1970). “Static cone to compute static settlement over sand”, In ASCE, Journal of the Soil Mechanics and Foundations Division. Vol. **96**(3), 1011-1043.

Schnaid, F., Consoli, N. C., Cumdani, R. and Milititsky, J. (1995). “Load-settlement response of shallow foundations in structured unsaturated soils”. Proceedings of the 1st International Conference on Unsaturated Soils, Paris, 999-1004.

Seed, H. B., Tokimatsu, K., Harder, L. F., and Chung, R. M. (1985). “Influence of SPT procedures in soil liquefaction resistance evaluations”, Journal of the Geotechnical Engineering Division, ASCE, Vol. **111**(12), 1425-1445.

Steensen-Bach, J. O., Foged, N., and Steenfelt, J. S. (1987). “Capillary induced stresses – fact or fiction?”, In Proceedings of the 9th European Conference on Soil Mechanics and Foundation Engineering, Dublin, Ireland, A.A. Balkema, Rotterdam, the Netherlands, 83-89.

Terzaghi, K. (1943). Theoretical soil mechanics, John Wiley and Sons, New York.

Terzaghi, K. and Peck, R. B. (1948). Soil Mechanics in Engineering Practice, Asia Publishing House.

Vanapalli, S. K., and Mohamed, F. M. O. (2007). “Bearing capacity of model footings in unsaturated soils”, In Experimental Unsaturated Soil Mechanics, Springer-Verlag, Berlin Heidelberg, Germany, 483-493.

Vanapalli, S. K., Fredlund, D. G., Pufahl, D. E., and Clifton, A. W. (1996). “Model for the prediction of shear strength with respect to soil suction”, Canadian Geotechnical Journal, Vol. **33**(3), 379-392.