Influence of Footing Size and Matric Suction on the Behavior of Shallow Foundations in Collapsible Soil

Ana Paula Fontana Vianna, José Carlos A. Cintra, Nelson Aoki

Abstract. This work analyses the influence of footing size and soil matric suction on the behavior of shallow foundations on unsaturated sandy soil, in terms of bearing capacity and settlements. Fourteen plate load tests were performed at the Experimental Site of USP/São Carlos. Rigid metal plates were used, with diameters varying between 0.20 m and 0.80 m and reinforced concrete footings, with circular base diameter 1.50 m. All the plates and the footings were installed at a depth of 1.5 m. These tests were conducted either with matric suction monitoring using tensiometers installed at the bottom of the hole or with soil flooding. The important role of the matric suction was confirmed. A reduction of the matric suction close to zero causes a great decrease in the bearing capacity and a significant increase in the settlement. In relation to the footing size (B), the bearing capacity as well as the settlements did not present a constant linear increasing variation. This work also proved the importance of considering the soil collapsibility in unsaturated soil shallow foundations design. When this factor is not considered, the calculated allowable bearing capacity may cause very high settlements if soil flooding occurs.
Key words: plate load tests, shallow foundations, footing size, matric suction, bearing capacity, settlements, allowable bearing capacity.

1. Introduction

The footing size has an important effect on the bearing capacity and on the settlements of shallow foundations on sandy soils. In theoretical formulations, as for example Terzaghi's equation (1943) represented by the continuous line in Fig. 1, the bearing capacity (σ_r) varies in a linear and increasing way with the width (B) of the footing.

$$\sigma_r = cN_c S_c + qN_q S_q + \frac{1}{2}\gamma B N_\gamma S_\gamma \quad (1)$$

Nevertheless, such behavior is not valid for footings of small sizes. In this case, contradicting the assumption in theory that σ_r decreases linearly with the decrease of B, the bearing capacity tends to strongly increase with the decrease of the footing width when B is close to zero. The dotted line in Fig. 1 shows this behavior. An evidence of this behavior are the results of CPT tests. The diameter of the cone is only 36 mm but the value of the tip resistance (q_c) is much higher (about 20 a 30 times) than the bearing capacity of foundations of footings installed in the same site and at the same depth.

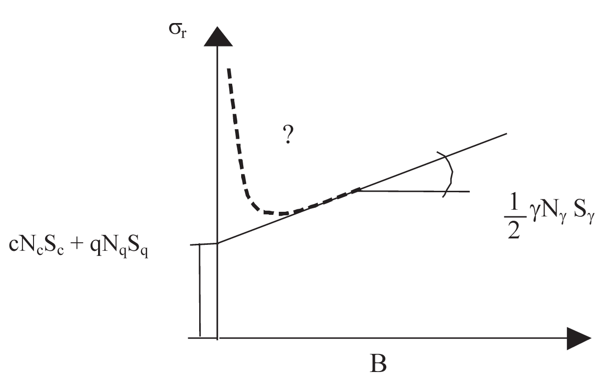

Figure 1 - Bearing capacity in relation to the footing width.

A data analysis performed by De Beer (1965) shows that the bearing capacity factor N_γ increases significantly with the decrease of the footing width for "low" values of B, as shown in Fig. 2.

Similar behaviour is observed in relation to settlements. The theory of linear elasticity shows, for the same stress level, a linear and increasing variation of settlements (ρ) with the foundation size (B) for the case of homogeneous soils (Eq. (2)):

$$\rho = \sigma B \left(\frac{1-\upsilon^2}{E_s} \right) I_\rho \quad (2)$$

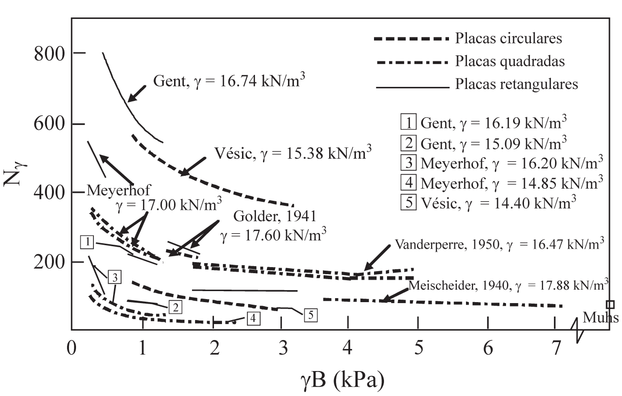

Figure 2 - Effect of the size on the bearing capacity factor N_γ for foundations by footings on sand (De Beer, 1965).

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Submitted on August 18, 2006; Final Acceptance on July 13, 2007; Discussion open until April 30, 2008.

which is represented in Fig. 3 by a straight line towards the origin. Thus, for *B* tending to zero the settlement also tends to zero.

Gorbunov-Possadov & Davidov (1973) demonstrate the non linear dependence between settlement and the plate sizes and footings, according to Fig. 4. Accordint to these authors: "In the first section AB settlement sharply increases due to the plastic deformations of the soil, whose role decreases with the surface area of the plate, which in fact leads to reduced settlement. Further on, the role of plastic deformations is insignificant, and the dependence of settlement on the plate width becomes linear, which corresponds to the formulas of the theory of elasticity. Tentatively, this section refers to test plate widths from 0.5-0.7 m to 3.0-5.0 m. Then the increase in settlement slows down, and at *B* > 10 to 20 m settlement becomes practically independent of the plate width."

The matric suction is also another important factor that must be considered in the analysis of foundation behavior on unsaturated soils. This relevant role of the matric suction, in terms of bearing capacity in shallow foundations, was revealed by Fredlund & Rahardjo (1993). They used Terzaghi's bearing capacity equation (1943) and considered the increase of cohesion (*c*) due to the matric suction (ψ_m):

$$c = c' + \psi_m \operatorname{tg} \phi^b \tag{3}$$

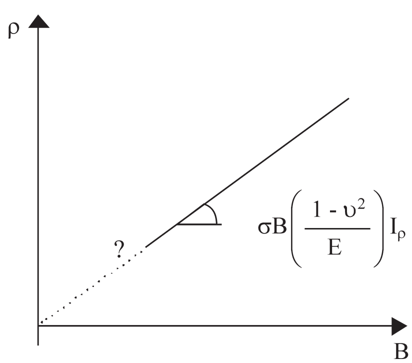

Figure 3 - Settlements of footing in relation to the footing width.

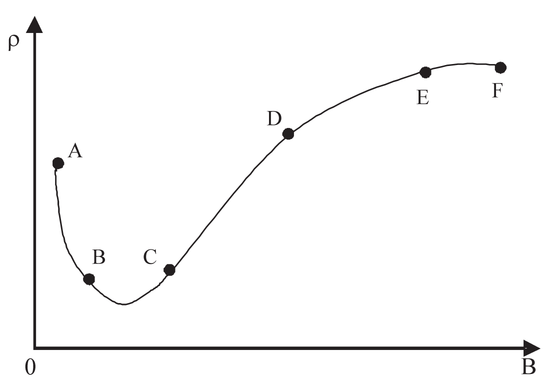

Figure 4 - Settlements variation (ρ) with the size (*B*) of the footings and rigid plates (Gorbunov-Possadov & Davidov, 1973).

where *c*' is the effective cohesion and ϕ^b the shearing strength increase rate due to the soil matric suction.

These authors obtained the results shown in Fig. 5 by adopting parameters for the soil (*c*' = 5 kPa, ϕ' = 20°, ϕ^b = 15° and unit weight γ = 18 kN/m^3) and considering spread footings with *B* equal to 0.5 and 1.0 m at depth (*h*) of 0.5 m. A significant increase of the bearing capacity with the matric suction can be observed.

Afterwards, Costa (1999) proved experimentally that in unsaturated soil the matric suction has a great influence on the bearing capacity. Using metal plates load tests with a 0.8 m diameter installed at 1.5 m deep, it was verified that a small increase on the matric suction causes a substantial increase in the bearing capacity. This may be observed in Fig. 6, where ψ_m represents the average matric suction of the soil determined by four tensiometers. Other analyses of this research are shown by Costa *et al.* (2003).

The important role of the matric suction on the behavior of plate-soil system was also found by Macacari (2001) and Cintra *et al.* (2005), for the deeper plates, installed up to 6 m deep.

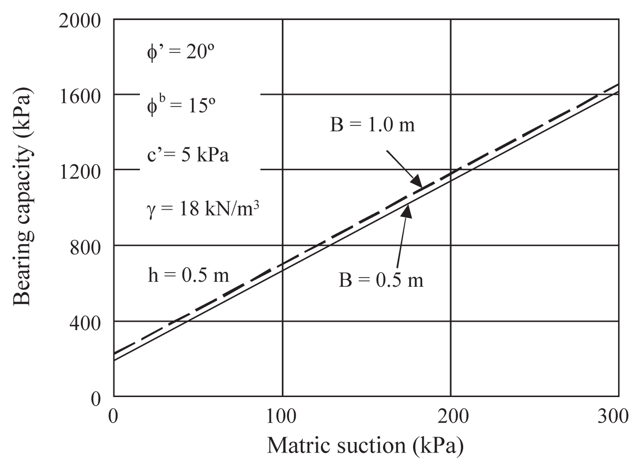

Figure 5 - Bearing capacity of spread footing foundations of width *B* in relation to the matric suction (Fredlund & Rahardjo, 1993).

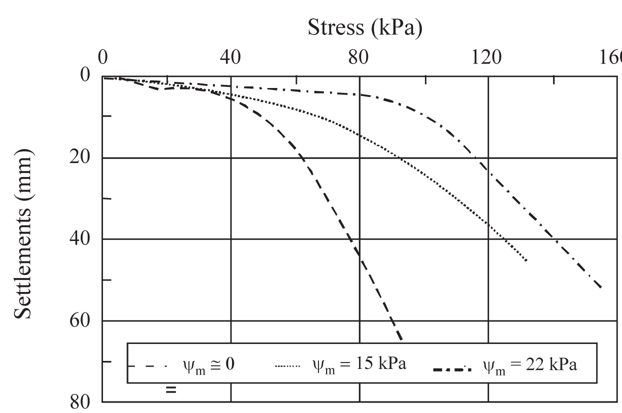

Figure 6 - Stress *vs.* settlement curves of plate load tests on collapsible soil for different levels of matric suction (Costa, 1999).

In order to evaluate the simultaneously influence of the size of the shallow footings, particularly the ones with small sizes, and of the matric suction on the behavior of the shallow foundations in collapsible sandy soil, this work presents a research that was conducted at the Foundations Experimental Site of USP/São Carlos.

Load tests were performed on plates of three different diameters (0.20; 0.40; and 0.80 m) and in footings with 1.50 m diameter, installed in different holes, 1.50 m deep. The tests were conducted under two conditions: a) with no flooding of the area and with the matric suction monitored using tensiometers; b) with the area pre-flooded, in order to represent the diminishing matric suction condition which is inherent to the collapse scenario.

2. Foundations Experimental Site

The representative geotechnical-geologic profile of the Experimental Foundation Site of USP/São Carlos presents a superficial layer, characterized by brown clayey sand, 6 m thick. The action of weathering under weather conditions typical of tropical regions caused the process of laterization. The resulted material is very porous and collapsible. A line of quartz pebbles and limonite separates the superficial layer of the residual soil at a depth of approximately 6 m. The residual soil is constituted by reddish clayey sand, originated from sandstone of the "Bauru Group". The level of the water table varies in between 7 to 10 m deep, depending on the season.

Geotechnical information of this Experimental Site is summarized in Fig. 7. The average value of the standard penetration resistance N_{SPT}, obtained from various campaigns, performed in different times of the year, does not exceed 4 blows/30 cm on the most superficial layer. The void ratio reaches a value close to 1.2 on the surface and tends to decrease with the depth. Regarding the stresses, a practically linear increase is observed in geostatic stress with the depth, due to a small variation of the unit weight. It is also possible to observe that the pre consolidation stress tends to reduce when it goes from non-flooded soil (σ_{po}) to flooded soil condition (σ^*_{po}), which is a common behavior of the collapsible lateritic soils of the Southeast region of Brazil.

3. Tests Performed

Fourteen static plate load tests were performed on rigid metallic circular plates of three different diameters (0.20; 0.40; 0.80 m), and on reinforced concrete footings with circular base with 1.50 m diameter. All elements were installed 1.50 m deep, in different holes with 0.50; 0.60; 0.90 and 1.70 m diameters.

In five tests, the area was pre-flooded for at least 48 h, always maintaining a water layer of at least 50 mm at the bottom of the hole. These tests are represented by codes F-20, F-40, F1-80, F2-80 and F-150, where the letter "F" refers the flooded condition and the numbers refer to the plate or footing diameter, in centimeters.

For the other nine tests performed with no flooding, in different seasons throughout the year, tensiometers were installed at the bottom of the hole in order to monitor the matric suction during the test. Table 1 shows the average matric suction values obtained in the non-flooded tests. The letter "N" refers to the non-flooded condition and the numbers indicate the plate or footing diameter, in centimeters.

The plate load tests were performed according to the NBR-6489 (1984) with the execution methodoly adapted from the quick method of loading (QML) from NBR 12131/91, but with stages that lasted 15 min. The settlement readings were obtained at 0, 1, 2, 3, 6, 9, 12 and 15 min, in each stage, and the unloading was performed in two stages of 15 min. Before unloading the test, there was no maintained load until simultaneous stabilization of load and settlement.

Figs. 8 to 11 show the stress *vs.* settlement curves obtained in all of the plate load tests. The values in brackets correspond to the average matric suction for each test, in kPa.

4. Analyses of the Results

4.1. Bearing capacity

The stress *vs.* settlement curves in Figs. 8 to 11 present the same pattern, characterized by a final stretch that shows an almost linear relationship between settlement and the corresponding applied stress. However, these curves do neither demonstrate a clear rupture nor the evidence a physical rupture. Thus, it is necessary to apply conventional rupture criteria in order to evaluate the bearing capacity of the plate-soil system.

Five criteria were considered as listed bellow:

1. Terzaghi (1943): this criterion states that the bearing capacity of the plate-soil system corresponds to the point from which the stress *vs.* settlement curve starts to show a linear behavior on its final stretch.

Table 1 - Average matric suction in the non-flooded plate load tests.

Plate load tests code	Plate/footing diameter B (m)	Matric suction ψ_m (kPa)
N1-20	0.20	15
N2-20	0.20	18
N1-40	0.40	13
N2-40	0.40	12
N1-80	0.80	15
N2-80	0.80	22
N3-80	0.80	33
N1-150	1.50	21
N2-150	1.50	23

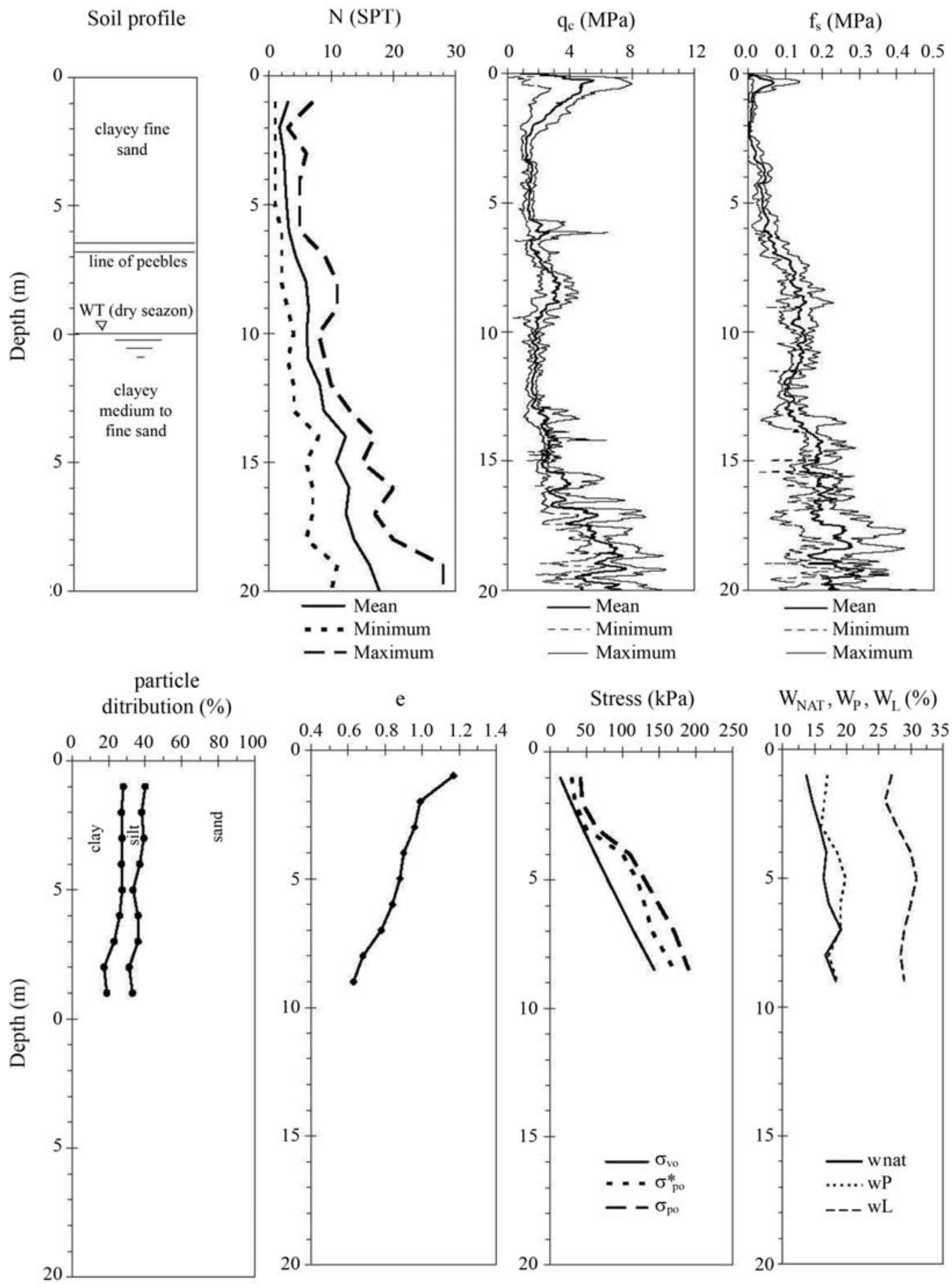

Figure 7 - Geotechnical characteristics of the foundations experimental site of USP/São Carlos (adapted from Menegotto & Vianna, 2000; Giachetti, 2001).

2. Leonards (1962): in this criterion, the bearing capacity is given by the intercepting point of the two tangents, one at the initial portion of the curve and the other at the final portion.

3. "Pre-consolidation" stress: according to the procedure adopted by Macacari (2001), this criterion consists in converting the stress axis to the logarithmic scale and applying the Pacheco Silva method (1970). This is possible due to the similarity of the curves obtained in the plate load tests with the log stress curves *vs.* void ratio of saturated clays consolidation tests.

4. Settlement equal *B*/10 or 10% *B* (Terzaghi, 1942): the bearing capacity corresponds to the stress correspondent to the settlement equal to 10% of the diameter of the plate.

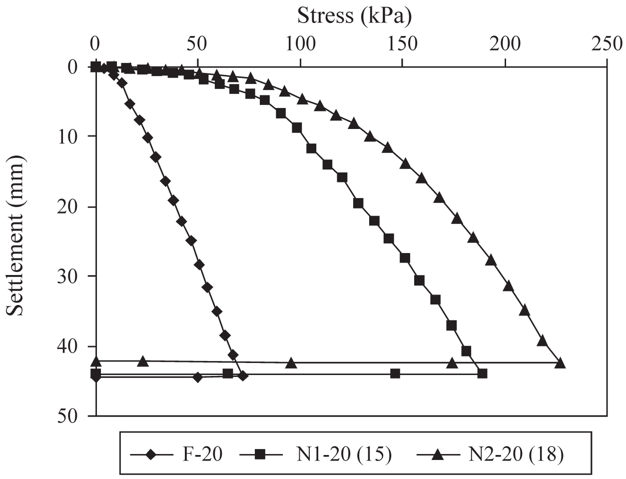

Figure 8 - Stress *vs.* settlement curves of one flooded test and two non-flooded tests (0.20 m diameter plate).

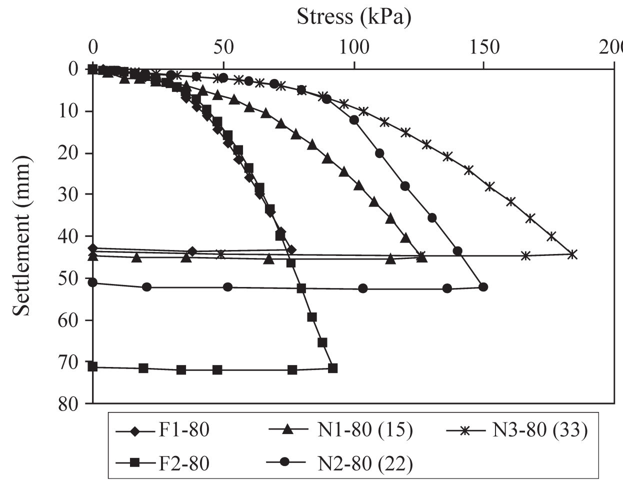

Figure 10 - Stress *vs.* settlement curves of two flooded tests and three non-flooded tests (0.80 m diameter plate).

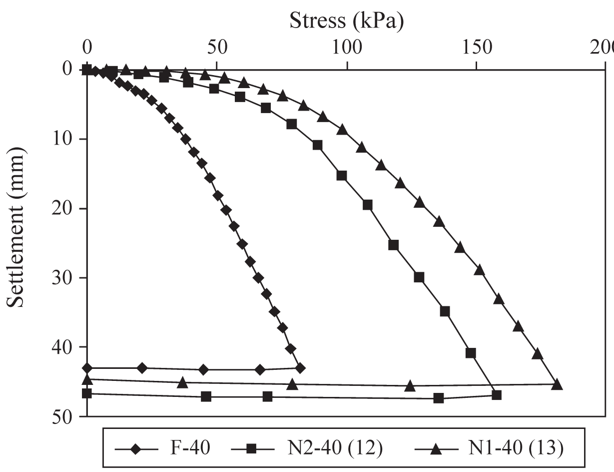

Figure 9 - Stress *vs.* settlement curves of one flooded test and two non-flooded tests (0.40 m diameter plate).

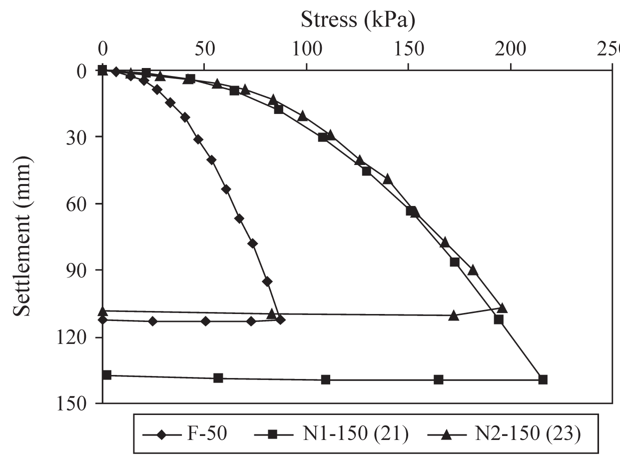

Figure 11 - Stress *vs.* settlement curves of one flooded test and two non-flooded tests (1.50 m diameter footing).

5. Settlement equal *B*/30: the bearing capacity corresponds to the stress correspondent to the settlement equal to 30% of the diameter of the plate (approximately 25 mm, particularly for the plate with diameter *B* = 0.80 m).

Since the application of these different criteria resulted in values reasonably similar, this work presents only the analysis correspondent to the Terzaghi criterion (1943), which is specific to the pattern of curves obtained in this research. The other four analyses may be checked out in Vianna (2005). In particular, the analysis referring the criteria of 10% *B* was published by Vianna *et al.* (2004).

Table 2 shows bearing capacity values (σ_r) obtained in all tests according the conventional rupture criterion by Terzaghi (1943), as well as corresponding values of settlement (ρ_r).

When the bearing capacity values are determined, the values of applied stress may be made dimensionless in the tests dividing the applied stresses by the bearing capacity. The values of settlement may also be normalized dividing them by the plate or footing diameter. Therefore, the stress *vs.* settlement curves are dimensionless for the 14 tests, which are shown in Fig. 12.

It is possible to observe that the dimensionless curves do not show any tendency of converging to a single curve, which implies the existence of the scale effect, in this case.

4.2. The matric suction influence

The behavior of the plate-soil system (or footing-soil) with the variation of the matric suction may be analyzed from the results shown in Figs. 8 to 11.

In terms of deformability, if the curves obtained for plates with the same diameter are compared, it is possible to observe that the settlement for a certain level of stress decreases proportionally with increasing measured matric suction during the plate load tests. It is as if the soil gained an increase of stiffness with the matric suction increase.

As for the resistance of the system, it is possible to observe that the greater the matric suction acting on the soil, the greater the bearing capacity, when tests on plates of the same diameter are compared. Correlating the values of the bearing capacity (σ_r) with the respective values of the matric suction (ψ_m), both values in kPa, it is possible to obtain a reasonably linear variation for each plate diameter as depicted in Fig. 13. The equations resultanting from linear regression analyses are presented in Table 3.

Table 2 - Values of bearing capacity and settlement obtained using Terzaghi criteria (1943).

Test	Bearing capacity σ_r (kPa)	Settlement ρ_r (mm)
F-20	25	10
N1-20	144	25
N2-20	185	24
F-40	54	20
N1-40	144	26
N2-40	109	19
F1-80	56	22
F2-80	68	34
N1-80	102	28
N2-80	100	12
N3-80	144	24
F-150	54	40
N1-150	151	64
N2-150	140	49

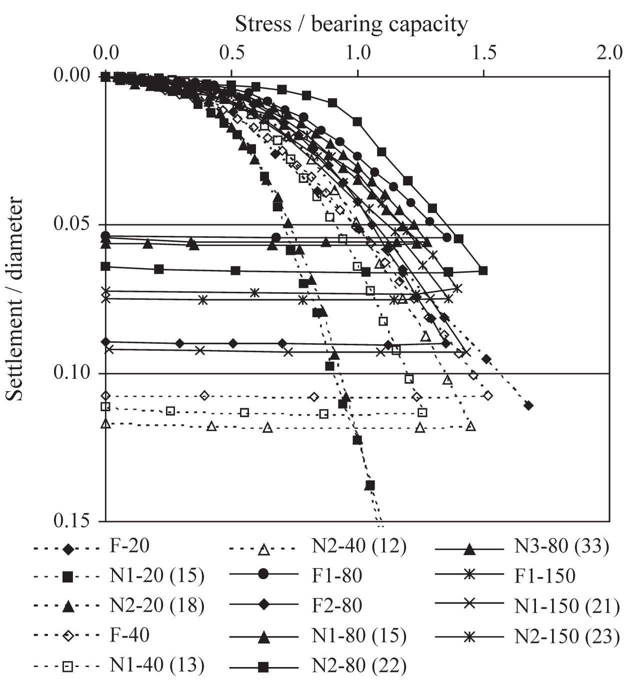

Figure 12 - Dimensionless stress *vs.* settlement for the 14 plate load tests.

In these four straight-line equations, the angular coefficient varies between 2.3 and 8.6, which is compatible with the calculations by Fredlund & Rahardjo (1993), presented in Fig. 5, where the angular coefficient is 5.

4.3. Influence of the plate size on the bearing capacity

Figs. 8 to 11 show that the bearing capacity varies simultaneously with the plate size (or footing size) and with the matric suction. Only for the flooded soil condition, or for suction practically null, it is possible to make a direct analysis of the exclusive influence of the plate or the footing diameter on the bearing capacity. Therefore, considering only the flooded tests, Fig. 14 is obtained, which shows the variation of the bearing capacity with the diameter.

It is possible to observe in Fig. 14 a significant increase of the bearing capacity from a diameter of 0.20 m to 0.40 m. However, the variation of the bearing capacity changes very little between diameters of 0.40 m and 1.50 m.

In order to complement that graph an additional data point could be included corresponding to the diameter of

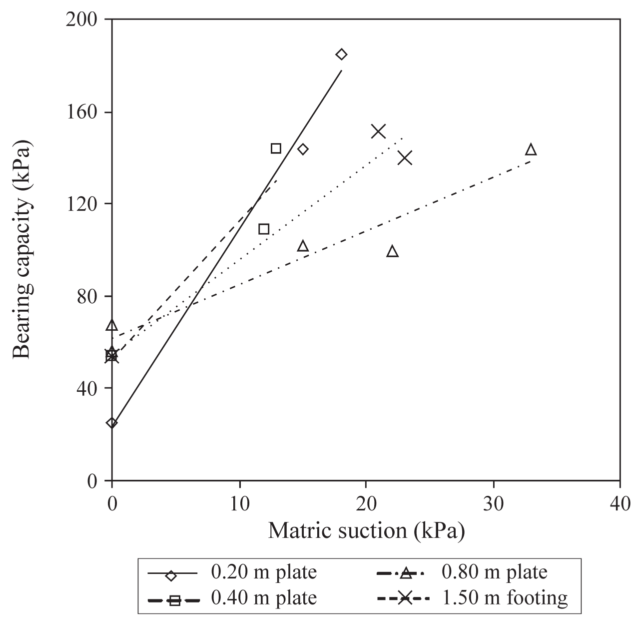

Figure 13 - Variation of the bearing capacity in relation to the matric suction for each plate or footing.

Table 3 - Correlations between bearing capacity σ_r (kPa) and matric suction ψ_m (kPa).

B (m)	$\sigma_r = f(\psi_m)$	R^2
0.20	$\sigma_r = 8.6\ \Psi_m + 24$	0.991
0.40	$\sigma_r = 5.9\ \Psi_m + 53$	0.897
0.80	$\sigma_r = 2.3\ \Psi_m + 61$	0.937
1.50	$\sigma_r = 4.1\ \Psi_m + 55$	0.967

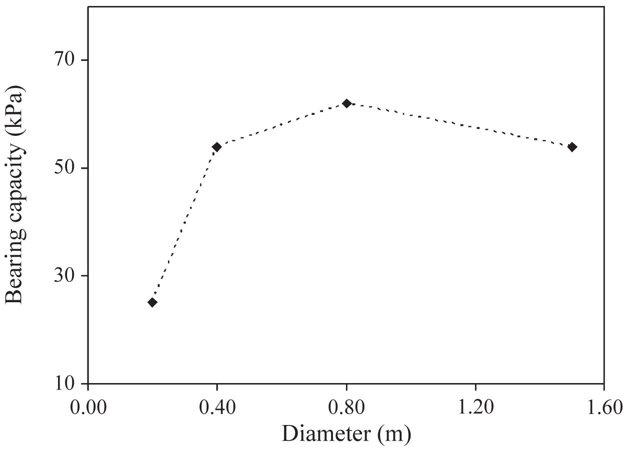

Figure 14 - Bearing capacity *vs.* diameter (flooded tests).

only 28.4 mm. This is the tip diameter of a manual penetrometer utilized by Tshua (2003) and Tsuha *et al.* (2004), for which a resistance of 482 kPa is obtained, in the same place, at the same depth, in the flooded soil condition. Therefore, the bearing capacity obtained with the penetrometer, whose diameter is around 50 times smaller than the tested footing, is approximately nine times greater than that found in the footing load test, with flooded soil. This is coherent with the empiric correlations existing in literature, in which the cone's tip resistance (static penetration test) is always much greater than the bearing capacity of shallow foundations.

For the non-flooded tests it is not possible to make such an analysis directly, because there are no results for different diameters with the same matric suction value.

With the correlations in Table 3 it is possible to calculate the bearing capacity for each plate diameter varying the matric suction values, for example from 0 to 30 kPa in 10 kPa increments. These values calculated for the bearing capacity are presented in Table 4, where the values obtained for the portable penetrometer (B = 28 mm) are included, and for which the following correlations is valid:

$$\sigma_r = 26\,\Psi_m + 482 \quad (4)$$

with R^2 = 0,960 (Tsuha, 2003).

In the same way, Fig. 15 is obtained, which presents the bearing capacity variation with the plate or footing diameter, for each matric suction level (ψ_m).

It is possible to observe in Fig. 15 that, except for the flooded soil case, initially the bearing capacity decreases with the diameter increase, which is consistent with what was demonstrated by De Beer (1965) in Fig. 2. Actually, the corresponding curve to the flooded soil presents a significant similarity with the experimental curve, presented in Fig. 14.

For the 10 kPa curve, the bearing capacity is basically constant up to a diameter of 0.5 m. From this point on, the behaviour is similar to those of the 20 kPa and 30 kPa curves. Only above a diameter of 0.80 m, the bearing capacity may increase with the plate or footing size and this increase is more significant the greater the matric suction is. Coincidently, this is the plate diameter adopted by the Brazilian Standard NBR 6489. This figure proves that this was a correct choice regarding establishing this diameter for plate load tests for foundations design purposes.

In Table 4 it can be noted that the values obtained for the portable penetrometer are the highest ones, since these occur with the results of the cone penetration tests (CPT), as opposed to the shallow foundations bearing capacity values.

4.4. The influence of plate size on the settlements

From the stress *vs.* settlement curves that were obtained in flooded tests, it is possible to obtain the settlement

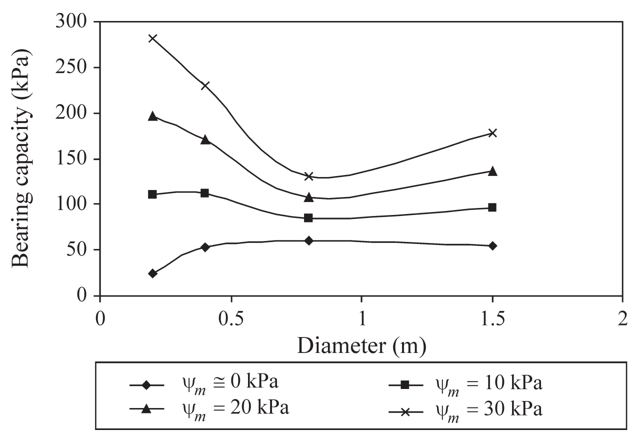

Figure 15 - Variation of the bearing capacity with the diameter, for different matric suction levels.

Table 4 - Calculated values of the bearing capacity for different levels of the matric suction.

Matric suction ψ_m (kPa)	Bearing capacity σ_r (kPa)				
	B = 28 mm	B = 0.20 m	B = 0.40 m	B = 0.80 m	B = 1.50 m
0	482	24	53	61	55
10	742	110	112	84	96
20	1002	196	171	107	137
30	1262	282	230	130	178

values corresponding to several stress levels, for example from 10 to 70 kPa in 10 kPa increments. Therefore, it is possible to establish, for the flooded tests, the influence of the plate diameter on the settlements, for each level of stress, as shown by the curves in Fig. 16.

It is possible to observe that these curves reproduce the pattern shown in Fig. 4, particularly its BF segment. A diameter smaller than 0.20 m, for example 0.10 m, could represent point A of that figure. Therefore, the settlements initially are decreasing as the diameter increases, up to *B* around 0.60 m. From this point on, the settlements begin to increase with the increase of *B* and this growth is more significant as the applied stress increases. This demonstrates the non-linear behaviour of the settlements with the foundation diameter.

For non-flooded tests it is not possible to make a direct analysis of the influence of the plate size on the settlements, because there are no tests with different sizes and the same matric suction. Because of that, a specific procedure was adopted in order to estimate this influence. The values of bearing capacity were calculated for each diameter, utilizing the equations in Table 3 and matric suction values of 10 kPa, 20 kPa and 30 kPa. Afterwards, these points were marked on the graphs of Figs. 8 through 11 and a new curve "parallel" to the existing curves in the graphs was drawn by hand, corresponding to the matric suction adopted values. Then, for each adopted level of matric suction, settlement variation versus plate diameter curves were found for different levels of stress, as shown in Figs. 17 through 19.

Again, it is possible to see the same shape of part of Fig. 4, now using the portion from an intermediate point between *B* and C until F. With other tests, with diameters smaller than 0.20 m, points A and B would probably be defined. In the absence of these points, it is possible to observe on the three figures a certain settlements consistency between diameters 0.20 m and 0.40 m. Between 0.40 m and 0.80 m the settlements increase as *B* increases. For *B* grater then 0.80 m there is a less significant settlement increase for *B* greater than 0.80 m. The curve shape is not affected by the matric suction, but the changes in the settlements will be more pronounced at higher stress levels, as the applied stress increases, for the same matric suction.

5. Allowable Bearing Capacity

Disregarding the tests on smaller plates, it may be considered that the tests on the 0.80 m plate, the Brazilian Standard one, were performed for the purpose of determining the allowable bearing capacity for the 1.50 m footing design.

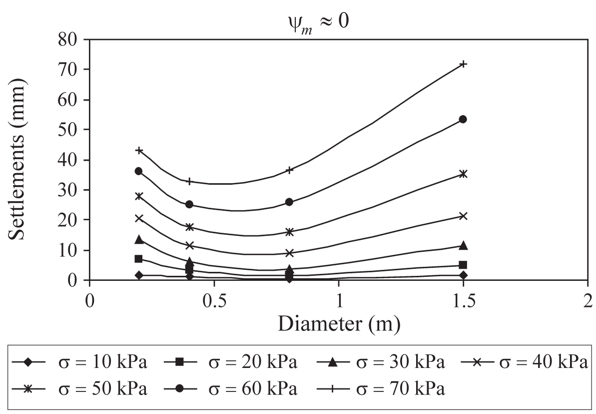

Figure 16 - Variation of the settlement with the plate diameter for different levels of stress (flooded tests).

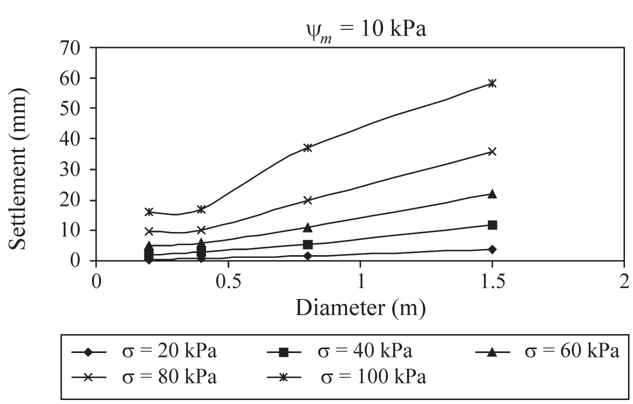

Figure 17 - Variation of the settlement with the diameter for different levels of stress (matric suction of 10 kPa).

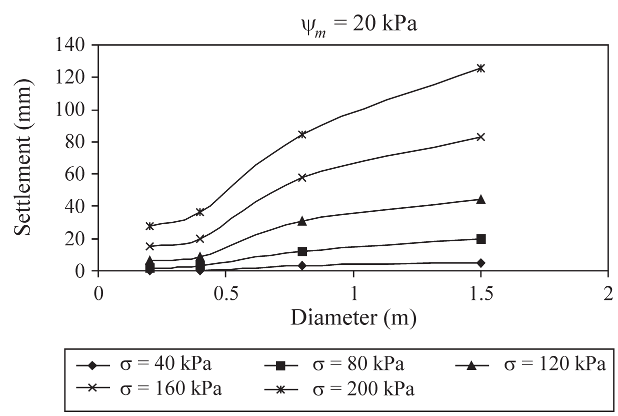

Figure 18 - Variation of the settlement with the diameter for different levels of stress (matric suction of 20 kPa).

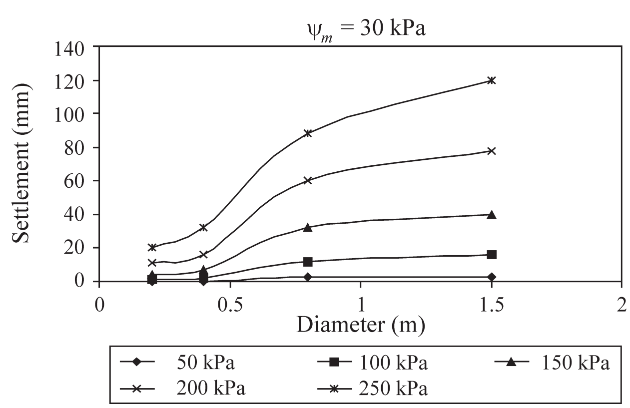

Figure 19 - Variation of settlement with the diameter for different level of stress (matric suction of 30 kPa).

This is a hypothetical case, since the use of shallow foundations on this collapsible soil would demand a soil treatment, through compaction for example (Souza *et al.*, 1995). Nevertheless, this is a very interesting analysis in order to explain the problem of foundation design on collapsible soil. In order to achieve this, two scenarios will be shown, considering or not the soil collapsibility in the design.

5.1. Analyses considering collapsibility

In order to consider the soil collapsibility in the design it is necessary to perform at least one plate load tests with pre-flooding, besides the plate load tests without flooding.

In order to interpret the non-flooded tests stress *vs.* settlement curves, the Boston criterion is used. By this criterion the allowable bearing capacity (σ_a) is given by the smallest of two values: the stress that causes the 10 mm settlement (σ_{10}) and half of the stress corresponding to the 25 mm settlement ($\sigma_{25}/2$). According to Teixeira & Godoy (1996), this criterion stablishes for the plate an admissible settlement of 10 mm and a conventional rupture criterion in which the bearing capacity (σ_r) is associated with the 25 mm settlement. The denominator 2 corresponds to a safety factor.

For the plate load tests performed with soil flooding, the same criterion is used, but the safety factor is 1.5 instead of 2, according to the methodology proposed by Cintra (2004).

Table 5 presents values obtained for the allowable bearing capacity (σ_a), up to the next nearest multiple of 10 in kPa, as well as the corresponding values for settlement (σ_n for non flooded tests; σ_f for flooded tests).

Therefore, even if only one non-flooded test had been performed and only one flooded, the conclusion would still be the same, an allowable bearing capacity of 40 kPa, which is the smallest value found. This allowable bearing capacity of 40 kPa would generate on the plate maximum settlements of 7.3 or 8.8 mm, for the extreme situation of soil flooding.

With this allowable bearing capacity value, the stress *vs.* settlement curves of the plate load tests performed on the footings (N1-150, N2-150 and F-150) shown in Fig. 11, indicate that the footing settlement would be 3.8 mm for the non-flooded tests (matric suctions corresponding to 21 and 23 kPa), but it would increase to 21.0 mm if soil flooding takes place.

5.2. Analyses not considering the collapsibility

Without taking into consideration the soil collapsibility on the footings design, the load tests would not be performed on plates with soil flooding. This would result in higher values of allowable bearing capacity. According to Table 5, in this case one of these three values of allowable bearing capacity would be obtained: 50, 60 or 70 kPa, depending on if the test sample would coincide with N1-80, N2-80 or N3-80, respectively. The corresponding settlement would be totally acceptable (less than 7 mm in any of the tests).

However, if there was a soil flooding, the settlement would increase significantly, which could be quantified with the introduction of those values for allowable bearing capacity on the curves for the flooded tests (F1-80 or F2-80) in Fig. 10. The plates's settlements would be around 14, 24 and 37 mm, respectively, for stresses of 50, 60 and 70 kPa. Therefore, the problem would become even more serious if the allowable bearing capacity is defined based on plate load tests performed in seasons of less humidity (higher matric suction).

This conclusion is confirmed for the footing. When one of these three values for allowable bearing capacity is applied to the stress *vs.* settlement curve of the flooded test (F-150), in Fig. 11, the corresponding settlements of 34, 54 and 70 mm are obtained. Therefore, it is confirmed the seriousness of the problem generated by foundation designs on collapsible soils that do not take in consideration soil collapsibility. Without this consideration, the soil flooding occurrence causes settlements of unacceptable magnitude.

6. Conclusions

Results obtained in 14 plate load tests with metal plates of three different diameters (0.20 m to 0.80 m) and with footings of reinforced concrete of 1.50 m diameter, installed 1.5 m deep, at the Foundations Experimental Site USP/São Carlos were analysed. These results drew important conclusions about the role of the matric suction and about the influence of the diameter on the bearing capacity, as well as on shallow foundations settlements.

Table 5 - Allowable bearing capacity and corresponding settlement.

Test	Matric suction Ψ_m (kPa)	Allowable bearing capacity σ_a (kPa)	Settlement σ_n (mm)	Settlement σ_f (mm)
N1-80	15	50	6.5	–
N2-80	22	60	2.8	–
N3-80	33	70	3.8	–
F1-80	≈ 0	40	–	7.3
F2-80	≈ 0	40	–	8.8

The greater the matric suction acting in the soil, the greater the system's bearing capacity, regardless of the plate or the footing diameter (*B*). For each tested diameter, a linear correlation was established between the matric suction (Ψ_m) and the bearing capacity (σ_r).

The stress *vs.* settlement curves obtained in the plate load tests also show higher values of matric suction result for smaller settlements, regardless of stress level and diameter. On the other hand, decreasing the matric suction to nearly zero induces significant increases in settlements. Therefore, there is no doubt that the matric suction is a factor that cannot be neglected in the bearing capacity analysis and on the settlement of shallow foundations on unsaturated soils.

Using these results it was possible to plot curves in order to define the bearing capacity variation with the diameter. It was found that at lower diameters the bearing capacity decreases as the diameter increases until a minimum bearing capacity value is reached at a diameter of 0.80 m. After this point the bearing capacity increases with increasing plate diameters or footing sizes. This increase is more significant when the matric suction is greater. Therefore, for the research conducted in this type of unsaturated sandy soil, it is unrealistic to consider that the bearing capacity is increasing linearly with the plate or footing diameter, as assumed by the theoretical formulations of shallow foundations bearing capacity.

Curves were also generated for the variation of the settlement with the diameter, for different levels of applied stresses. In the non-flooded tests, a certain consistency of settlements was observed between diameters of 0.20 m and 0.40 m. For *B* between 0.40 m and 0.80 m there is an increase in settlements with an increase in *B*. For *B* greater than 0.80 m there is a less significant increase in the settlements. The curve shape was not affected by the matric suction, but it was much more pronounced with the applied stress increase, for the same matric suction.

For the flooded tests, it was observed that the settlements initially decrease with increasing diameter, up to *B* around 0.60 m. From this point onward, the settlements start to increase with an increase of *B* and this increase is more significant when the applied stress is greater. This work demonstrates that for each level of stress, the settlement variation is very non-linear and always increases with the diameter.

For the hypothesis of the tests on the 0.80 m diameter plate performed for 1.50 m footing design, the conclusion is that performing plate load tests in flooded soil condition is essential in order to determine the allowable bearing capacity.

According to the methodoloty proposed by Cintra (2004), which includes a safety factor of 1.5 for the bearing capacity obtained in the flooded test, the allowable bearing capacity would be 40 kPa. The settlements on footings corresponding to this stress would be 3.8 mm (for an average matric suction of 22 kPa) and they would increase to 21.0 mm in case of soil flooding.

However, if the design was conducted without the soil collapsibility consideration, and therefore without flooded test results, the allowable bearing capacity would vary from 50 to 70 kPa, depending on the season in which the non-flooded test was performed, *i.e.*, depending on the matric suction acting on the soil on the test day. For these values of allowable bearing capacity, the settlements on footings would increase to 34 to 70 mm if soil flooding occurs.

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