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Long-Term vs Short-Term Bearing Capacity of Shallow Foundations on Clays

Erick Christian V. Cruz – *Project Engineer, Schnabel Engineering, Austin (Texas, USA)*
ecvcruz@gmail.com

Jean-Louis Briaud – *Professor, Texas A&M University, College Station (Texas, USA)*
briaud@tamu.edu

ABSTRACT: *Determining the ultimate bearing capacity is crucial for the efficient design of shallow foundations. Design codes and standards generally provide guidance in estimating the ultimate bearing capacity of shallow foundations. These codes and standards suggest calculating the ultimate bearing capacity of shallow foundations on clays, considering that the undrained/short-term bearing capacity is more critical than the long-term/drained bearing capacity. This notion is true for normally consolidated to lightly overconsolidated clays. However, when shallow foundations are situated on heavily overconsolidated clays, the generated excess pore water pressure can either be positive or negative depending on the stress history of the soil and the imposed strain on the soil. Thus, the critical ultimate bearing capacity for heavily overconsolidated clays needs to be examined by comparing predicted and measured bearing capacities from actual load tests, as well as by comparing predicted undrained and drained ultimate bearing capacities using actual soil shear strength parameters. A database of shallow foundation load tests conducted on fine-grained soil was organized in a large spreadsheet called TAMU-SHAL-CLAY-Load Test. Information includes the geometry of the load test, soil shear strength parameters, in-situ field test data, and load-settlement data. The measured ultimate bearing capacity was obtained from the load-settlement data, while the predicted bearing capacity was calculated using the general bearing capacity equation with c' and ϕ' for the drained bearing capacity, and Skempton's equation with S_u and direct strength equations with SPT N-value, PMT p_L and CPT q_c for the undrained bearing capacity. In order to validate the results of the analyses, information in the database was supplemented by c'- ϕ' data of soils obtained from different sites around Houston, Texas. The comparison showed that the undrained bearing capacity is critical for clays with S_u < 120 kPa, while the drained bearing capacity is critical for clays with S_u > 120 kPa.*

KEYWORDS: ultimate bearing capacity, shallow foundations, clay, database, TAMU-SHAL-CLAY-Load Test

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INTRODUCTION

Shear failure occurs when the bearing pressure exerted by the foundation reaches or exceeds the ultimate bearing capacity of the soil. This failure is characterized by significant yielding or deformation of the building's foundation, often leading to a sudden or progressive collapse of the structure (ULS). The ultimate bearing capacity of the soil is determined using well-established bearing capacity theories, which are primarily a function of the effective cohesion *c'* and the effective friction angle ϕ' for drained behavior, or the undrained shear strength S_u for undrained behavior. Structures are typically subjected to sustained loads and transient loads, necessitating the determination of both short-term (undrained) and long-term (drained) ultimate bearing capacities for foundations on clays. The critical ultimate bearing capacity is taken as the lesser of the two values.

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According to relevant codes and standards, the ultimate bearing capacity of shallow foundations on clays is primarily governed by the undrained ultimate bearing capacity. This is logical because continuous loading of clays up to shear failure induces excess pore water pressures, resulting in an undrained behavior in the early stages of construction. According to laboratory tests by Ladd (1964), shearing of normally consolidated (NC) to lightly overconsolidated (OC) clays results in the generation of positive excess pore water pressures. Consequently, this leads to a reduction in the effective stress within the soil mass, resulting in a decrease in shear strength. In contrast, shearing of heavily overconsolidated clays results in the development of negative excess pore water pressures. The negative excess pore water pressure leads to a temporary increase in the shear strength of such clays. Over time, the negative excess pore water pressure dissipates, resulting in a reduction in shear strength. In the field, the bearing pressure exerted by the foundation on a heavily OC clay generates positive (volumetric component) and negative (deviatoric component) excess pore water pressures (Zdravković et al., 2003). As a result, the critical ultimate bearing capacity of foundations in OC clays is uncertain.

The main purpose of this article is to determine whether the ultimate bearing capacity of shallow foundations in fine-grained soils is predominantly controlled by the undrained shear strength or by the drained shear strength. This is accomplished through a comparative analysis of the estimated undrained (short-term) and the drained (long-term) ultimate bearing capacities, obtained from empirical and theoretical equations, with the ultimate bearing capacity measured in full-scale load tests. Case histories of footing load tests and relatively large-sized plate load tests on fine-grained soils were collected for this study. These case histories include soil data crucial for estimating undrained and drained ultimate bearing capacities. The relationship between the estimated and measured ultimate bearing capacities is examined for each bearing capacity equation. Furthermore, it is well-recognized that the undrained shear strength is not an intrinsic soil property; its magnitude varies depending on the testing method employed. Consequently, the predicted undrained ultimate bearing capacity will also vary based on the magnitude of undrained strength utilized in the calculation. Therefore, the accuracy of each test in predicting the mobilized undrained shear strength during a footing load test is also evaluated. Finally, the predicted drained and undrained bearing capacities are compared to identify the critical bearing capacity of shallow foundation on clays. The information summarized in the database is supplemented by shear strength data specific to Houston, Texas, soils to validate the findings of the database analysis.

TAMU-SHAL-CLAY-Load Test DATABASE

TAMU-SHAL-CLAY-Load Test is a database of shallow footing load tests and relatively large-sized plate load tests conducted on normally consolidated to overconsolidated clays. It consists of 97 load tests performed at 26 different locations. Out of the 97 load tests, 29 were part of the *TAMU-SHAL-CLAY* database previously prepared by Bahmani and Briaud (2021). Thirty-one (31) load tests came from the French load test database (Canepa and Depresles, 1990) provided by Philippe Reiffstek of Université Gustave Eiffel. The other 37 were obtained from publicly available documents.

TAMU-SHAL-CLAY-Load Test has been organized in an Excel spreadsheet divided into five main sections: Record Information, Footing/Plate Properties, Stratification and Soil Properties, Available Shear Strength Data, and Load-Test Data. A summary of case histories included in the database is presented in Table 1.

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Type of Load Test, Size of Loaded Area, and Embedment Ratio (D_f/B)

One of the main selection criteria for the load test to be included in the database was that the footing/steel plate should have a minimum width/diameter of 0.3 m. Out of the 97 load-settlement curves, 43 were obtained from footing load tests with equivalent diameters ranging from 0.34 m to 9.44 m. 54 load-settlement curves were obtained from plate load tests with equivalent diameters ranging from 0.30 m to 1.13 m. Overall, the mean equivalent diameter of the loaded area is 1.1 m, with a standard deviation of 1.06 m. 27 footing load tests and 43 plate load tests were conducted without embedment. The remaining load tests were performed with embedment ratios ranging from 0.22 to 4.52 m, a mean of 1.41 m and a standard deviation of 1.33 m.

Shear Strength Parameter:

Undrained Shear Strength S_u and In-Situ Field Test Data

Data for S_u came from laboratory tests such as the unconfined compression test (UC), the unconsolidated-undrained triaxial test (UU), the consolidated-undrained triaxial compression test (CXUC), the consolidated-undrained triaxial extension test (CXUE), and the direct simple shear test (DSS). Some case histories included data for S_u obtained from in-situ field tests such as the field vane test (FVT) and the pocket penetrometer test (PPT). When S_u is not provided, empirical correlations using in-situ field test data such the standard penetration test (SPT) N-value and Equation 1 by Terzaghi and Peck (1967), the pressuremeter test (PMT) limit pressure p_L and Equation 2 by Briaud (1992), and the cone penetrometer test (CPT) tip resistance q_c and Equation 3 were utilized to obtain an estimate of the undrained shear strength.

$$S_u(\text{kPa}) = 6.7 \times N(\text{in bpf}) \tag{1}$$

$$S_u(kPa) = 0.67 \times [p_L(\text{in kpa})]^{0.75} \tag{2}$$

$$S_u = \frac{q_c - \sigma_{v0}}{N_k} \tag{3}$$

In Equation 3, σ_{v0} is the total overburden stress and N_k is the cone factor. Briaud (2013) suggested an average N_k value of 14 $\pm$ 5 to be used for the correlation to the undrained shear strength. In this paper, an average N_k value of 14 was used in correlating CPT q_c to S_u.

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Table 1. *Summary of TAMU-SHAL-CLAY-Load Test database case histories (cont.).*

No.	Location	References	No. of Tests	Type of Test	Equivalent Diameter of Loaded Area (m)	Soil Type	Suction (kPa)	Stress History	Loading Type
1	Bothkennar, Scotland	Jardine et al. (1995)	1 1	Footing	2.48 2.71	Soft Estuarine Clay		NC to Lightly OC	UU CU
2	New South Wales, Australia	Gaone et al. (2018)	2 1	Footing	2.03	Estuarine Clay		NC to Lightly OC	UU CU
3	Kinnegar, Ireland	Lehane (2003)	1	Footing	2.26	Highly Plastic Silt		NC to Lightly OC	UU
4	Essex, UK	Schnaid et al. (1993)	1	Footing	9.44	Very soft to Firm Clay		NC	UU
5	Corvallis, Oregon	Newton (1975)	3	Footing	0.34 - 0.6	Very soft to Soft Plastic Silt (ML)		OC	UU
6	Baytown, Texas	Stuedlein & Holtz (2010)	3	Footing	0.76 - 3.09	Clay (CL)		OC	UU
7	Rangsit, Thailand	Brand et al. (1972)	5	Footing	0.68 - 1.18	Sensitive Marine Clay		NC	UU
8	Ottawa, Canada	Bauer et al. (1976)	1 3	Footing Plate	3.5 0.46	Lacustrine and Marine Clay		OC	UU
9	Houston, Texas	Sheikh & O'Neill (1983)	1	Footing	2.29	Stiff to Very Stiff Clays (CH)		OC	UU
10	Porto Alegre, Brazil	Consoli et al. (1998)	3 3	Footing Plate	0.45 - 1.13 0.3 - 0.6	Lightly Cemented Unsaturated Clay (CL)	10		UU UU
11	Adelaide, Australia	Pile (1975)	1	Footing	1.29	Silty Clay		Lightly OC	
12	Lund, Sweden	Larsson (2001)	3	Footing	0.56 - 2.26	Clay Till		OC	UU
13	Vagverket, Sweden	Larsson (1997)	3	Footing	0.56 - 2.26	Silt/Silty Clay		Lightly OC	UU
14	Vatthammar, Sweden	Larsson (1997)	2 1	Footing Footing	0.56 - 1.13 2.26	Very Stiff Silt/Clay	28		UU
15	Haga, Norway	Andersen & Stenhamar (1982)	2	Plate	1.13	Medium Stiff Clay		OC	UU
16	Texas City, USA	Tand et al. (1986)	8	Plate	0.58	Stiff to Very Stiff Clays (CH)		OC	UU
17	Cowden, UK	Marsland & Powell (1980)	1	Plate	0.87	Clay Till		Lightly OC	UU
18	Watford, UK	Marsland & Powell (1991)	1	Plate	0.87	Chalky Clay Till		OC	UU
19	India	Sultana & Dey (2019)	6	Plate	0.34 - 0.51	Clay (CH)		NC	UU
20	India	Deshmukh & Ganpule (1994)	2	Plate	0.68	Marine Clay (CH)		OC	

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No.	Location	References	No. of Tests	Type of Test	Equivalent Diameter of Loaded Area (m)	Soil Type	Suction (kPa)	Stress History	Loading Type
21	Cochabamba Bolivia	Rojas et al. (2007)	2	Plate	0.3	Lean Clay	3		UU
22	Kanpur, India	Yudhbir et al. (1979)	2	Plate	0.3 - 0.45	Kankar (Silty/Clayey Soil)		OC	UU
23	Adana, Turkey	Ornek et al. (2012)	3	Plate	0.45 - 0.9	Medium Stiff Silty Clay (CH)		Lightly OC	UU
24	Jossigny, France	Canepa & Depresles (1990)	5	Footing	0.80 - 1.38	Silt		NC	UU
25	Lognes, France	Canepa & Depresles (1990)	5	Footing	0.8	Clay		OC	UU
26	Provins, France	Canepa & Depresles (1990)	6	Plate	0.8 - 1.13	Stiff Clay		OC	UU

Table 2 summarizes the statistics of the average undrained shear strength data of soils within the zone of influence taken as one footing width or 1B (Briaud, 2023) below the bottom of the loaded area in the *TAMU-SHAL-CLAY-Load Test* database. Table 3 summarizes the average field test data within the zone of influence of the loaded area and the corresponding undrained shear strength using the empirical correlations specified previously.

Table 2. *Summary of S_u in TAMU-SHAL-CLAY-Load Test database.*

Type of Test	No. of case histories	No. of sites	Range of Values (kPa)	Mean, μ (kPa)	Standard Deviation, σ (kPa)
UC	23	5	9.5 – 73.9	26.5	19.6
UU	58	14	8.4 – 249.5	59.4	45.4
CXUC	17	8	13.4 – 174.9	63.6	52.5
CXUE	8	5	8.5 – 37	16.9	10.6
DSS	5	3	12.5 – 59.8	32.7	24.7
FVT	25	9	11.6 – 373.3	90.5	106.1
PPT	14	3	58.6 – 101.4	81.5	17.6

Table 3. *Summary of in-situ field test data and the corresponding S_u in TAMU-SHAL-CLAY-Load Test database.*

Type of Test	No. of case histories	No. of sites	Data	Range of Values (kPa)	Mean, μ (kPa)	Standard Deviation, σ (kPa)
SPT	43	9	*N*-value	4 – 16.2 blows per foot	8.5	3.9
			S_u from Equation 1	26.8 – 108.5	56.8	26.3
PMT	61	12	p_L	140.3 – 1383.3	631.2	356.4
			S_u from Equation 2	27.3 – 152	82.1	34.3
CPT (arithmetic mean)	64	16	q_c	213.1 – 3797.1	1730.9	889
			S_u from Equation 3	12.4 – 266	121.1	63.7
CPT (geometric mean)	39	14	q_c	211.9 – 3796.8	1408.8	1013.8
			S_u from Equation 3	12.3 – 265.9	97.8	72.1

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Drained Shear Strength Parameters

56 load tests from 14 locations included c’ and ϕ’ data obtained from consolidated-drained triaxial tests or consolidated-undrained triaxial tests with pore pressure measurements. The range of c’ values is 0 – 55.0 kPa, with an average value of 12.1 kPa and a standard deviation of 11.0 kPa. The range of ϕ’ values is 12o – 36o, with an average value of 28.6o and a standard deviation of 6.2o.

Matric Suction Data

Eleven load tests were done on soils that were partially saturated. These load tests were performed at Porto Alegre in Brazil, Cochabamba in Bolivia, and Vatthammar in Sweden. A single representative value of matric suction u_w was provided for the site in Brazil and Bolivia. Both sites have matric suction of less than 10 kPa. A matric suction profile was provided for the site in Sweden. An average value of matric suction within one footing width dimension (1B) below the bottom of the foundation is used in the bearing capacity analysis for this location. The average value of the matric suction within the zone of influence for the site in Sweden is determined to be 28 kPa.

The effect of matric suction on the bearing capacity of soil is considered by calculating the apparent cohesion c_{app} using Equation 4, and then adding it to the cohesion term of the ultimate bearing capacity equation for shallow foundations. Because the degree of saturation is provided in all three test locations, it is convenient to estimate the water area ratio α to be equivalent to the degree of saturation S_r (Briaud, 2023), as shown in Equation 5. The degrees of saturation are 0.78, 0.85, and approximately 1.0 for the Brazil, Sweden, and Bolivia test locations, respectively.

$$c_{app} = -\alpha u_w \tan \phi' \tag{4}$$

$$\alpha = S_r \tag{5}$$

Loading Type

In the load tests, the soil was brought to failure by pushing the loaded area using a stress-controlled (incremental load) type of loading or a strain-controlled (constant rate of penetration) type of loading. In a stress-controlled loading, the footing/plate is pushed to failure by adding weight after a specific time interval. On the other hand, a strain-controlled test is done by applying a constant displacement rate to the footing/plate until the soil reaches failure.

In Table 1, UU refers to an unconsolidated-undrained type of load test. In a UU test, the soil is sheared to failure rapidly without any pore water pressure dissipation. In a strain-controlled test, the soil is constantly being pushed, and excess pore water pressure is continuously generated during the test. Therefore, a strain-controlled load test can be associated with a UU test condition. On the other hand, during an incremental load test, dissipation of pore water pressure is possible because the load is maintained for a certain time interval before applying any additional load. However, since the load tests were done on fine-grained soils, it is unlikely that some dissipation of excess pore water pressure took place between load increments. It is reasonable to assume that 95 of the 97 load tests listed in Table 1 are undrained tests. However, two of the 97 load tests had a long enough load step that they could be considered as drained tests associated with a CU type of loading.

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In a CU load test, the load is constantly increased until a predetermined load level is achieved. Once the predetermined load level is reached, the load is maintained for days or months to allow dissipation of the generated excess pore water pressure before the soil is sheared to failure. In the CU test on the NC to lightly OC clay of Bothkennar, Scotland (Load Test ID 2), the soil was loaded to 65% of the estimated undrained ultimate bearing capacity. This magnitude of stress was maintained for eleven years, and the soil was then sheared to failure in 2.6 days. Because of the consolidation stage, the ultimate bearing capacity of the soil increased by 48% (Lehane and Jardine, 2003). In the CU test on the NC to lightly overconsolidated clay of New South Wales, Australia (Load Test ID 5), the soil was consolidated twice prior to shearing. In the first stage of the test, the soil was loaded to 30% of the estimated undrained ultimate bearing capacity. This magnitude of stress was held for 18 months, and the load was then increased to 67% of the estimated undrained ultimate bearing capacity. After six days, the soil was sheared to failure. The observed increase in bearing capacity due to preloading was about 15% of the undrained ultimate bearing capacity (Gaone et al., 2018). The increase in bearing capacity due to preloading from these two tests agrees well with the numerical prediction of preloading effect on the undrained bearing capacity by Zdravković et al. (2003).

Definition of the Measured Ultimate Bearing Capacity

The ultimate bearing pressure measured from the load-settlement curve corresponds to the applied bearing pressure that causes the soil to reach a predetermined failure criterion. Typically, the failure criterion is based on the magnitude of the resulting settlement. For the case histories included in the database, failure was typically defined as the load corresponding to a settlement equal to 10% or 15% of the footing/plate width. To standardize the data analysis, the ultimate bearing pressure was taken as the pressure that will result in a settlement magnitude equal to 10% of the footing/plate width (Vesić, 1975).

For load tests that were not pushed far enough to meet the failure criterion, a hyperbolic extrapolation was performed to determine the ultimate bearing pressure. This methodology is based on the proposed soil model by Duncan and Chang (1970), where the load displacement curve is approximated by a hyperbolic function, as shown in Equation 6.

$$p = \frac{s}{a + b \times s} \tag{6}$$

Here, p refers to the applied bearing pressure, s refers to the resulting settlement, and a and b are hyperbolic fitting parameters. The parameter a is the inverse of the slope of the tangent to the curve at the origin ($s = 0$), and the parameter b is the asymptote of the hyperbola. Hyperbolic parameters a and b are determined by transforming the load-settlement plot into an s/p versus s plot. The s/p versus s plot is fitted with a straight line that has an intercept a and a slope b. By performing linear regression on the transformed load-settlement data, the hyperbolic parameters a and b are determined.

During the extrapolation, emphasis was given to load settlement curves that reached higher settlement over footing width ratios (s/B). For the hyperbolic regression, the last four points on the load-settlement data were used to obtain the hyperbola parameters. Figure 1 illustrates how the measured ultimate bearing capacity from the load test $p_{ult,LT}$ was determined from the load settlement curve.

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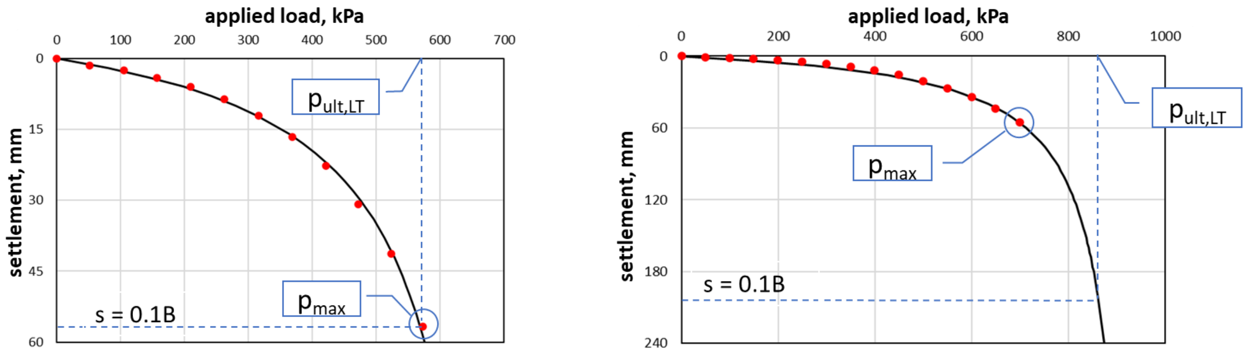

a. $p_{max}/p_{ult,LT} = 1.0$ (Load Test ID 40) b. $p_{max}/p_{ult,LT} > 0.67$ (Load Test ID 30)

Figure 1. *$p_{ult,\ measured}$ from load settlement curve: a) read directly from the load settlement curve; b) extrapolated from the load settlement curve.*

ULTIMATE BEARING CAPACITY EQUATIONS

Undrained/Short-Term Ultimate Bearing Capacity

Skempton (1948) proposed an equation to estimate the ultimate bearing capacity of shallow foundation on undrained clays (Equation 7).

$$p_{ult} = S_u N_c + \gamma D_f \tag{7}$$

In Equation 7, N_c is the bearing capacity factor that is a function of the shape and the embedment ratio D_f/B of the foundation, γ is the total unit weight of the soil above the bottom of the foundation, D_f is the depth of embedment, and B is the width of the foundation. The value for N_c can be determined from Table 4. The N_c value to be used for rectangular footings is determined by adjusting the N_c value for a strip footing by a factor equal to $1 + 0.2(B/L)$, where L is the length of the foundation.

Table 4. *Tabulated N_c values for use with Skempton's equation (adapted from Skempton, 1948).*

D_f/B	N_c	
	Square	**Strip**
0	6.2	5.14
0.25	6.7	5.6
0.5	7.1	5.9
0.75	7.4	6.2
1.0	7.7	6.4
1.5	8.1	6.8
2.0	8.4	7.0
2.5	8.6	7.2
3.0	8.8	7.4
4.0	9.0	7.5
> 4.0	9.0	7.5

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Empirical relationships to directly estimate the undrained ultimate bearing capacity of clays using data from in-situ field tests are also available. The general form of these equations, shown in Equation 8, is similar to the form of Skempton's equation (Briaud, 2023). In this equation, k is the bearing capacity factor and s_{str} is a measure of the soil's shear strength averaged over the zone of influence.

$$p_{ult} = k s_{str} + \gamma D_f \tag{8}$$

The following empirical equations from Briaud (2023) are utilized in this paper to estimate undrained ultimate bearing capacity of shallow foundations from SPT N-value (Equation 9), from PMT limit pressure p_L (Equation 10), and from CPT cone tip resistance q_c (Equation 11). According to Briaud (2023), the bearing capacity factors for shallow foundations on clays are 0.4, 0.9, and 0.4 for k_N, k_p, and k_c, respectively. In Equation 9, N is in blows per foot and p_a corresponds to the atmospheric pressure constant (101.324 kPa).

$$p_{ult} = k_N N p_a + \gamma D_f \tag{9}$$

$$p_{ult} = k_p p_L + \gamma D_f \tag{10}$$

$$p_{ult} = k_c q_c + \gamma D_f \tag{11}$$

Drained/Long-Term Ultimate Bearing Capacity

Accoring to AASHTO LRFD 9th edition/FHWA GEC No. 6, CFEM 4th ed., and EC 7, the drained ultimate bearing capacity of a shallow foundation on clays can be estimated using the general bearing capacity equation, shown in Equation 12, together with the appropriate bearing capacity factors to account for the effect of shape of foundation, the depth of embedment of the foundation, and the effect of load inclination. The proposed equations by Prandtl (1921) and Reissner (1924) are the most widely accepted expression to estimate N_c and N_q, respectively, while several expressions for N_γ exist due to the different assumtions made on the shape of the failure wedge (Briaud, 2023). The expression for N_γ by Vesić (1975) was specified in the AASHTO/FHWA bearing capacity recommendations, while Briaud (2023) suggested an expression for N_γ from Meyerhof (1963). Furthermore, AASHTO/FHWA adopted the shape, embedment, and depth factors by Vesić (1975). Meanwhile, Briaud (2023) reviewed established equations for these factors and suggested expressions which represent reasonable averages of all shape factors and inclination factors found in the literature, as shown in Table 5. Note that, in the database, most load tests wereconducted on an excavated surface, free of any influence of embedment depth.

$$p_{ult} = c' N_c s_c i_c d_c + q N_q s_q i_q d_q + \frac{1}{2}\gamma B N_\gamma s_\gamma i_\gamma d_\gamma \tag{12}$$

Table 5. *Influence factors for the general bearing capacity equation (adapted from Briaud, 2023).*

Shape factors	Inclination Factor
$s_c = 1 + 0.2(B/L)$	$i_c = (1 - \beta/90)^2$
$s_q = 1$	$i_q = (1 - \tan\beta)^{1.5}$
$s_\gamma = 1 - 0.3(B/L)$	$i_\gamma = (1 - \tan\beta)^{2.5}$

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The ultimate bearing capacity of soils with water tension is typically calculated by including the effects of the water tension on the cohesion component of the general bearing capacity equation. The additional cohesion, called the apparent cohesion c_{app}, is estimated using Equation 4; the ultimate bearing capacity equation for soils with water tension is given by Equation 13.

$$p_{ult} = (c' + c_{app})N_c s_c i_c d_c + qN_q s_q i_q d_q + \frac{1}{2}\gamma B N_\gamma s_\gamma i_\gamma d_\gamma \tag{13}$$

COMPARISON OF MEASURED AND ESTIMATED ULTIMATE BEARING CAPACITIES

This section presents the results of the comparison between the measured ultimate bearing capacity from the load test $p_{ult,measured}$ and the estimated ultimate bearing capacity $p_{ult,predicted}$. The measured ultimate bearing capacity was taken as the asymptotic value obtained from the load test (equal to $p_{ult,LT}$). The estimated ultimate bearing capacity was obtained using Skempton's equation (Equation 7) and direct strength equations using in-situ field test data (Equation 9 to Equation 11) for the short-term bearing capacity, and using the general bearing capacity equation for soils with water in compression (Equation 12) and for soils with water in tension (Equation 13) for the long-term bearing capacity. For the long-term bearing capacity estimation, two sets of bearing capacity factors (AASHTO/FHWA and Briaud (2023) recommendations) were considered in the analysis. The ratio between $p_{ult,predicted}$ and $p_{ult,measured}$ was determined by performing linear regression from plots with $p_{ult,predicted}$ on the y-axis and $p_{ult,measured}$ on the x-axis. Detailed plots and histograms are available in Cruz (2024). Table 6 summarizes the resulting $p_{ult,predicted}/p_{ult,measured}$ from the comparison, including the number of data points for each case. Note that only load test data where the maximum applied pressure exceeded 67% of the measured ultimate bearing capacity were further considered in the comparison.

Table 3. *Finite difference cases to match Brown (2013) cantilever wall experiment.*
Summary of the comparison between predicted and measured ultimate bearing capacities from TAMU-SHAL-CLAY-Load Test database.

Bearing capacity equation with strength parameters	No. of data points	$p_{ult,predicted}/p_{ult,measured}$	R^2
General bearing capacity with c'-φ' and:			
Using AASHTO/FHWA factors	53	1.50	0.81
Using Briaud (2013) factors	53	1.12	0.81
Skempton's equation with S_u from:			
UC	23	0.62	0.79
UU	57	0.89	0.90
CXUC	15	0.97	0.94
CXUE	6	0.58	0.97
DSS	4	0.90	1.00
FVT	21	1.50	0.87
PPT	14	1.36	0.94
SPT *N*-value correlation (Terzaghi & Peck, 1967)	43	0.81	0.84
PMT p_L correlation (Briaud, 1992)	59	0.94	0.96
CPT arithmetic mean q_c correlation	61	1.57	0.90
CPT geometric mean q_c correlation	36	1.35	0.92
Direct strength equations with:			
SPT *N*-value (Briaud, 2013)	43	0.77	0.82
PMT p_L (Briaud, 2013)	59	1.05	0.94
CPT arithmetic mean q_c (Briaud, 2013)	61	1.37	0.88
CPT geometric mean q_c (Briaud, 2013)	36	1.12	0.91

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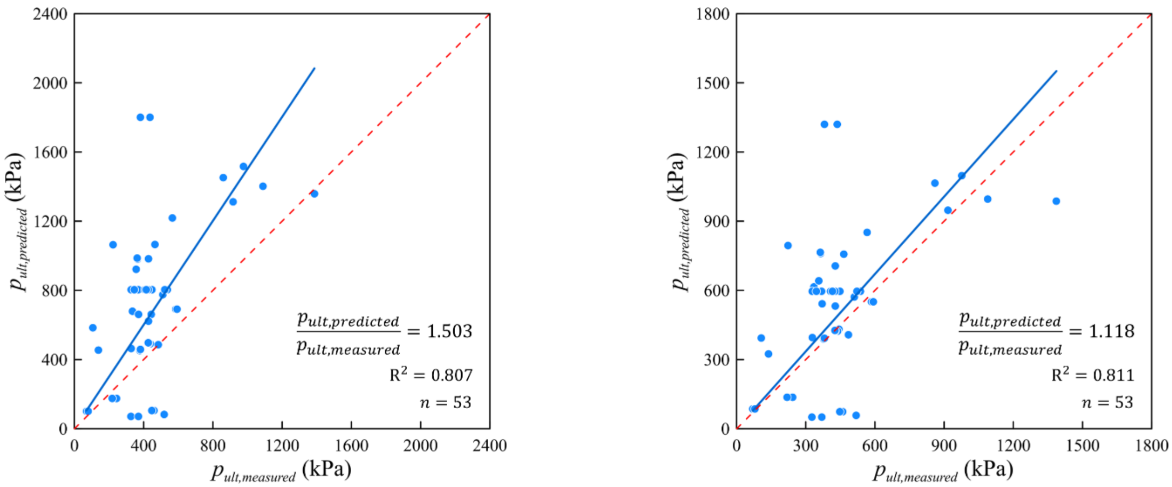
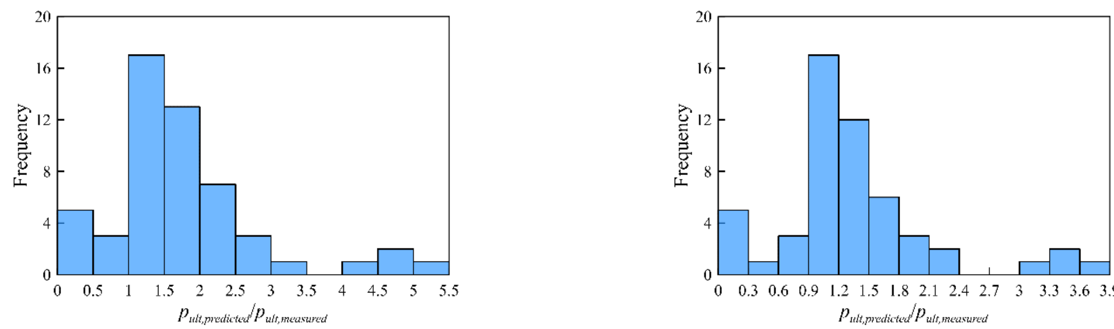
From Table 6, it is evident that, regardless of the bearing capacity factors and influence factors employed, the drained ultimate bearing capacity equation consistently overestimates the measured ultimate bearing capacity from load tests. This discrepancy is expected, as load tests in clays tend to simulate undrained shearing conditions. Figure 2 shows the plot of $p_{ult,predicted}/p_{ult,measured}$ using the two sets of bearing capacity factors and their corresponding histograms.



a. AASHTO/FHWA bearing capacity factors.

b. Briaud (2023) bearing capacity factors.



c. Histogram for AASHTO/FHWA bearing capacity factors.

d. Histogram for Briaud (2023) bearing capacity factors.

Figure 2. *Comparison of $p_{ult,measured}$ and $p_{ult,predicted}$ using the general bearing capacity equation: a) with AASHTO/FHWA bearing capacity factors; b) with Briaud (2023) bearing capacity factors; c) histogram of $p_{ult,predicted}/p_{ult,measured}$ for AASHTO/FHWA; and d) histogram of $p_{ult,predicted}/p_{ult,measured}$ for Briaud (2023) factors.*

The undrained ultimate bearing capacity predicted using Skempton's equation is generally lower than the measured ultimate bearing capacity when the undrained shear strength is determined from laboratory tests. As observed in Table 6, the undrained shear strength measured from a triaxial compression test provided the most accurate prediction of the ultimate bearing capacity. This accuracy is expected, as the CXUC test precisely simulates the stress path of the soil beneath a shallow foundation load test. Moreover, the effect of sample disturbance is minimized in a CXUC test, ensuring that the measured shear strength is a reliable representation of the actual value and, consequently, leads to a good estimate of the measured ultimate bearing capacity. The use of S_u from a UU test resulted in a good estimate of the measured ultimate bearing capacity on average, considering that the effect of sample disturbance is not minimized in a UU test. This finding justifies the efficiency of a UU test in estimating S_u for shallow foundation design. Figure 3 shows the plot of $p_{ult,predicted}/p_{ult,measured}$ using the S_u obtained from a CXUC test and a UU test, and their corresponding histograms.

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The undrained ultimate bearing capacity predicted by Skempton's equation, using undrained shear strength estimated from field tests like FVT and PPT, resulted in an overprediction of the ultimate bearing capacity.

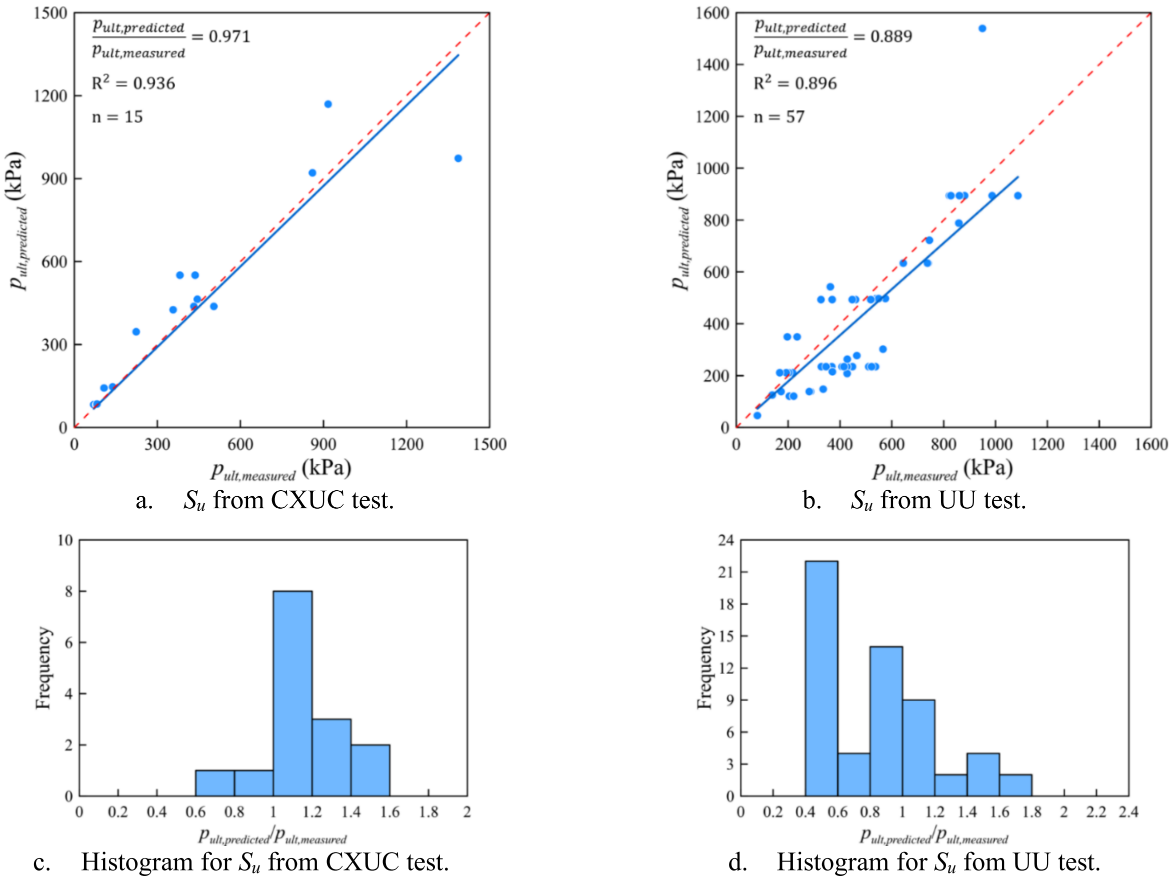

Figure 3. *Comparison of $p_{ult,measured}$ and $p_{ult,predicted}$ using Skempton's equation: a) with S_u from a CXUC test; b) with S_u from a UU test; c) histogram of $p_{ult,predicted}/p_{ult,measured}$ for S_u from CXUC test; and d) histogram of $p_{ult,predicted}/p_{ult,measured}$ for S_u from UU test.*

Using Skempton's equation with S_u determined from empirical correlations to field tests, such as the SPT *N*-value and the PMT p_L, resulted in a predicted undrained ultimate bearing capacity lower than the measured capacity. Conversely, Skempton's equation with S_u determined from empirical correlation to CPT q_c resulted in a predicted undrained ultimate bearing capacity greater than the measured capacity. The discrepancy in bearing capacity prediction using empirical correlation of S_u from CPT q_c is likely due to the use of a single value for N_k (equal to 14) in the correlation. It is generally known that different sites have different N_k values, and the correlation value depends on various factors (Mayne, 2007; Schmertmann, 1978). Kim et al. (2006) provided a comprehensive discussion of empirical and analytical studies of the cone factor N_k, showing a wide range of N_k values from 7.3 to 26.

A similar trend is evident in predicting undrained ultimate bearing capacity using direct strength equations with in-situ field test data obtained from SPT, PMT, and CPT. The undrained ultimate bearing capacity determined using SPT *N*-value and PMT p_L is either less than or approximately equal to the measured ultimate bearing capacity. Conversely, the predicted undrained ultimate bearing capacity derived from CPT q_c exceeds the measured value.

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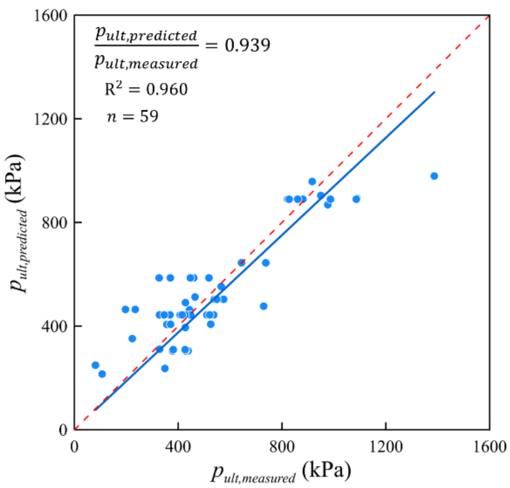
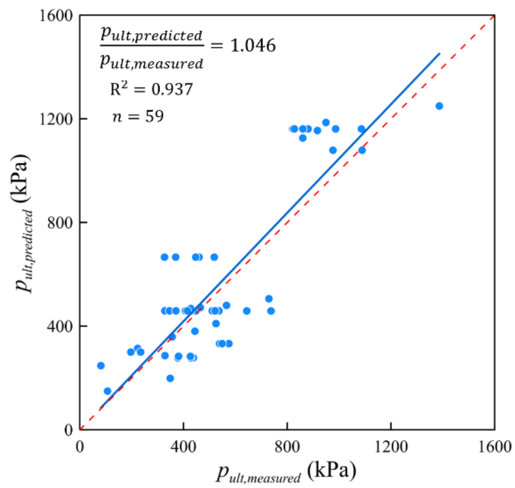
The use of the geometric mean of q_c, as opposed to the arithmetic mean, resulted in a predicted ultimate bearing capacity that closely aligns with the actual ultimate bearing capacity. This can be primarily attributed to the fact that the geometric average softens the impact of outliers in the mean value of the CPT q_c. During CPT testing, encountering spikes in the tip resistance value is not uncommon. Therefore, employing the geometric average for correlation with undrained shear strength or estimating undrained ultimate bearing capacity using the geometric mean of the CPT q_c proves advantageous.

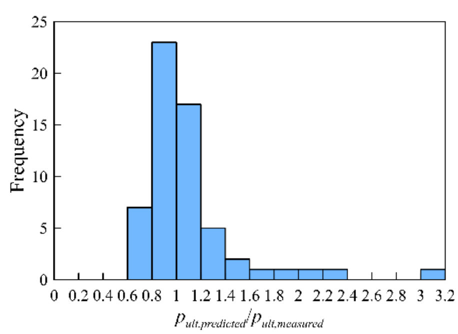
Remarkably, utilizing PMT p_L resulted in a very good comparison between the predicted undrained ultimate bearing capacity and the measured ultimate bearing capacity. One can argue that the PMT gives the horizontal capacity and not the vertical capacity. However, it can be shown (Briaud, 2023) that the horizontal capacity contributes the largest amount to the vertical capacity of shallow foundations. This maybe the reason why, in addition to the PMT being a mini load test, the predictions are close to the measurements. Figure 4 shows the plot of $p_{ult,predicted}/p_{ult,measured}$ using Skempton's equation with S_u obtained from PMT p_L correlation and using direct strength equation with PMT p_L, and their corresponding histograms.



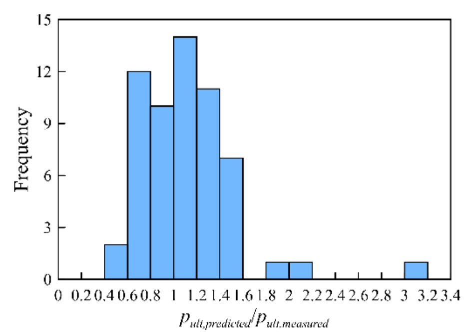
a. Skempton's Equation with S_u from PMT p_L.



b. Direct Strength Equation with PMT p_L.



c. Histogram for Skempton's equation with S_u from PMT p_L.



d. Histogram for Direct Strength Equation with PMT p_L.

Figure 4. *Comparison of $p_{ult,measured}$ and $p_{ult,predicted}$: a) using Skempton's equation with S_u correlated with PMT p_L; b) using direct strength equation with PMT p_L; c) histogram of $p_{ult,predicted}/p_{ult,measured}$ for S_u correlated with PMT p_L; and d) histogram of $p_{ult,predicted}/p_{ult,measured}$ for direct strenth equation with PMT p_L.*

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DIRECT COMPARISON OF LONG-TERM AND SHORT-TERM BEARING CAPACITIES

In the preceding section, it was shown that using Skempton's equation, with S_u obtained from a CXUC test and from a correlation to PMT p_L, resulted in a good approximation of the ultimate bearing capacity of shallow foundations on clays measured in a short-term load test. In addition, utilizing the direct strength equation with the PMT p_L yielded a comparable but slightly higher approximation of the ultimate bearing capacity. In this section, the estimated drained ultimate bearing capacity and the estimated undrained ultimate bearing capacity are compared for these specific cases mentioned previously to determine the governing ultimate bearing capacity of shallow foundations on clays. Two sets of bearing capacity factors are again utilized to calculate the drained ultimate bearing capacity.

Only 14 load test data from six different test locations have pairs of S_u from a CXUC test and the corresponding c'-ϕ' information. The comparison of the undrained ultimate bearing capacity calculated using Skempton's equation with S_u obtained from a CXUC triaxial test $p_{ult,undrained}$ to the calculated drained ultimate bearing capacity using AASHTO/FHWA recommendations and Briaud's (2023) recommendations $p_{ult,drained}$ is shown in Figure 5a. This figure indicates that the drained ultimate bearing capacity calculated using AASHTO/FHWA recommendations and Briaud's (2023) recommendation is 1.7 and 1.2 times greater than the undrained ultimate bearing capacity, respectively.

On the other hand, 41 load test data from seven different test locations have pairs of p_L and c'- ϕ' information. The comparison of the undrained ultimate bearing capacity calculated using Skempton's equation with S_u obtained from limit pressure correlation $p_{ult,undrained}$, to the calculated drained ultimate bearing capacity using AASHTO/FHWA recommendations and Briaud's (2023) recommendations $p_{ult,drained}$ is shown in Figure 5b. This figure indicates that the drained ultimate bearing capacity calculated using AASHTO/FHWA recommendations and Briaud's (2023) recommendation is 1.5 and 1.1 times greater than the undrained ultimate bearing capacity, respectively. The comparison of the undrained ultimate bearing capacity calculated using the direct strength equation with limit pressure data $p_{ult,undrained}$ to the calculated drained ultimate bearing capacity using AASHTO/FHWA recommendations and Briaud's (2023) recommendations $p_{ult,drained}$ is shown in Figure 5c. This figure indicates that the drained ultimate bearing capacity calculated using AASHTO/FHWA recommendations is 1.3 times greater than the undrained ultimate bearing capacity. However, Briaud's (2023) recommendations resulted in a drained bearing capacity that is approximately equal to the undrained bearing capacity. Note that the existence of outliers, with $p_{ult,drained}/p_{ult,undrained}$ of 0.08-0.11, caused the mean value of the ratio to decrease. Without these outliers, the resulting relationship between the drained ultimate bearing capacity using Briaud's (2023) recommendation and the undrained ultimate bearing capacity ($p_{ult,drained}/p_{ult,undrained}$ = 1.12) would be consistent with the previous two comparisons.

The results of the comparison revealed that, on average, the predicted undrained ultimate bearing capacity is less than the drained ultimate bearing capacity; hence, the undrained bearing capacity is more critical for the design of shallow foundations on clays. This outcome is expected, given that most clays included in the database exhibited undrained strengths below 100 kPa. Indeed, this tends to indicate that those clays were normally consolidated or lightly overconsolidated.

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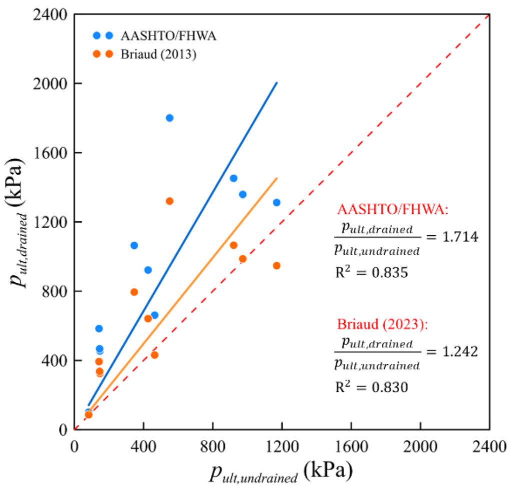
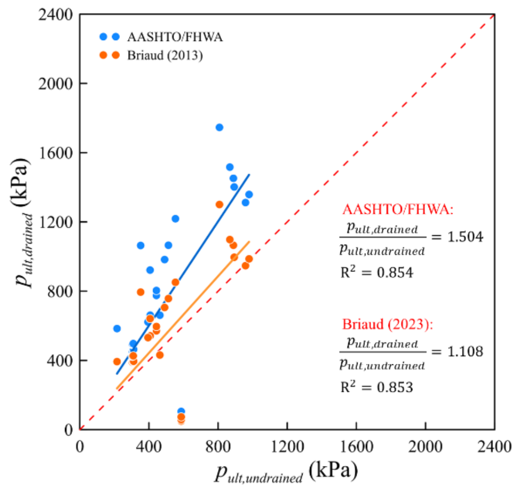
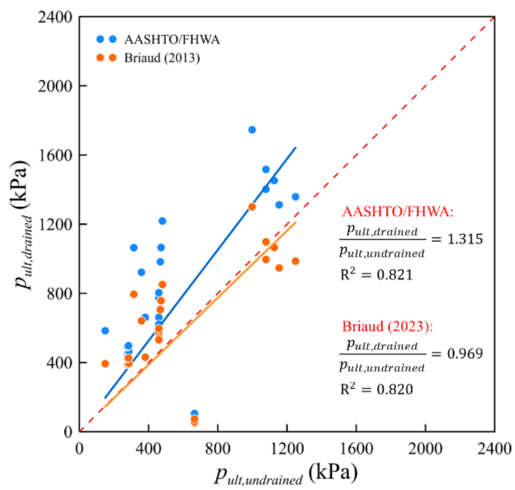


a. Undrained bearing capacity from Skempton's equation with S_u from CXUC test.



b. Undrained bearing capacity from Skempton's equation with S_u from PMT p_L correlation.



c. Undrained bearing capacity from direct strength equation with PMT p_L correlation.

Figure 5. *Comparison of $p_{ult,drained}$ and $p_{ult,undrained}$ with undrained bearing capacity estimated: a) using Skempton's equation with S_u from CXUC test; b. using Skempton's equation with S_u from PMT p_L correlation; and c) using direct strenth equation with PMT p_L.*

DATA OF HOUSTON, TEXAS, FINE-GRAINED SOIL

To further validate the finding that the undrained bearing capacity is more critical than drained bearing capacity for shallow foundations on clays, actual shear strength data of clays found in Houston, Texas, were considered in the bearing capacity prediction. 36 pairs of undrained shear strength and the corresponding drained shear strength parameters were provided by the Intertek PSI Houston office to aid in the validation. This set of shear strength data is from UU and CXUC laboratory tests, performed on low plasticity (CL) to high plasticity (CH) clays obtained from 36 different borehole locations, and at various depths. The set of data is shown in Table 7.

The range of S_u values is from 24.8 to 248.6 kPa, with an average value of 113.6 kPa and a standard deviation of 68.8 kPa. The range of c' values is from 0 to 59.8 kPa, with an average value of 21.1 kPa and a standard deviation of 12.8 kPa. The

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range of ϕ' values is from 14.4º to 37.5º, with an average value of 22.6º and a standard deviation of 5.8º. Ground water and unit weight information were also included in the information provided to the authors.

Table 7. *Set of shear strength data of clays found in Houston, Texas.*

Data No.	Depth, m	USCS	S_u, kPa	c', kPa	ϕ', º
1	3.0	CH	184.8	31.6	18.2
2	10.7	CH	209.7	5.3	22.3
3	9.1	CL	215.5	16.7	22.1
4	13.7	CH	189.1	29.7	18.4
5	10.7	CL	216.9	31.6	32.2
6	27.4	CH	208.8	32.5	17.9
7	18.3	CH	155.1	9.6	26.2
8	27.4	-	234.8	31.1	16.6
9	10.7	-	228.2	40.2	20.6
10	24.4	CH	179.6	12.0	23.1
11	22.9	CH	248.6	25.8	25.5
12	6.1	CH	96.9	30.1	15.4
13	9.1	CL	50.7	37.3	18.1
14	4.6	CH	39.0	15.8	26.3
15	16.8	CH	63.4	59.8	19.7
16	9.1	CH	56.2	37.3	18.1
17	9.1	CL	93.8	26.3	20.2
18	3.0	CL	80.3	7.7	33.1
19	6.1	CL	117.2	0.0	37.5
20	6.1	CH	79.3	13.9	32.4
21	7.6	CH	86.2	12.0	21.4
22	6.1	CH	162.7	27.3	14.4
23	7.6	CH	86.2	27.3	19.6
24	7.6	CH	81.0	23.5	17.5
25	7.6	CH	24.8	3.8	18.3
26	4.6	CH	37.9	17.2	24.3
27	10.7	CH	87.2	0.0	20.8
28	3.0	CL	50.3	21.5	21.6
29	2.4	CH	86.5	10.1	27.5
30	7.6	CH	81.0	18.2	14.6
31	2.4	CH	67.2	21.1	27.0
32	1.5	CH	27.2	12.0	31.7
33	7.6	CH	80.3	11.5	30.5
34	4.6	CL	68.3	21.1	19.5
35	7.6	CL	36.9	9.1	20.4
36	6.1	CH	78.6	31.1	22.1

The undrained ultimate bearing capacity is calculated using Skempton's equation, and the drained ultimate bearing capacity is calculated using the general bearing capacity equation with Briaud (2023) bearing capacity factors considering a fictitious

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square footing that has a width equal to the embedment depth of 3 m. The ratio of $p_{ult,drained}$ and $p_{ult,undrained}$ is plotted against the undrained shear strength S_u, (Fig. 6). This figure indicates that $p_{ult,undrained}$ is greater than $p_{ult,drained}$ for clays with S_u greater than 120 kPa, while $p_{ult,drained}$ is greater than $p_{ult,undrained}$ for clays with S_u less than 120 kPa.

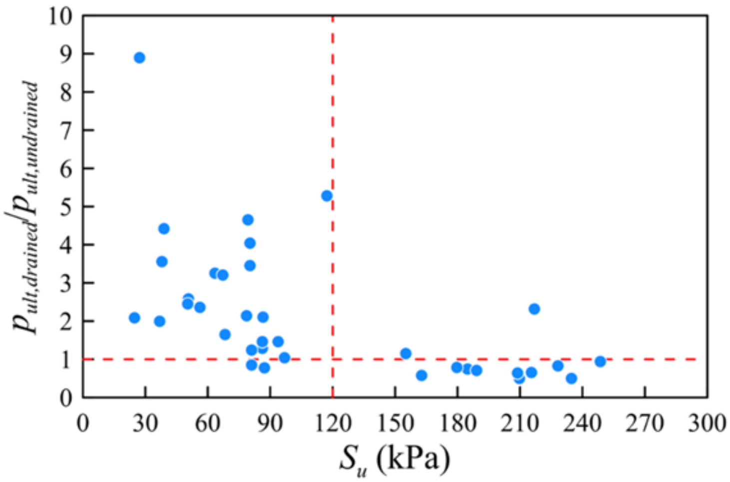

Figure 6. *Plot of $p_{ult,drained}/p_{ult,undrained}$ vs S_u for Houston, Texas, soil data (36 data points).*

The information from *TAMU-SHAL-CLAY-Load Test* database is combined with the Houston, Texas, soil data, and the resulting plots of $p_{ult,drained}/p_{ult,undrained}$ vs S_u are shown in Fig. 7. Considering both sets of data, the findings that $p_{ult,undrained} > p_{ult,drained}$ for $S_u > 120$ kPa and $p_{ult,undrained} < p_{ult,drained}$ for $S_u < 120$ kPa still hold true.

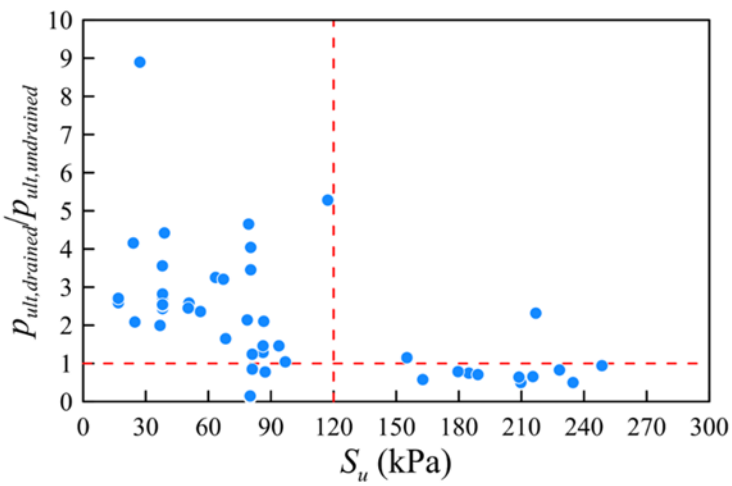

Figure 7. *Plot of $p_{ult,drained}/p_{ult,undrained}$ vs. S_u for combined TAMU-SHAL-CLAY-Load Test information and Houston, Texas, soil data (64 data points).*

CONCLUSIONS

The *TAMU-SHAL-CLAY-Load Test* database is a comprehensive database summarizing and organizing the results of 97 load tests performed on large-scale footings and steel plates across 26 different sites of fine-grained soil deposits. The data collected included various information, such as the test location, reference document, test results, information on soil

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stratification, and shear strength parameters. These parameters include S_u obtained from different laboratory tests (UC, UU, CXUC, CXUE, and DSS), field tests (FVT and PPT), and empirical correlations (SPT, PMT, and CPT). Additionally, it included c'-ϕ' obtained from CXUC triaxial tests with pore water pressure measurements. The calculated long-term/drained ultimate bearing capacity and the short-term/undrained ultimate bearing capacity were compared to the measured ultimate bearing capacity obtained from load tests. The long-term/drained ultimate bearing capacity was calculated using the general bearing capacity equation with c'-ϕ', incorporating bearing capacity factors and influence factors based on the recommendations from AASHTO/FHWA and Briaud (2023). The short-term/undrained ultimate bearing capacity was calculated using Skempton's equation with S_u and direct strength equations utilizing field test data (SPT, PMT, and CPT). The result of the comparison using the database information was validated by considering actual soil shear strength data from Houston, Texas, soils. The following conclusions were obtained:

- It was found that regardless of the bearing capacity factors and influence factors used, the calculated long-term/drained ultimate bearing capacity was 1.12 to 1.50 times the ultimate bearing capacity measured from the load test. This finding is likely due to the fact that most load tests can be considered as undrained.
- The calculated short-term bearing capacity using Skempton's equation with S_u from laboratory tests was 0.62 to 0.97 times the measured ultimate bearing capacity, while the calculated short-term bearing capacity was 1.36 to 1.50 times the measured ultimate bearing capacity for S_u determined directly from field tests such as FVT and PPT.
- Using Skempton's equation with S_u determined from empirical correlations to field tests, such as the SPT N-value and the PMT p_L, resulted in a calculated short-term/undrained ultimate bearing capacity that was 0.81 to 0.94 times the measured ultimate bearing capacity, respectively.
- Using Skempton's equation with S_u determined from an empirical correlation to CPT q_c resulted in a calculated short-term/undrained bearing capacity that was 1.35 to 1.57 times the ultimate bearing capacity measured from the load test, which can be attributed to the use of a single value for N_k in the analysis.
- A similar trend was observed for the short-term/undrained ultimate bearing capacity calculated using direct strength equations. The short-term/undrained ultimate bearing capacity calculated using SPT N-value, and PMT p_L was 0.77 and 1.05 times the measured ultimate bearing capacity, respectively, while the calculated short-term/undrained ultimate bearing capacity from CPT q_c was 1.12 to 1.37 times the measured ultimate bearing capacity.
- Using the geometric mean of q_c instead of the arithmetic mean resulted in a calculated ultimate bearing capacity that closely aligned with the measured ultimate bearing capacity.
- Using S_u obtained from a CXUC test to estimate the undrained ultimate bearing capacity yielded a prediction that was 0.97 times the measured undrained ultimate bearing capacity.
- Using the PMT p_L to estimate S_u with Skempton's equation, or to estimate the undrained ultimate bearing capacity using a direct strength equation, yielded predictions that were 0.94 and 1.05 times the measured ultimate bearing capacity, respectively.
- The combined data from Houston, Texas, soils and the data from *TAMU-SHAL-CLAY-Load Test* suggest that the short-term/undrained ultimate bearing capacity is greater than the long-term/drained ultimate bearing capacity for $S_u > 120$ kPa, and that the short-term/undrained ultimate bearing capacity is less than the long-term/drained ultimate bearing capacity for $S_u < 120$ kPa.

DATA AVAILABILITY

Some or all data that support the findings of this study are available from the corresponding author upon reasonable request.

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