Validation of the GT direct CPT footing method

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ABSTRACT: A Georgia Tech direct CPT method for vertically-loaded shallow foundations provides the magnitudes of displacements and bearing capacity using a simple algorithm that was developed from analyzing full-scale load test data on 70 footings situated on sands, silts, clays, and fissured geomaterials. Since publication in 2014, new footing load test data have become available that provide an opportunity to independently cross-check the method. Four new case studies involve footings on: natural sand, dynamically compacted sand, natural soft clay, and partially saturated silt. In addition, measured settlement data compiled from 5 prior databases totaling some 60 very large footings from buildings and bridges on granular soils also confirm the general trends at working load design.

Keywords: cone penetration; capacity; displacements; footings; foundations

1. Introduction

Shallow foundations must be assessed for bearing capacity and tolerable settlements during their design in order to provide safety and good performance. The calculations require a proper geotechnical characterization to ascertain the stratigraphy and geoparameters for analyses. For this, the cone penetration test (CPT) is an ideal instrument as it provides three measurements with depth: (a) cone tip resistance, q_t (b) sleeve friction, f_s, and (c) porewater pressure, u_2.

With CPT, there are two alternate paths that the data can be utilized for evaluating footing response. In the classical approach, CPT readings are interpreted to determine soil parameters (i.e., γ_t = unit weight, ϕ' = friction angle, and/or s_u = undrained shear strength) for bearing capacity via limit plasticity solutions and ground stiffness (i.e., soil modulus, E) that is input into elastic continuum solutions to calculate magnitudes of displacements. An alternative approach is to use the measurements straightforward in a direct CPT approach.

A review of available direct CPT methods for footings show 10 for sands and 5 methods for clay [1]. For instance, Tand et al [2] developed a CPT method for evaluating vertical capacity of footings based on a review of 90 load tests involving steel plates and concrete footings on 13 clays. However, none of the clays were normally-consolidated and many of the clays were fissured overconsolidated geomaterials. The CPT data included a mix of electric and mechanical cone systems, thus the uncorrected q_c was employed rather than the total cone tip resistance (q_t) now specified by ISO, CEN, and ASTM standards.

In another scheme, Eslami and Gholami [3] devise a direct CPT method for bearing capacity of shallow footings but do not distinguish drained from undrained response of footings situated on clays and sands. The method is applied to footings on only 5 soils.

The magnitude of footing displacements or settlements can also be analyzed using direct CPT methods, for instance, using the well-known Schmertmann [4] approach for sands.

In this paper, a recently-developed CPT method that offers load-displacement-capacity response of footings on a variety of soil types is discussed, with several new case studies employed to cross-check its validity.

2 GT direct CPT method

A unified direct CPT method was developed at Georgia Tech that was based on 70 full-scale load tests, including 34 footings on sands, 12 on silts, 13 footings on intact clays, and 11 on fissured clays [1, 5]. The study excluded model tests and small size plate load tests ($B < 0.3$ m) because of well-known issues involving scale effects [6]. Thus, all footings had a $B > 0.5$ m and the mean size $B \approx 1.3$ m.

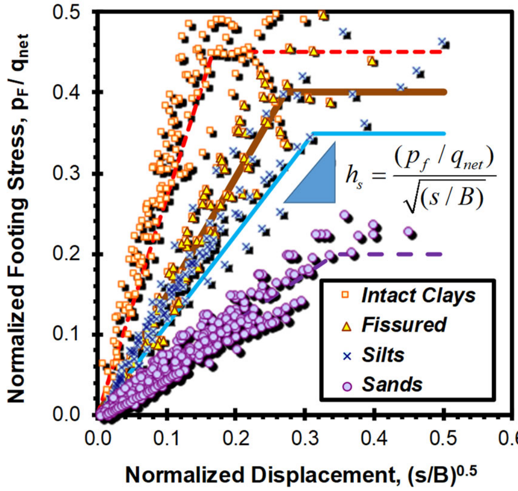
For the GT direct CPT method, Figure 1 provides a summary of the derived relationship between the normalized applied footing stress (p_f/q_{net}) and normalized displacements (s/B), where $q_{net} = (q_t - \sigma_{vo})$. The relationship can be captured by a single algorithm [5, 7]:

$$p_f = h_s \cdot q_{net} \cdot (s/B)^{0.5} < p_{ult} \quad (1)$$

where p_f = applied foundation stress, q_{net} = net cone resistance (average to 1.5B below bearing elevation), s = foundation displacement, B = foundation width, and h_s = empirical soil formation factor. For drained behavior, h_s = 0.58 for sands and 1.12 for silts, whereas undrained loading of intact clays, h_s = 2.70. In addition, fissured and jointed clays are characterized by h_s = 1.47.

Full details on the GT direct CPT method are given elsewhere [1, 5, 7, 8, 9, 10, 11, 12, 13]. In order to distinguish drained versus undrained response, Robertson [14] suggests that I_c = 2.60 as an approximate boundary, where $I_c < 2.60$ is indicative of drained behavior and $I_c > 2.60$ is characteristic of undrained response.

The foundation bearing capacity (p_{ult}) is simply expressed as a function of q_{net} and soil type. For drained behavior involving sands and sandy silts, the Euro criterion for capacity can be taken as the stress when (s/B) ≈ 10%. This more or less gives the capacity ratio: p_{ult}/q_{net} = 0.20 for sands and 0.35 for silts. For undrained loading of intact clays: p_{ult}/q_{net} = 0.45, whereas for fissured clays: p_{ult}/q_{net} = 0.40, which both compare well with the earlier study by Tand et al. [2]. In fact, the capacity ratio tracks well with CPT material index (I_c), as shown by Figure 2.



$$p_{Footing} = h_s \cdot q_{net}\sqrt{(s/B)} \leq q_{max}$$

- Bearing Capacity
- Deformations

Soil Type	Number Sites	Number Footings	Factor h_s	Capacity p_{max}/q_{net}
Clays:	6	13	2.70	0.45
Fissured	5	12	1.47	0.40
Silts	4	11	1.12	0.35
Sands	13	34	0.58	0.20
Total	*28*	*70*		

Figure 1. Normalized footing stress to net cone resistance versus square root of normalized diaplacment for 70 full-scale foundation load tests

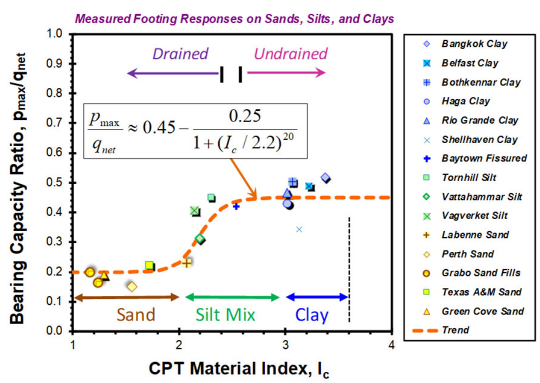


Figure 2. Trend of capacity ratio (p_{max}/q_{net}) with CPT material index (I_c) for uncemented, inorganic, and insensitive geomaterials.

A statistical evaluation of the method is made by assessing the magnitude of applied footing stress versus the calculated stress from the soil type, mobilized displacements (s/B), and corresponding q_{net} for the four categories, as shown in Figure 3. The coefficient of determination (r^2) for each grouping was quite good, including intact clays ($r^2 = 0.92$), fissured clays ($r^2 = 0.93$), silts ($r^2 = 0.88$) and sands ($r^2 = 0.94$).

Note that for intact clays, the direct CPT method provides only the magnitudes of displacement due to undrained distortional deflections. Additional calculations

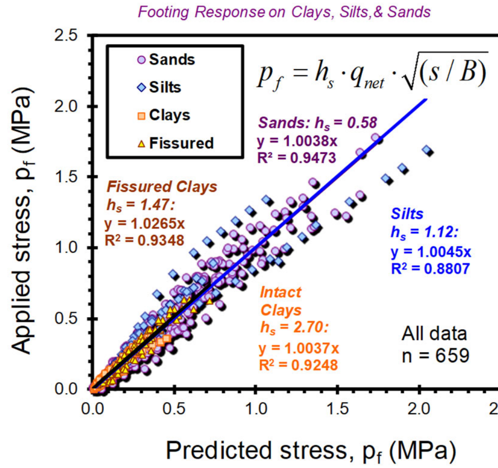


Figure 3. Actual footing stress versus calculated stress (n = 659).

would be necessary to evaluate displacements that occur due to drained settlements from primary consolidation and long-term creep.

3 New case studies

Since the advent of the method, several new case studies have become available (or known about) that allow to cross-check and validate the existing approach. These include four footing load tests involving soft clay, loose natural sand, dense dynamically-compacted sand, and partially-saturated silts tested at two different seasons.

3.1 Ballina soft clay prediction

A footing prediction symposium was sponsored by the Australian Research Council in conjunction with ISC-5 held in 2016. The newly-established Ballina experimental test site served as the foundation testing grounds where the property is underlain by soft estuarine clays that have received comprehensive laboratory, in-in-situ, and geophysical measurements. Details are given by Kelly et al. [15].

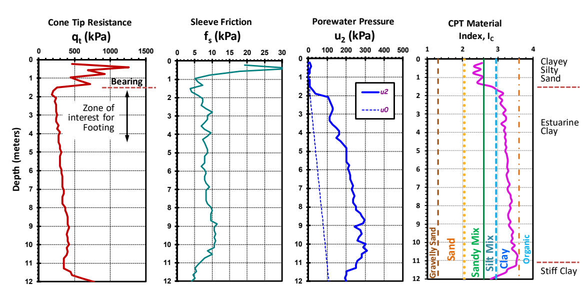


Figure 4. Representative piezocone sounding in Ballina soft clay

The prediction involved field-constructed square concrete footings (B = 1.8m) that were 0.6 m thick and built 1.5m below grade with an extra perimeter zone to remove side friction. The footing bearing elevation was situated atop a soft estuarine deposit of clay. Figure 2 shows a representative CPTU at the site, clearly showing an upper variable crustal zone that more or less extends about 1.5

m deep. The CPT I_c value places the soil type in zone 3 that is characteristic of clays and silty clays.

Using equation (1) with h_s = 4.7, a class A prediction was prepared and submitted to the ARC group by Mayne & Woeller [16]. Later, two summary papers documented the outcomes from the load tests along with a total 50 predictions that were submitted. [17, 18]

A comparison of the measured load-displacement curves for the four foundations and the predicted undrained (average) response from the direct CPT approach are shown in Figure 5. While the predicted curve is rather smooth and well-behaved, the individual curves for each footing show other inflections, nuances, and perhaps local variability. Of additional note, it appears that the field performance and forensic studies suggest that the failure occured by tilting rather than a true vertical bearing capacity mode.

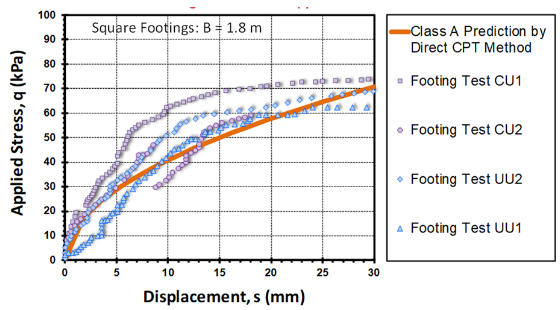


Figure 5. Comparison of measured response of 4 footing load tests with Class A prediction using the GT direct CPT method.

3.2 Loose sand, Turkey

A full-scale footing load was constructed on natural sands with a square foundation: B = 2.10 m and thickness t = 0.5 m [19]. The footing was built about about two meters below grade to avoid a dense sand layer and bear on loose sands (SP to SP-SM). The CPTs are shown in Figure 6 and indicate a representative q_t = 5.56 MPa for the loose bearing stratum.

Using a soil formation factor h_s = 0.58 and the CPT data, the measured and calculated footing response are shown in Figure 7, with relatively good agreement. In the

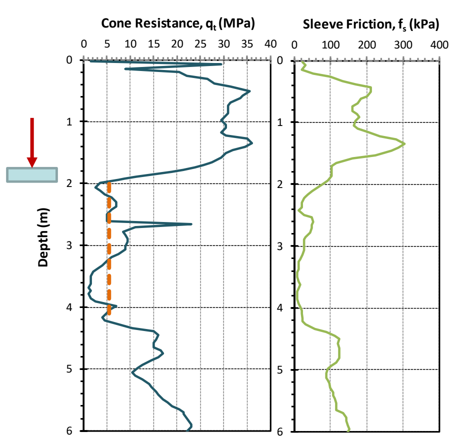


Figure 6. Representative CPT in sands at Turkish test site

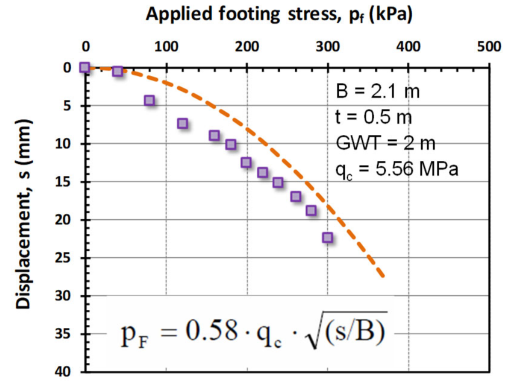


Figure 7. Measured and calculated footing response, Turkey

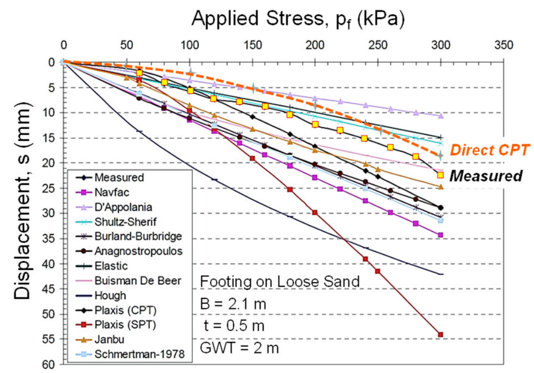


Figure 8. Comparison of 13 predictive methods with measured performance at Turkish footing test site. (modified after [19]).

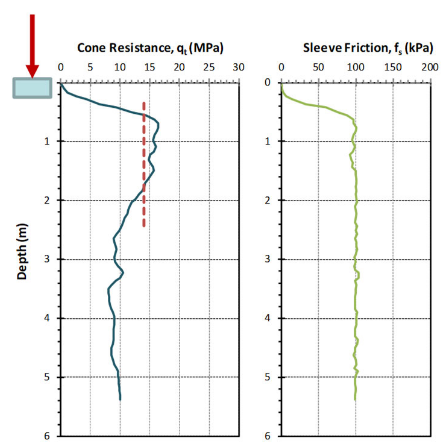


Figure 9. Representative CPT in densified sands, Oman

reporting paper, 10 different methods were evaluated in comparison to the measured response, as well as two FEM simulations via PLAXIS. These are presented together in Figure 8 and further demonstrate the reasonable curves obtained from direct CPT solution.

3.3 Densified sand, Oman

A series of zone load tests (ZLT) were performed as part of a quality control program to vertify the dynamic compaction works to densify sands in Oman [20]. A representative CPT at the site is presented in Figure 9. In addition, pressuremeter tests (PMT) were conducted at the site. The geotechnical investigation used available methods for PMT and elastic modulus estimates from CPT to estimate the foundation performance. Both approaches showed rather conservative results when compared to the measured load tests, as seen in Figure 10.

For the ZLT, three large plate load tests with thick square steel plates were utilized (B = 2.5m). The plates were nominally-embedded below grade, as presented in Figure 11. The direct CPT method was employed with q_t (ave) = 14 MPa and h_s = 0.58 to provide the calculated curve that agrees very well with the ZLT results.

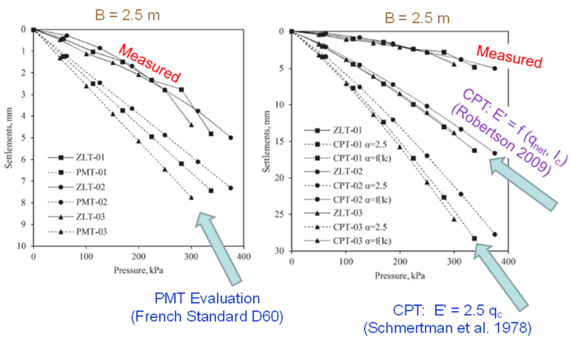


Figure 10. Estimated footing response from PMTs and CPTs using traditional approaches at Oman sand site. (modified after [20]).

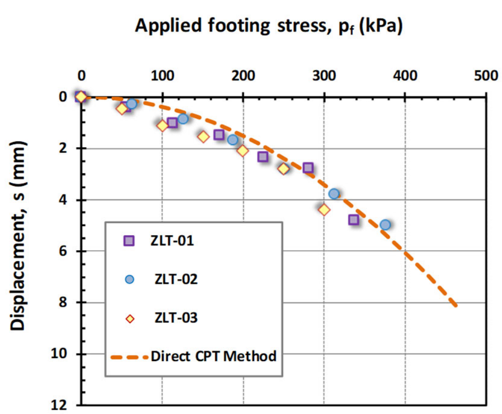


Figure 11. Measured and calculated footing behavior using direct CPT approach at Oman sand site.

3.4 Partially-saturated silts, Oregon

A series of footing load tests on silts was carried out at the Hinsdale Research Facility at Oregon State University in Corvallis, OR (Figure 12). Details are given by Huffman et al. [21]. The site is underlain by stiff dilative silts and the groundwater table varies seasonally. In the fall, the groundwater depth is about 2.5 m that rises to about 0.8 m in the springtime. The series of CPTU soundings from fall term and spring term show differences as well, as indicated by Figure 13.

The footings consisted of cast-in-place circular concrete foundations (d = 0.76 m) that were embedded 0.76 m below grade. These can be converted to equivalent square footings with B = 0.67 m.

The net cone resistances for fall and spring terms give mean values of q_{net} = 1263 kPa and 942 kPa, respectively. Using a soil formation factor of h_s = 1.12 that is assigned to silts, the measured and calculated footing responses are presented in Figure 14. While there are some differences noted, the method was originally developed from load tests on either dry and/or saturated soils, and not specifically on the basis of partially saturated soils. Yet, both the CPTU and footing performance data are affected by the groundwater table conditions and capillarity effects in the vadose zone.

Figure 12. Hinsdale Testing Facility, Oregon State University

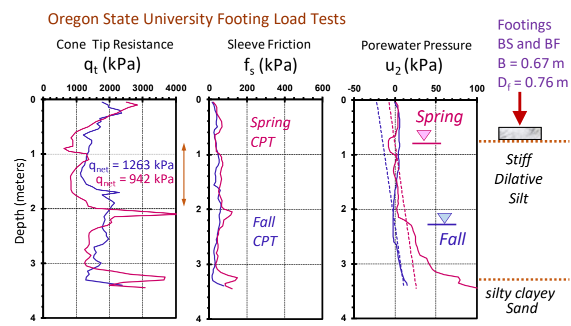


Figure 13. Representative CPTU soundings in natural silts in the spring and autumn terms at OSU

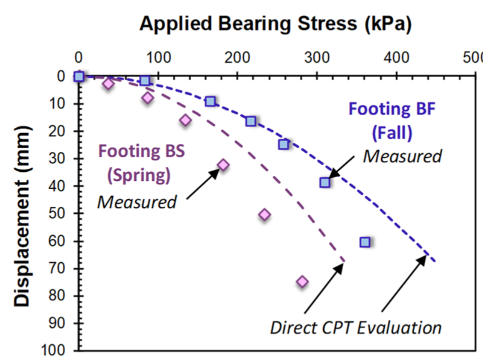


Figure 14. Measured and calculated footing load-displacement curves in spring and autumn terms at OSU.

4. Building and Bridge Foundations on Sands

In addition to full scale load tests, settlement data on very large footings were compiled from 4 prior review studies that were added to the aforementioned 34 footings on sands [7, 10]. The majority of these data came from monitoring of large bridge foundations, buildings, and other civil engineering structures. Many of these were rectangular foundations with width B and length A. All sites were subjected either to electric or mechanical CPT. This increased the total number of shallow foundations on sands to N = 130. However, in these cases, only one displacement (i.e., settlement) was recorded at the respective working load.

The sizes of these foundations ranged up to B_{max} = 56 for the largest width and up to A_{max} = 86 m for the largest length. The dimensions in this master compilation gave width B (ave) = 6.7 m and length A (ave) = 10.1 m. Those data generally followed the aforementioned trends but required a slight modification based on elastic solutions to accommodate rectangular footings:

$$\text{Sands:} \quad p_f = 0.58 \cdot q_{net} \cdot \sqrt{(s/B)} \cdot (A/B)^{-0.345} \qquad (2)$$

Figure 15 presents the data from 122 footings situated mainly on quartz and silica sands (n = 451) and exhibits a very good coefficient of determination ($r^2 = 0.912$).

Surprisingly, taking the ratio p_f/q_{net} = 20% as the capacity criterion, the performance data of actual building and bridge settlements indicate the majority of shallow foundations are actually built with mobilized factors of safety FS > 10. Consequently, it would appear less conservatism may be order for the practicing engineer for reasons of economy and cost savings.

An additional set of 8 footings on calcareous sands of western Australia were also considered [22], completing the data set of 130 footings [10]. These results more or less confirmed the trends above, despite the differences in sand mineralogies.

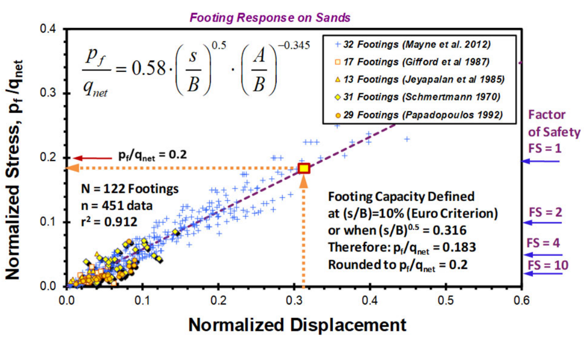


Figure 15. Normalized stress versus normalized displacements for 122 footings on quartz-silica sands (after [7][10])

5. Conclusions

A direct CPT method for shallow foundations that relies on soil type and net cone resistance has been calibrated using field performance from 130 foundations. The method provides vertical load-displacement-capacity evaluations via empirical algorithms.

The method is applied to four new sites with 10 footing load tests that were not considered during the original database compilation. These case studies include: 4 footings on soft clay with undrained response; 2 footings on partially saturated silts; 1 footing on natural loose sand, and 3 footings on densified sands. Good to excellent agreement is observed in the measured and calculated load-displacement behavior for these situations and helps to validate its reasonableness in practical situations.

6. Acknowledgments

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