An alternative CPT averaging procedure to estimate pile base capacity

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ABSTRACT

A wide variety of cone penetration test (CPT) based methods of estimating pile base capacity exist. These methods typically link the base resistance at some specified pile base settlement level to a representative value of cone resistance q_c through a correlation factor to account for pile installation effects. The representative or design q_c value is derived using procedures which typically average the cone resistance over a number of pile diameters above and below the pile tip. As the averaging procedure varies from region to region attempts to unify design methods are hampered by uncertainties related to the design value that should be adopted. In this paper two series of laboratory CPT tests on layered soil deposits are used to calibrate an alternative CPT averaging procedure that, when compared to existing procedures, can adequately capture the transition in q_c across a variety of soil conditions.

Keywords: pile base capacity, CPT-based method, calibration chamber tests on layered soils

1 INTRODUCTION

Cone penetration test (CPT)-based methods for the calculation of pile base capacity are widely used because of their ease of application combined with high reliability (Briaud and Tucker, 1988). In general, the design q_c (cone resistance) value is obtained using an averaging procedure which considers values over a number of pile diameters, D, above and below the pile tip. The purpose of averaging the values in this zone is to account for the scale effect present between the cone penetrometer and the foundation pile, since the volume of soil influenced during loading depends on the base dimensions. In homogeneous soil deposits such a method is not required. However, close to soil layer interfaces, the base resistance will be influenced by the current layer and the over- or underlying layer. This zone is called the transition zone (Tehrani et al, 2017). At a certain distance from the interface, the underlying layer will be felt (sensing distance, H_s) and a certain penetration in the underlying layer is needed to get rid of the effect of the overlying layer (development distance, H_d), see Fig. 1.

Boulanger and DeJong (2018) summarized the findings from numerical and physical studies of cone penetration in layered soil profiles. Whit respect to H_s and H_d, they conclude that:

i. soils in front of the cone tip have a greater influence on penetration resistance than the soils behind the cone tip;
ii. both H_s and H_d are smaller in a weaker soil overlying or underlying a stronger soil than those in a stronger soil overlying or underlying weaker layers;
iii. sensing and development distances in a stronger layer overlying or underlying a weaker layer increase as the ratio of the soil layer strengths increases.

These findings are fully in line with results of CPT in layered soil as presented by Van der Linden et al. (2018) and De Lange (2018). Boulanger and DeJong have used these conclusions to develop an inverse filtering procedure to correct cone penetration data for thin-layer and transition effects. The present authors believe that the same conclusions should be used to develop an appropriate averaging procedure for pile base capacity. Meanwhile, this has been endorsed by others as well (Bittar et al, 2020).

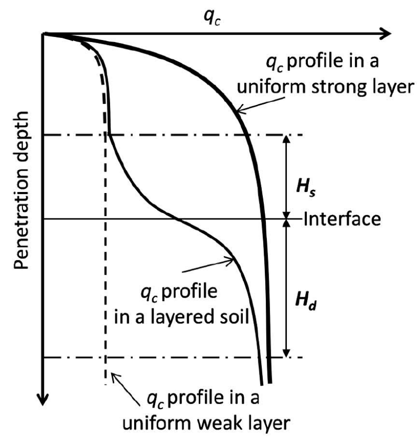

Fig. 1. Sensing and development distance (after Tehrani et al, 2017).

Currently popular methods of determining the design q_c value are the LCPC method and the Dutch (or Koppejan) method. The LCPC method determines averages value over a 1.5*D* distance below and above the pile tip, excluding extreme values that fall outside 70% to 130% of the average q_c value in the zone 1.5*D* above the tip and values that are above 130% of the average value below the tip, see Bustamante and Gianeselli (1982). In a review Xu et al. (2008) concluded that this zone was too small for calculating representative q_c values in layered soils. Considering the review of the physical models of CPT in layered soil, the LCPC method does not account for any of the observed phenomena.

The Dutch method (Van Mierloo and Koppejan, 1952) calculates a representative q_c value through a conservative average between at least 0.7*D* and maximum 4*D* below the pile tip, and 8*D* above the pile tip. Soft layers within this zone are governing due to the application of a minimum path rule, accounting for possible punch through mechanisms. Van Tol et al. (2013) observed that the correlation between the base capacity and the representative q_c value calculated by the Dutch method has a dependency with the penetration level into the bearing sand layer. In the model, soils in front of the pile tip have similar weight as soils above the pile tip and the zone of influence above the tip (8*D*) is at least twice as large as the zone in front of the pile (0.7-4*D*). These rules are not in line with phenomena (i) and (iii) observed from the physical models and can be at least a partial explanation of the findings by Van Tol et al. The Dutch method is, however, in line with phenomenon (ii), what possibly explains why Xu et al. (2008) concluded that the Dutch averaging method is the most appropriate of the currently available methods. Further it should be mentioned that also very tiny soft layers do have a very significant effect on the design q_c value in the Dutch method due to the adoption of a minimum path rule, what does not seem to be very realistic.

This paper presents a new alternative averaging procedure developed, based on the concepts of Boulanger and DeJong (2018), being calibrated against data from CPT calibration laboratory tests, with the main goal being to improve the accuracy of the estimation of pile base capacity.

2 MATERIAL AND METHODS

2.1 CPT laboratory tests

The calibration of the proposed alternative averaging procedure is based on a series of well documented CPT laboratory tests. The advantage of using these laboratory tests are the controlled environment as well as the accuracy of the data obtained. Data from two different test series has been used to evaluate current methods and to develop an alternative method.

The first dataset is taken from Tehrani et al. (2018). Cone penetration tests were performed with a half-circular model penetrometer (d_{cone} = 31.75 mm). Two layered, uniformly graded silica sand samples were prepared in a calibration chamber. Different configurations were tested: loose over dense, dense over loose, medium dense over dense and dense over medium dense sand. Besides layered samples, also uniform samples were tested as reference cases: loose, medium dense and dense sand. A 50 kPa surcharge load was applied on top of the sample during testing.

The second dataset was taken from De Lange (2018). Cone penetration tests were performed with full penetrometers (d_{cone} = 25 mm & 36 mm). Samples, containing multiple thin alternating sand and clay layers, sandwiched between two thicker layers, were prepared in a calibration chamber. Different thicknesses of the thin layers (2 cm, 4 cm and 8 cm) and different sand densities were tested (loose and medium dense). Besides layered samples, also uniform samples were tested as reference cases. Surcharge loads on top of the sample ranging from 10 kPa to 100 kPa and a lateral pressure equal to 50% of the vertical stress were applied during testing.

2.2 Model calibration and analyses

The parameters of the proposed alternative averaging procedure are determined by applying the model to hypothetical $q_{c:true}$ profiles, which correspond to the laboratory test configurations. Herein, $q_{c:true}$ refers to the cone resistance that would be measured if the test data were dependent solely on the soil properties at a point, while not being influenced by adjacent soil layers (Boulanger and DeJong, 2018). The $q_{c:true}$ profiles were determined based on CPT laboratory tests in homogeneous sand or clay as presented in Tehrani et al. (2018) and De Lange (2018). Homogeneous soil properties within the individual layers were assumed. For correct simulation a running mean was applied over the height of the conical tip (De Lange, 2018).

It has been assessed how well the averaging method procedure does capture the transition zones around layer interfaces compared to the laboratory tests measurements for different parameter combinations. Data points close to the top and bottom boundary of the soil sample were not compared to eliminate any boundary effects. The parameters were adjusted based on a visual analysis and a mean squared error (MSE) analysis. In total 11 CPT laboratory tests from De Lange (2018) and 4 CPT laboratory tests from Tehrani et al. (2018) were used for the visual analysis and MSE analysis. The MSE was calculated by means of the difference between the values returned by the averaging method and the laboratory test data at each cone penetration level (De Boorder, 2019).

2.3 Alternative averaging procedure

The filtering method presented by Boulanger and DeJong (2018) is not suitable for the thin layers which has been tested by De Lange (2018). Therefore, a simplified method has been proposed, which is in line with the filtering method and which could be calibrated against the laboratory test data.

A first aspect of this method is the decreasing influence of soils as the distance to the pile tip increases. Boulanger and DeJong propose a weight distribution which also depends on the contrast between q_c at tip level and q_c at distance from the tip. For simplicity, the latter dependency has been neglected in the alternative method. A range of functions were tested and the best fit with test data was obtained using a damped cosine function, see Fig. 2. As can be observed, the shape of the weight distribution is almost similar to that one in the filtering method, however, the zone of influence is much smaller (about a factor 5). The latter could also explain why the filtering method did not work for thin layers.

The weight related to the distance to the pile base, w_1, is given by:

$$w_1 = e^{-f|z'|}\cos(0.5\pi|z'|)$$

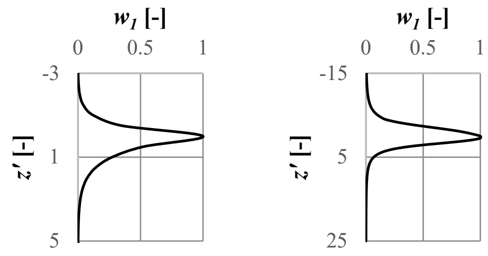

Fig. 2. Weight related to distance from the pile base: (left) alternative method and (right) filtering method.

with:

f damping factor (=13.5);

z' the normalized distance to the pile base, given by:

$$z' = \frac{z - z_{tip}}{C * D}$$

$z - z_{tip}$ the distance to the pile base;

D the (equivalent) pile diameter;

C a constant which determines the zone of influence (=6.5 above the pile base; 10.5 below the pile base).

A second aspect is the strength ratio. Like the filtering method, but simplified, this is considered using the ratio of q_c at the pile tip level and the q_c values within the zone of influence around the pile tip, such that weaker soils have a larger influence on the calculated representative q_c value. The weight related to the strength ratio, w_2, is given by:

$$w_2 = \left(\frac{q_{c,tip}}{q_c}\right)^s$$

with:

$q_{c,tip}$ the cone resistance at the pile tip level;

q_c the cone resistance at level z;

s a fit parameter (0.56 above the pile base and 0.79 below the pile base).

A third aspect is that soils in front of the cone tip have a greater influence on penetration resistance than the soils behind the cone tip, which is partly obtained by the differentiation in C-values and partly by the differentiation in s-values. The differentiation in C-values results in a asymmetrical influence zone, while the differentiation in s-values results in a smaller contribution of weaker layers above the tip compared to similar weaker layers below the tip. The latter is not present in the filtering method. Both weights are combined, to calculate the representative q_c value, $q_{c;avg}$, using the following equation:

$$q_{c,avg} = \sum q_c \frac{w_1 w_2}{\sum(w_1 w_2)}$$

This alternative method is demonstrated in Fig. 3, using an idealized two layered soil profile, clay overlaying sand. In Fig. 3, the idealised $q_{c:true}$ profile is given first. The alternative averaging method has been applied to this artificial $q_{c:true}$ profile. The distributions of $w_{d,j} w_{qc,j}$ for two pile tip levels are shown in the bottom subfigures. The pile tip is respectively 1D above the layer interface and 1D below the layer interface in these figures. The hatched areas show the contribution of the individual layers for these specific pile tip levels. In the first case nearly all weight originates from the clay layer, which is mainly a result of w_2 (the weight related to the strength ratio). At 1D below the layer interface, the sand layer contributes 83% towards the calculated representative q_c value and the remaining 17% originates from the clay layer. The top right subfigure shows the results of the averaging procedure for the whole soil profile. The two specific pile tip levels are marked with a dot.

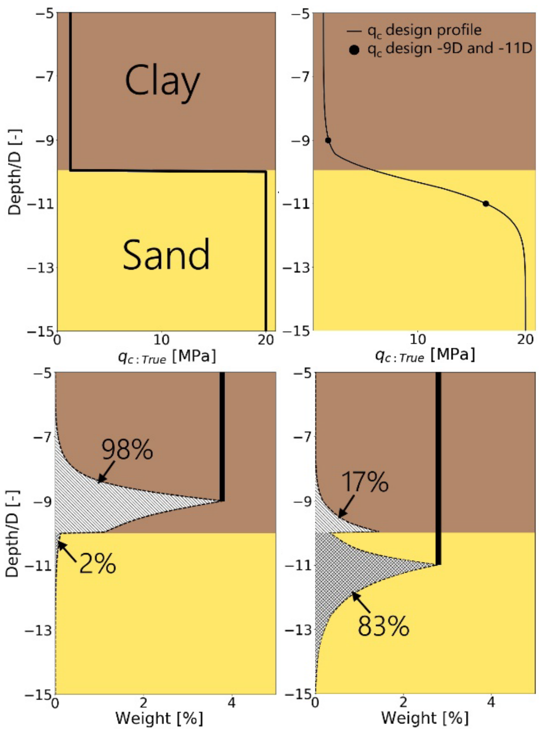

Fig. 3. Demonstration of alternative averaging procedure by means of idealized two layered soil profile: (top left) idealized $q_{c:true}$-profile; (top right) final results of the procedure; (bottom left) weight distribution for 9D penetration, (bottom right) weight distribution for 11D penetration.

3 RESULTS

Because of available space, only four soil configurations of the visual analysis are presented in this paper: (i) six 2 cm clay layers in loose sand, (ii) four 4 cm clay layers in loose sand, (iii) loose over dense sand and (iv) dense over loose sand, see Fig. 4 - 11. In these figures, the hypothetical $q_{c:true}$ profiles are given by a dotted line, the laboratory CPT data is given by a black line and the results of the averaging methods are given by coloured lines. A MSE equal to 0.0166 MPa with a Coefficient of Variation (CoV) equal to 0.96% were obtained for the alternative procedure. As mentioned before, test results near the boundaries of the soil sample were excluded in the analysis, focussing on the transition zones. The excluded test results are represented by a dashed line in the figures and were not considered in the MSE analysis.

From the (whole) visual analysis the following conclusions can be drawn:

- The alternative averaging procedure can capture the transition zones between soil layers and thin soil layers adequately, although there is still room for improvement. This has been observed across all the analysed laboratory tests.
- The Dutch method gives a conservative representative value. This was also stated by Xu (2008). Underestimations of the representative q_c values are present at the major soil boundaries. The underestimation starts at 4D above a weaker underlying layer and stops at a penetration of 8D into a stronger layer.
- The LCPC method overestimated the representative q_c value in the thin layered soil laboratory tests. This is in line with the findings of Xu (2008). Additionally, when penetrating from a strong soil layer into a weaker layer, the transition is not captured adequately, and the strength is overestimated. For the transition from weak to strong soil, a better estimation is made.

4 CONCLUDING REMARKS

An alternative CPT averaging procedure has been developed for the estimation of pile base capacity. This procedure is mainly based on the filtering method of Boulanger and DeJong (2018) and has been calibrated against multiple laboratory CPTs in layered soils. Additionally, two current averaging procedures were evaluated. The alternative averaging procedure captures the transition zones between soil layers and thin soil

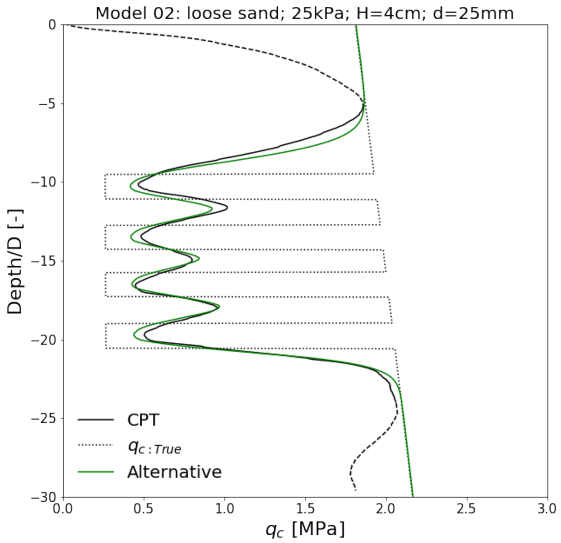

Fig. 4. Results of alternative procedure vs. test results.

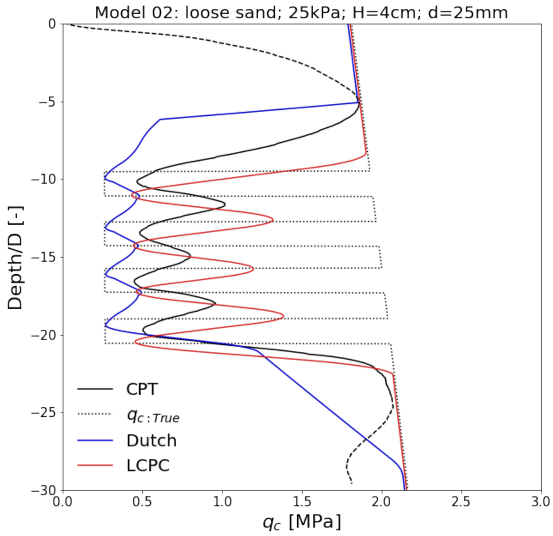

Fig. 7. Results of current procedures vs. test results.

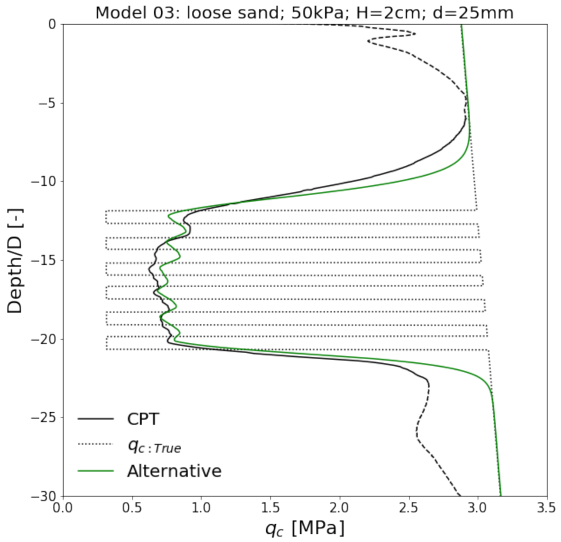

Fig. 5. Results of alternative procedure vs. test results.

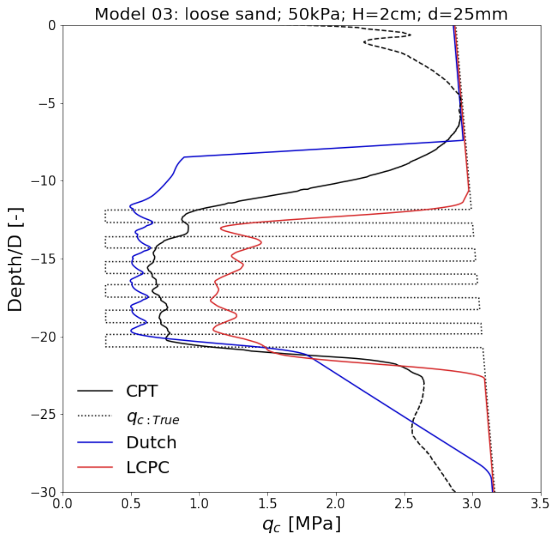

Fig. 8. Results of current procedures vs. test results.

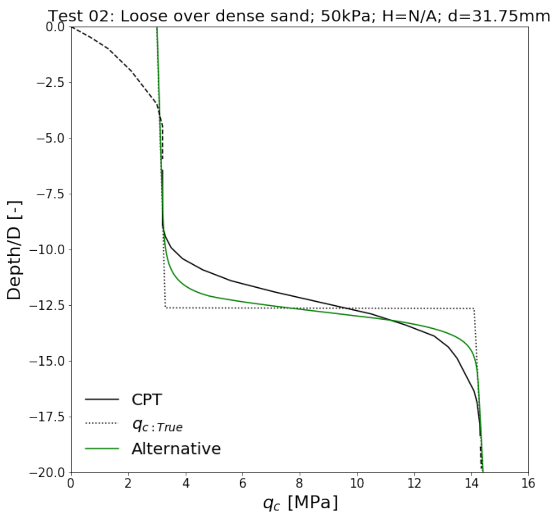

Fig. 6. Results of alternative procedure vs. test results.

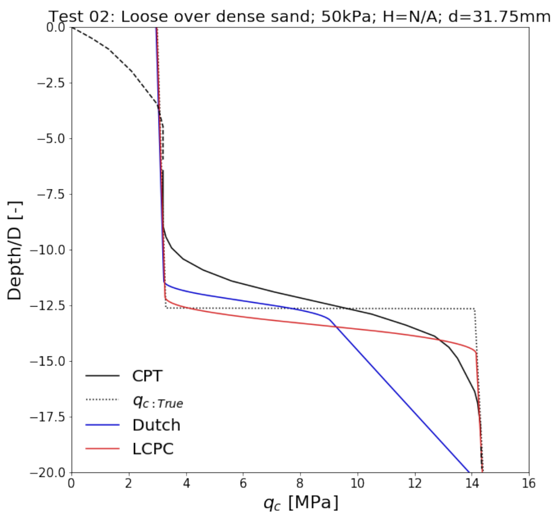

Fig. 9. Results of current procedures vs. test results.

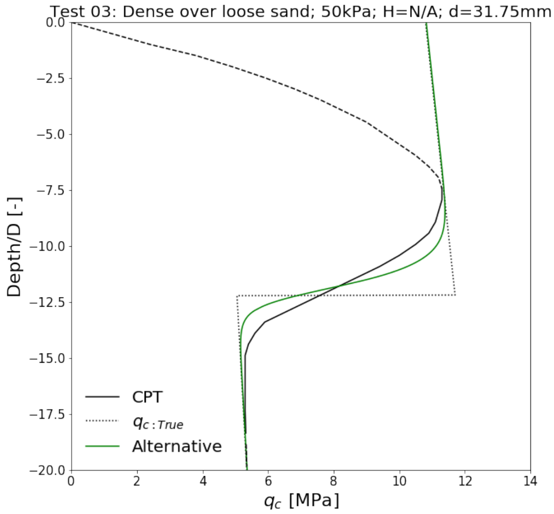

Fig. 10. Results of alternative procedure vs. test results.

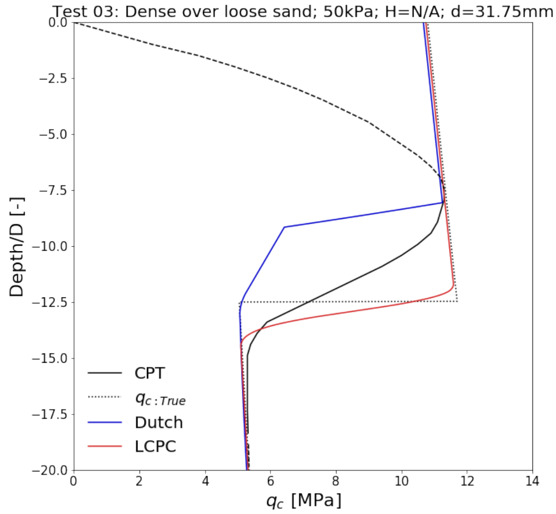

Fig. 11. Results of current procedures vs. test results.

layers adequately across a variety of soil conditions, indicating that the concepts presented by Boulanger and DeJong (2018) should be incorporated in an appropriate averaging method. These concepts are: (a) the effects of a soil layer decreases when the distance from the pile tip to that layer increases, (b) soils in front of the pile tip have a greater influence on penetration resistance than the soils behind the pile tip and (c) the effects of a soil layer away from the pile tip depends on the stiffness or strength ratio of that layer and the soil at tip level. The predictive value of the Dutch method and the LCPC method varies, which can be explained by these aspects. In its current state, the alternative averaging method is a simple mathematical model. However, improvements can be made to further increase its accuracy and simplicity.

5 ACKNOWLEDGEMENTS

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