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Augustesen, Anders; Andersen, Lars

Published in:
Geotechnical Engineering/Construction Technology & Management

Publication date:
2008

Document Version
Publisher's PDF, also known as Version of record

8th International Congress on Advances in Civil Engineering, 15-17 September 2008
Eastern Mediterranean University, Famagusta, North Cyprus

Assessment of calculation procedures for piles in clay based on static loading tests

A. H. Augustesen[1], L. Andersen[1]

[1]Department of Civil Engineering, Aalborg University, Denmark

Abstract

Numerous methods are available for the prediction of the axial capacity of piles in clay. In this paper, two well-known models are considered, namely the current API-RP2A (1987 to present) and the recently developed ICP method. The latter is developed by Jardine and his co-workers at Imperial College in London. The calculation procedures are assessed based on an established database of static loading tests. To make a consistent evaluation of the design methods, corrections related to undrained shear strength and time between pile driving and testing have been employed. The study indicates that the interpretation of the field tests is of paramount importance, both with regard to the soil profile and the loading conditions. Based on analyses of 253 static pile loading tests distributed on 111 sites, API-RP2A provides the better description of the data. However, it should be emphasised that some input parameters in the ICP method have been estimated based on relatively uncertain correlations, which might affect the results. The ICP method could preferably be applied for piles loaded in tension. However, it is recommended not to use the ICP method for piles driven open-ended and loaded in compression. Especially, API-RP2A underestimates the capacity of short piles (< 20 m) and overestimates the capacity of long piles (> 20 m). Neither method estimates the low shaft resistance measured in connection with piles installed in normally consolidated clay of low plasticity.

Keywords: *Pile; foundation; bearing capacity; static loading tests; clay.*

1 Introduction

Design methods for piles in clay have been a controversial matter within geotechnical engineering in many years due to their empirical nature. The stresses acting against the pile and the mechanical properties of the disturbed pile/soil contact zone are not completely known and the capacity can therefore not entirely be predicted by theoretical methods. Therefore, the design of piles has remained a constant source of attention, especially with regard to the methodology for predicting the capacity. As a result numerous calculation procedures are proposed in the literature, see for example De Cock and Legrand (1997), Jardine and Chow (1996), API (1993), Clausen and Aas (2000). The purpose of this paper is to elucidate the advantages and limitations of two well-known calculation procedures, namely API-RP2A (API, 1993) and the ICP method. The first is a part of the existing API (American Petroleum Institute) procedure, and it is included in this study because it is widely used. ICP has been developed at Imperial College in London by Jardine and his co-workers (Jardine and Chow, 1996, 1997 and Jardine et al., 2005). The assessment of the calculation methods is made by testing the methods against a database of measured capacities from static loading tests. The database includes 253 pile load tests distributed on 111 sites.

Even if a prediction method gives the correct answer for the total pile capacity, it may not give the correct distribution of skin friction with depth. In such cases, the method could be non-conservative for layered soil profiles. However, in this paper focus is entirely paid to the reliability of a given calculation procedure to predict the correct total pile capacity. Hence, though numerous parameters are interesting when assessing the methods in consideration, the primarily parameter employed here is the *C/M*-ratio and especially the average *C/M*-ratio, $\mu_{C/M}$, and the corresponding standard deviation, $\sigma_{C/M}$. The *C/M*-ratio is the calculated capacity *C* divided by the measured capacity *M* at a given reference time. A mean value $\mu_{C/M}$ equal to unity represents that, on the average, the predicted capacity equals the measured capacity. For $\mu_{C/M} < 0$, the method under consideration tends to underestimate the capacity, and for $\mu_{C/M} > 0$, the method has a tendency to overestimate the capacity. A measure for scatter exhibited by a predictive method is quantified by the standard deviation $\sigma_{C/M}$. If $\sigma_{C/M} = 0$ there is no scatter in the results, i.e. the capacity is systematically over- or underestimated.

2 Design methods

The API method (API, 1993) is based on an α approach. In this method, the shaft resistance is a function of the undrained shear strength s_u and the strength to the effective overburden pressure ratio s_u/p_0 which is highly correlated with the over-consolidation ratio *OCR*. Here, p_0 is the vertical effective stress. The toe resistance is a function of the undrained shear strength. API (1993) recommends unconsolidated undrained triaxial compression tests for establishing the strength profile variation, i.e. s_{uu} is the preferable strength measure to employ when applying the API method.

The ICP method (Jardine and Chow, 1996, 1997 and Jardine et al., 2005) is an effective stress based method (β approach) when considering the skin friction. The shaft resistance depends on the sensitivity S_t, the distance from the layer considered to the pile toe, the pile diameter, the pile/soil friction angle δ_f

(depends on the plasticity index), and the overconsolidation ratio *OCR*. Some of these input parameters are not normally measured in routine site investigations (Jardine and Chow, 1997). Jardine and Chow (1996) include alternative expressions, based upon parameters to be determined from oedometer tests, rather than direct use of S_t. The ICP method includes a length, or friction fatigue, factor as well as the effects of whether a pile is driven open-ended or closed-ended when calculating the shaft resistance. The toe resistance when the pile is located in clay is a function of the CPT tip resistance. The effects of tip conditions (open-ended or closed-ended) and the plugging behaviour are also taken into consideration.

3 Database

A database containing static pile load tests has been established. All test results are from published sources and only cases with reasonably good information regarding soil, pile, and testing conditions have been included. The database contains 253 individual static pile tests from 111 sites; hereof 199 compression

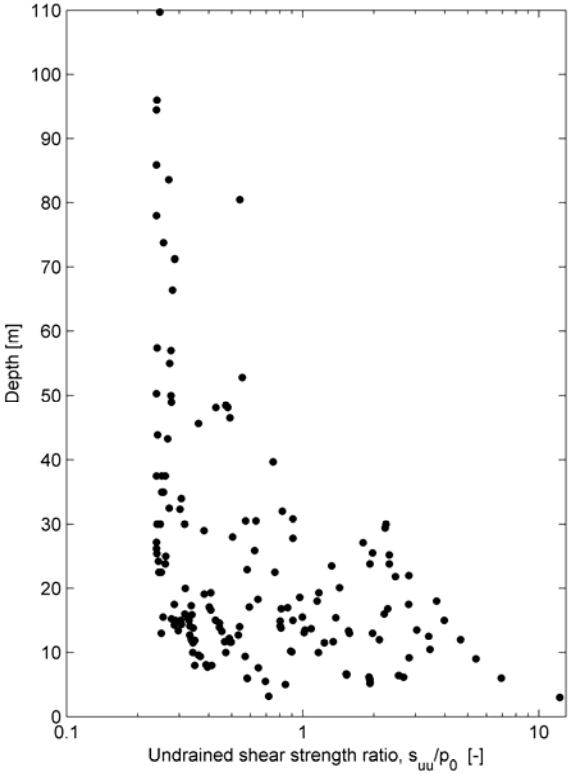

Figure 1. Range of data.

tests and 54 tension tests. 153 pile tests are conducted on steel piles, 65 on timber piles and 35 on concrete piles. The range of data in terms penetration depth and shear strength ratio is shown in Figure 1. A subset of 95 piles, referred to as “super piles”, has been established. These pile tests are considered to include the most important and well-documented tests. It should be mentioned that the database contains both offshore and onshore piles.

The two calculation procedures depend on different soil parameters as described in Section 2. Further, the undrained shear strengths associated with the different cases are not established in the same way. Therefore, in order to allow a meaningful assessment of the calculation procedures, a set of rules that convert one type of shear strength into another has been employed. Further, the over-consolidation ratio *OCR* and the sensitivity S_t associated with the ICP method are determined based on the undrained shear strength, if they have not been provided explicitly by measurements.

Since the loading tests represented in the database are performed at different times after driving, a time function that extrapolates the measured capacity at a given time to the capacity at a given reference time has been employed. Furthermore, if it is assumed that the calculation procedures estimate capacities corresponding to the same reference time, the design procedures can be assessed in a consistent way. The reference is chosen to be 100 days and the function employed to correct the measured capacities can be expressed as:

$$Q(t) = Q_0 \left[1 + \Delta_{10} \log_{10}\left(\frac{t}{t_0} \right) \right] \quad (1)$$

where Q is the vertical bearing capacity at time t after the end of installation and Q_0 is the reference capacity determined according to the reference time t_0. Further, Δ_{10} is the set-up factor, i.e. the capacity increase corresponding to a tenfold increase in time. Augustesen (2006) suggests employing $\Delta_{10} = 0.24$.

4 Results

Results of testing the API and ICP methods against the database are shown in Table 1 and Figure 1. API provides overall a reasonable estimate of the capacity. The low average *C/M*-ratio provided by the ICP method may reflect that some input parameters are estimated based on relatively uncertain correlations rather than a short-coming of the method as such. When it comes to steel piles, the API method is more reliable than the ICP method whereas the opposite is the case for timber piles. The accuracy of API and ICP in terms of $\mu_{C/M}$ is almost the same when considering the “super piles”. Generally, ICP and API provide the better description of tension piles and piles driven closed-ended, respectively. Further, based on Table 2, it is recommended not to use the ICP method for piles driven open-ended and loaded in compression. The reason for the large scatter related to

Table 1. API and ICP tested against all available data for piles in clay.

	No. of piles	API $\mu_{C/M}$ / $\sigma_{C/M}$	ICP $\mu_{C/M}$ / $\sigma_{C/M}$
All cases	253	1.03 / 0.40	0.89 / 0.44
Compression	199	1.03 / 0.44	0.86 / 0.33
Tension	54	1.04 / 0.57	0.99 / 0.72
Open-ended	84	1.00 / 0.29	0.74 / 0.26
Closed-ended	169	1.04 / 0.44	0.96 / 0.49
Steel	153	0.97 / 0.43	0.82 / 0.49
Compression	105	0.93 / 0.32	0.73 / 0.26
Tension	48	1.04 / 0.60	1.02 / 0.75
Open-ended	84	1.00 / 0.29	0.74 / 0.26
Closed-ended	69	0.92 / 0.55	0.93 / 0.66
Timber	65	1.11 / 0.27	0.94 / 0.32
Compression	65	1.11 / 0.27	0.94 / 0.32
Tension	-	- / -	- / -
Open-ended	-	- / -	- / -
Closed-ended	65	1.11 / 0.27	0.94 / 0.32
Concrete	35	1.15 / 0.39	1.05 / 0.36
Compression	29	1.17 / 0.43	1.12 / 0.35
Tension	6	1.02 / 0.13	0.72 / 0.08
Open-ended	-	- / -	- / -
Closed-ended	35	1.15 / 0.39	1.05 / 0.36
Super piles	95	0.90 / 0.49	0.87 / 0.58
Compression	51	0.78 / 0.29	0.73 / 0.27
Tension	44	1.04 / 0.62	1.02 / 0.78
Open-ended	39	0.92 / 0.28	0.78 / 0.30
Closed-ended	56	0.89 / 0.59	0.93 / 0.71

especially the piles loaded in tension, cf. Table 1, is mainly that the two methods do not estimate the low shaft resistance measured in connection with piles installed in normally consolidated clay of low plasticity.

On the average, API overestimates the capacity of piles installed in depths greater than 20 m more than the capacity of piles installed in depths less than 20 m, see Table 3 and Figure 2. Hence, API produces a skew distribution of *C/M*-ratios with penetration depth. The ICP method also produces a skew distribution of *C/M*-ratios with penetration depth but it is not as distinct. A possible reason for the observed tendencies is that API does not include a length factor accounting for "friction fatigue effects", whereas ICP does, cf. Section 2.

Back-calculated α-values ($\alpha = \tau_{\text{skin}} / s_{uu}$) for piles driven closed-ended and open-

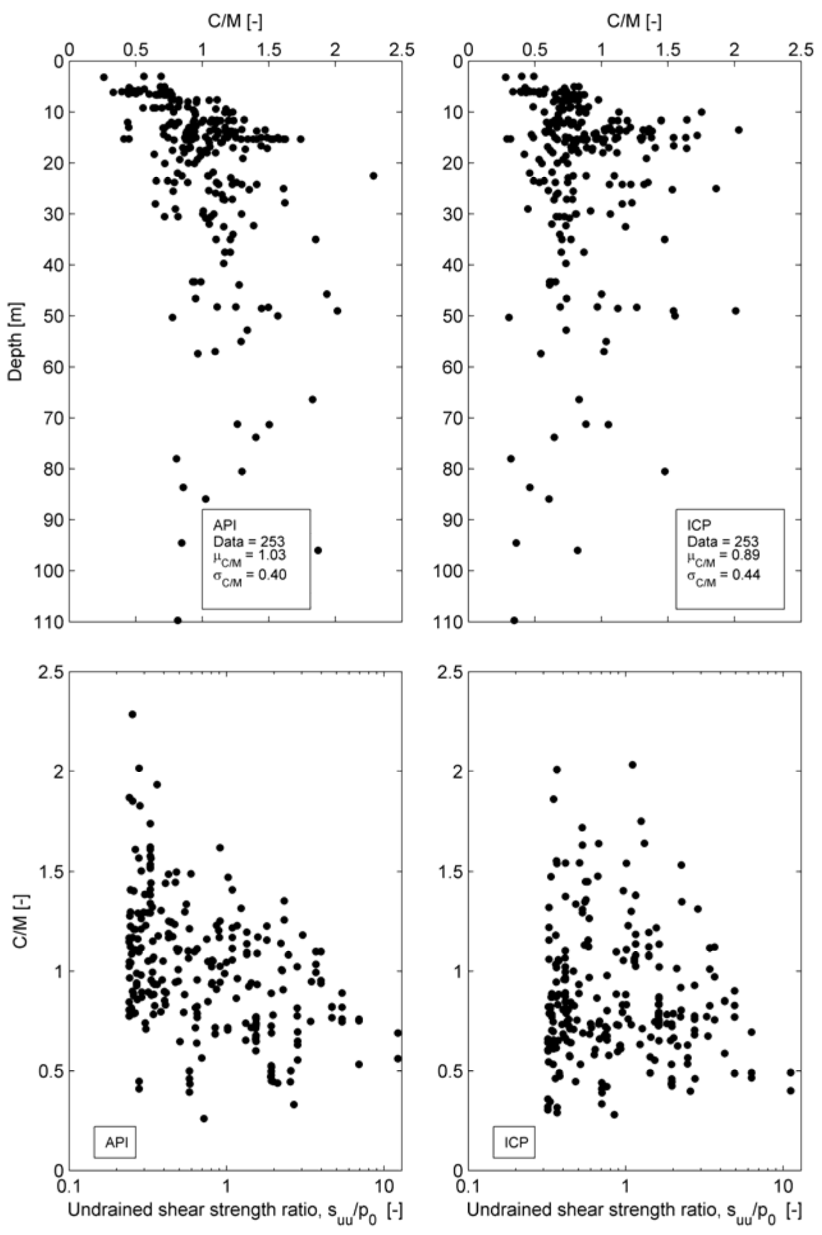

Figure 2. Calculated *C/M*-ratios (Calculated / Measured capacity) versus penetration depth and undrained shear strength ratio.

ended as well as the tendency line proposed by the API method are plotted against $\psi = s_{uu}/p_0$ in Figure 3. p_0 is the average vertical effective stress along the pile. For piles driven closed-ended and installed in clays with $0.25 < \psi < 0.5$, the

Table 2. Effects of driving and loading conditions.

Driving/ Loading	No. of piles	API $\mu_{C/M}$ / $\sigma_{C/M}$	ICP $\mu_{C/M}$ / $\sigma_{C/M}$
Open / TNS	24	0.97 / 0.27	0.92 / 0.31
Open / CMP	60	1.01 / 0.30	0.67 / 0.20
Closed / TNS	30	1.10 / 0.72	1.04 / 0.92
Closed / CMP	139	1.03 / 0.35	0.94 / 0.34

Table 3. API and ICP tested against piles with penetrations depths greater or less than 20 m.

Depth (m)	No. of piles	API $\mu_{C/M}$ / $\sigma_{C/M}$	ICP $\mu_{C/M}$ / $\sigma_{C/M}$
< 20	172	0.93 / 0.30	0.86 / 0.32
>20	81	1.23 / 0.49	0.95 / 0.63

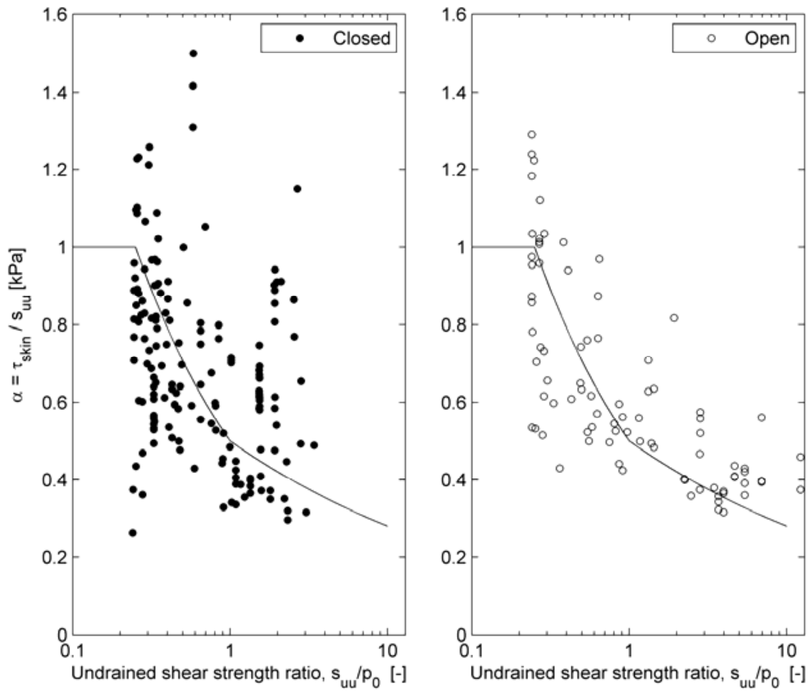

Figure 3. Back-calculated α-values for piles driven closed-ended (to the left) and open-ended (to the right). The solid line describes the relation between α and the undrained shear strength ratio according to API (1993).

measured α-values are lower than predicted by the API method, whereas the opposite is the case for clays with $1.5 < \psi < 3$. Compared to closed-ended piles there is a better correlation between measured and predicted α-values for open-ended piles. This is also indicated in Table 1.

5 Conclusions

The design methods, referred to as API and ICP, for piles in clay have been assessed based on a database containing 253 static pile load tests. In order to make a meaningful evaluation, corrections related to the undrained shear strength and the time between pile driving and testing have been employed. Overall, API provides the better description of the data. However, it should be emphasised that some input parameters for the ICP method have been estimated based on relatively uncertain correlations between different geotechnical properties, which might affect the results. The ICP method could preferably be applied for piles loaded in tension. However, it is recommended not to use the ICP method for piles driven open-ended and loaded in compression. Especially, API provides a skew distribution of *C/M*-ratios with penetration depth, which might be due to the fact that it does not incorporate a length factor, whereas the ICP method does. Compared to closed-ended piles there is a better correlation between measured and predicted (by the API method) α-values for open-ended piles.

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