# Semi empirical design procedures for axial pile capacity in clays

## Méthodes de calcul semi-empiriques pour la capacité portante des pieux dans les argiles

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ABSTRACT: Four new procedures for the design of piles for axial capacity in clays are reviewed; all are based on a semi empirical approach using data from in situ tests (piezocone, cone pressuremeter, Marchetti dilatometer and the Ménard Pressuremeter). All are shown to perform well and often better than more rigorous approaches. This project has demonstrated that the potential of direct design procedures can be realised and forms an important step in their evolution

RÉSUMÉ: Quatre nouvelles procédures de calcul de la capacité portante des pieux dans les argiles sont examinées ; elles utilisent toutes une approche semi-empirique à partir de résultats d'essais in situ (piézocône, pressiomètre à cône, dilatomètre Marchetti et pressiomètre Ménard). Elles donnent toutes des résultats satisfaisants et souvent meilleurs que des approches plus rigoureuses. Ce projet a montré les potentialités des méthodes de calcul directes et constitue une étape importante de leur évolution.

## 1 INTRODUCTION

This paper summarises some results of work carried out under a Brite EuRam Project entitled 'Development of Semi-Empirical Design Procedures for Foundations' (Shields et al 1996).

The concept of direct foundation design procedures, such as those developed in the Project, is that they use directly the measurements from in situ tests, instead of conventional soil properties. They thereby reduce the current level of uncertainty in design arising from the use of soil properties derived from laboratory and/or in situ tests by interpretation or the use of empirical correlations. The resulting design and construction process should be more efficient both in time and cost. In addition, the availability of sound economic procedures should discourage the current tendency to cut corners in foundation design and hence lead to better quality foundations. Some design is already carried out using procedures developed along these lines. However, much of the Industry is either uninformed or wary of the innovative concept. This is because the risk in using a particular design method falls to the designer and the Construction Industry has a tendency to be conservative and keep to well-known methods. The Project aimed to investigate and develop the potential of direct design methods.

Research carried out under the EC Brite EuRam Programme has been aimed at developing semi-empirical, otherwise known as 'direct', design procedures for piles and shallow foundations from the results of the three recently developed in situ testing devices, the cone pressuremeter (CPM), the dilatometer (DMT) and the triple element piezocone (CPTU3), and has also examined the existing French rules developed for the Menard Pressuremeter (MPM). The design procedures investigated were for ultimate load and settlement of axially loaded piles, displacements and bending moments of laterally loaded piles and bearing capacity and settlement of shallow foundations.

The paper briefly reviews the proposed design methods for axial capacity of piles in clays and then compares their relative performance and that of other procedures.

## 2 SITES AND FOUNDATIONS

Table 1 presents the 16 sites and types of foundation available at each. The soil conditions ranged from soft, normally consolidated, to stiff overconsolidated clays, but contained only two sand sites. For use in this paper there were altogether 63 piles which were mainly steel driven or jacked.

## 3 IN SITU TESTING AND INTERPRETATION

*Cone Pressuremeter (CPM)*

Cone pressuremeter (CPM) test results are available for all the Project sites, except Haga. The CPM tests at the sites were analysed using the Houlsby and Withers (1988) analysis. For the design procedures developed, the limit pressure, designated $p_{LCPM}$, and the cavity contraction shear modulus, $G_{cc}$, from the above analysis were used. The limit pressure was taken as the maximum pressure reached in the test. Full details of the testing methods are given in Powell and Shields (1995).

*Marchetti Dilatometer Test (DMT)*

DMT test results are available for all the sites. DMT tests are performed every 200mm down a profile. At each level gas pres-

Table 1. Sites and In situ testing

| Site | Piles | | Shallow found | | In situ tests | | | | Soil Type |
|---|---|---|---|---|---|---|---|---|---|
| | Axial behav | Lateral Behav. | Bearing Capac | Settl. | CPM | DMT | CPTU 3 | MPM | |
| **UK** | | | | | | | | | |
| Cowden | x | x | x | x | x | x | x | x | Glac. Till |
| Cannons P | x | x | | x | x | x | x | x | Oc clay |
| Bothkennar | x | | x | x | x | x | x | x | Soft clay |
| Pentre | x | | | | x | x | x | | Soft clay |
| Brent cross | x | x | | | x | x | | x | Oc clay |
| **Norway** | | | | | | | | | |
| Onsoy | x | | x | x | x | x | x | x | Soft clay |
| Lierstranda | x | | | | x | x | x | | Soft clay |
| Holmen | x | | | x | x | x | x | | Sand |
| Haga | | x | | | | x | | | Stiff clay |
| **France** | | | | | | | | | |
| Jossingy | | | x | x | x | x | x | x | Clay |
| Cubzac | | | x | x | x | x | x | x | Soft clay |
| Cran | x | x | x | x | x | x | x | x | Soft clay |
| Plancoet | x | x | | x | x | x | x | x | Clay& sand |
| **Denmark** | | | | | | | | | |
| Sollerod | | | | | x | x | x | x | Sand |
| Aalborg | x | | | | x | x | x | | Glac clay |
| Svenborg | | | | | x | x | x | x | Clay till |

sure is applied to inflate the membrane and the pressures $p_0$ (start of movement) and $p_1$ (1.05mm displacement) are recorded.

From the $p_0$ and $p_1$ results and the assumed equilibrium pore pressure distribution, the variations with depth of the Dilatometer parameters namely, horizontal stress index $K_D$, material index $I_D$ and dilatometer modulus $E_D$ are calculated (Marchetti 1997).

*Triple Element Pizocone Test (CPTU3)*
Triple element piezocone (CPTU3) tests were carried out at all the Project sites except for Brent Cross and Haga. Earlier piezocone test results were available for both these sites.

The CPTU3 is a 15 $cm^2$ subtractive cone penetrometer with a friction sleeve area of 200 $cm^2$. The device measures the cone resistance, $q_c$, and the combined cone resistance and sleeve friction, $q_c + f_s$, and also the pore water pressure at three locations, on the cone face ($u_1$), at the cone shoulder ($u_2$) and at the top of the friction sleeve ($u_3$). The cone penetrometer also has an internal inclinometer. Corrected cone resistance, $q_t$, and corrected sleeve friction, $f_t$ are obtained (see Lunne et al, 1997).

*Ménard Pressuremeter (MPM)*
Ménard pressuremeter (MPM) test results were only available for some of the sites (see Table 1).

The pressuremeter modulus $E_M$ and the limit pressure, designated here $p_{LMPM}$, are the two parameters determined from each test for use in the design rules. For obtaining these parameters, a procedure consistent with the French standard (AFNOR, 1991) has been used.

## 4 MEASUREMENTS OF AXIALLY LOADED PILE BEHAVIOUR

Most of the axially loaded piles in the Project were tested for displacement and bearing capacity. In all cases for bearing capacity, a clear ultimate pile load could be evaluated.

For some compression piles, the shaft and point resistances were measured. The measured point resistances have been taken as the load at ultimate pile load. It is recognised that this will give base loads somewhat less than the maximum, but this is safe when attempting to predict the total pile capacity. All the measured shaft and base loads are the total loads i.e. relative to a zero load prior to pile installation.

For tension piles, it has been assumed that all measured load is taken in shaft resistance, i.e. there is no point resistance, and the weight of the pile has been neglected.

## 5 PROPOSED METHODS FOR ULTIMATE LOAD OF AXIALLY LOADED PILES IN CLAYS

Methods for calculating the ultimate load of axially loaded piles have been examined for the CPM, DMT, CPTU3 and MPM. All rely on determining a unit shaft resistance, $q_s$, and a unit point resistance, $q_p$. The pile capacity is calculated by dividing the soil profile into layers and summing the shaft resistances for each layer down the pile and adding the base resistance over the cross-sectional area of the base. Instrumented piles were used to develop the methods as these allowed detailed studies of the shaft or base resistances against in situ parameters to be made. A summary of the final proposed methods is given below. Fuller descriptions can be found in Mokkelbost et al (2000) and Powell et al (2000 and 2001).

### *5.1 CPM*

#### *5.1.1 Unit Shaft resistance, $q_s$*
The proposed CPM method for the bearing capacity of piles in clay evolved from the French MPM rules. In the CPM method, a single curve relates limit unit shaft resistance, $q_s$ (in MPa), to net limit pressure, $p_{LCPM}*$ (in MPa). The equation is:

$q_s = 0.08\,(p_{LCPM}*/1.5)\,\{2 - (p_{LCPM}*/1.5)\}$ if $p_{LCPM}* \leq 1.5$ MPa

$q_s = 0.08$ if $p_{LCPM}* \geq 1.5$ MPa

where $p_{LCPM}*$ is the net limit pressure equal to $p_{LCPM} - \sigma_{h0}$
$\sigma_{h0}$ in situ horizontal stress, equals $0.5\sigma_{v0}' + u_0$ (from MPM rules)
$\sigma_{v0}'$ effective vertical stress in situ
$u_0$ in situ pore pressure

#### *5.1.2 Unit Point resistance, $q_p$*
The proposed method for calculation of point resistance is to use the MPM rules of 'Fascicule 62' (MELT, 1993) but with the CPM limit pressures.

$q_p = k_p \cdot p_{LCPMe}^*$

where $p_{LCPMe}^*$ is the equivalent net limit pressure $p_{LCPM}*$ (see 5.1.1) for the base of the foundation.
and $k_p$ is the bearing factor, a function of pile and soil type.

### *5.2 DMT*

For the DMT, two methods have been proposed for the calculation of the shaft resistance in clays. The first is the 'main method' developed for all piles, both tension and compression piles. The second is for compression piles only.

#### 5.2.1.1 Unit Shaft resistance, $q_s$ - main method
The features of the main design method for shaft resistance in clays are:

$I_D < 0.1$ $q_s/(p_1 - p_0) = 0.5$
$0.1 < I_D < 0.65$ $q_s/(p_1 - p_0) = -0.73077\, I_D + 0.575$
$I_D > 0.65$ $q_s/(p_1 - p_0) = 0.1$
For parts of a pile where $h/R > 50$, multiply the above by 0.85, where h is distance up the pile from the pile tip and R is the pile radius

#### 5.2.1.2 Unit Shaft resistance, $q_s$ - compression piles only

The features of the design method for compression piles only for shaft resistance in clays are:

$I_D < 0.6$ $q_s/(p_1 - p_0) = -1.1111\, I_D + 0.775$
$I_D > 0.6$ : $q_s/(p_1 - p_0) = 0.11$
For parts of a pile where $h/R > 50$, multiply the above by 0.85.

#### *5.2.2 Unit Point resistance*
The proposed method is:

point resistance = $k_{di}\, p_{1e}\, A_b$

where $k_{di}$ is defined as the new DMT bearing capacity factor

$p_{1e}$ is the equivalent $p_1$ beneath the base of the pile

Criteria for the variation of $k_{di}$ with soil type need to be established from a larger database of pile and DMT results, but in the present method the following criterion has been used:

For $E_D > 2$MPa, $k_{di} = 1.3$ for closed ended driven piles

For $E_D < 2$MPa, $k_{di} = 0.7$ for closed ended driven piles
For open-ended piles multiply these values by 0.5

Note: Not enough data were available to define a transition phase between the two criteria; this needs investigating.

### *5.3 CPTU3*

During the background work to the project it was found that the method proposed by Almeida et al. (1996) had the greatest potential, since it was the only method that used the piezocone and the corrected cone resistance.

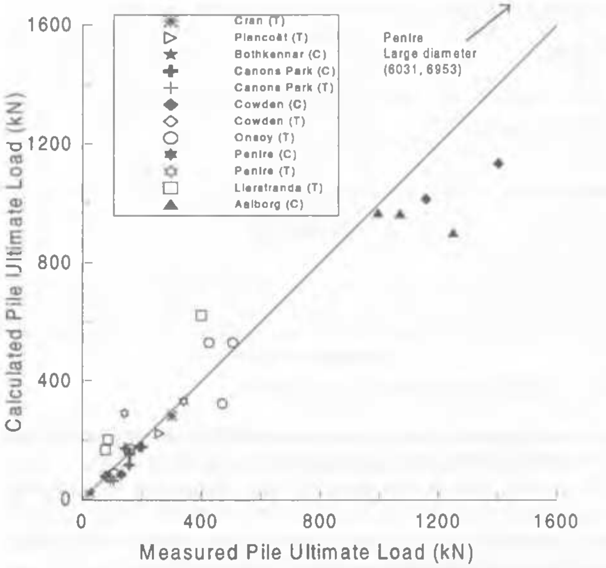


Figure 1. Predicted against measured capacity using the CPM method

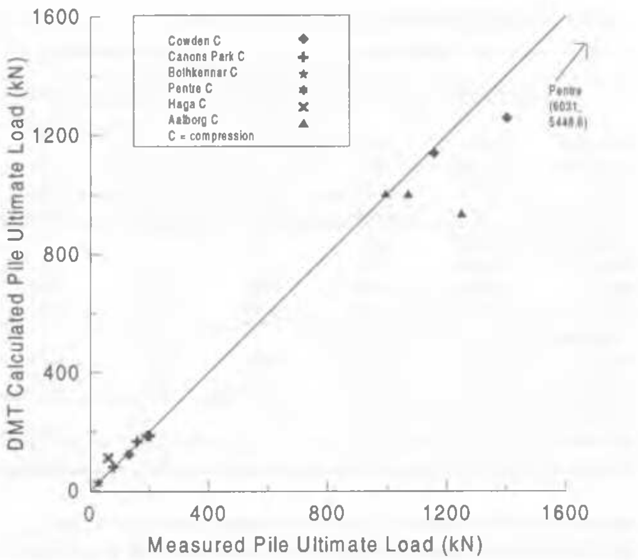


Figure 2. Predicted/measured capacity using DMT compression pile method

The method does not apply to very silty soils, and so has not been applied to the sites of Lierstranda and Pentre.

*5.3.1 Unit Shaft resistance, $q_s$*

The procedure is based on that of Almeida et al. (1996) –
The unit shaft friction of piles is computed from:

$q_s = q_{net}/k_1$

where $q_{net} = q_t - \sigma_{vo}$

$k_1$ is found from the equation:

$k_1 = 10.5 + 13.3 \log (q_{net}/ \sigma_{vo}')$ from the project database

For length/ diameter > 60, correction factors outlined by Almeida et al should be applied. This equation for $k_1$ gives more conservative predictions than that of Almeida et al but with less scatter.

*5.3.2 Unit Point resistance, $q_p$*

Unit point resistance, $q_p$, is found from Almeida et al. as:

$q_p = q_{net}/k_2$

$k_2 = N_{kt}/9$

$N_{kt}$ is the cone factor, taken as $N_{kt} = q_{net}/s_u$ , where $s_u$ is the undrained shear strength.

### *5.4 MPM*

*5.4.1 Unit Shaft resistance, $q_s$*

For the MPM it is proposed that:

- for stiff clays, use the MPM rules and curves of 'Fascicule 62' (MELT, 1993),
- for soft clays, use the MPM rules and curves of 'Fascicule 62' but they should be multiplied by a factor of 2.

*5.4.2 Unit Point resistance, $q_p$*

For $q_p$ follow 5.1.2 but using the $p_{LMPM}$ values.

## 6 COMPARISON OF THE PERFORMANCE OF METHODS FOR ULTIMATE LOAD IN CLAYS

Section 5 summarised the proposed methods for calculating the ultimate load for axially loaded piles. Figures 1 & 2 show examples of the results from two of the methods (CPM and DMT. 'compression piles') applied to full pile performance, shown as the predicted against measured results. It can be seen from the Figures that these methods appear to perform well with results generally on the conservative side i.e. slightly underpredicting.

In the study calculations were not performed using all the proposed methods for all piles. This was either because a particular in situ test was unfortunately not performed at a site, or because a certain soil type was excluded from the method.

Fuller discussions on the performance of the various methods with regard to individual piles, sites and soil types can be found in the references listed in section 5.

Figure 3 shows the data for all piles and methods as predicted/measured against individual pile. In general it can be seen that all methods give similar results and that the different methods show variations in performance for a given site that reflects the differences in measured pile behaviour.

An alternative way to view and compare the predictions from the different methods is in terms of the mean and standard deviations of the ratios of calculated to measured ultimate capacities. The proposed methods have all been applied to different numbers of sites and piles and therefore direct comparison for the different methods of the mean and standard deviation of the calculated/measured results will not give a true representation of their relative performance. However, for each method these statistics are meaningful and helpful for understanding the performance of the method. Therefore in Table 2 the statistical analysis is given for each method for the results from all the piles analysed. Also in the table are the same statistics but excluding piles for which, for various reasons (see refs in section 5), the method is at present not appropriate. These latter statistics are considered to provide a more representative basis for comparing the per-

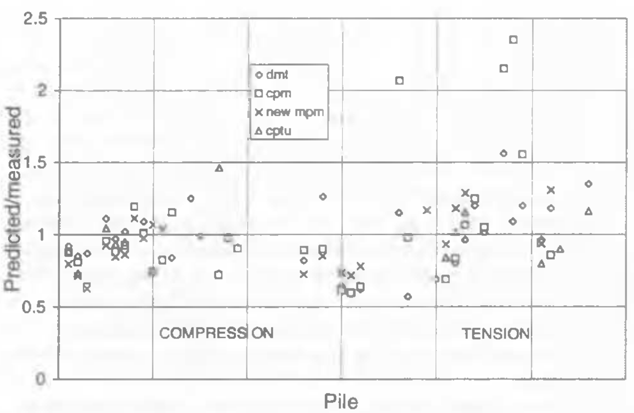


Figure 3. Predicted/measured capacity for all piles and all methods

Table 2 Statistical performance of the New methods

| | Calculated / Measured | | | | |
|---|---|---|---|---|---|
| | CPM | DMT | DMT compres. | CPTU3 | New MPM |
| All Sites | 9sites | 10 | 6 | 8 | 6 |
| and piles | 31 piles | 59 | 15 | 21 | 21 |
| Mean | 1.03 | 1.12 | 1.01 | 0.97 | 0.91 |
| S.D. | 0.43 | 0.28 | 0.25 | 0.27 | 0.22 |
| Applica- | 8 sites | 10 | 5 | 7 | 6 |
| ble sites | 27 piles | 36 | 13 | 18 | 21 |
| Mean | 0.89 | 0.95 | 0.95 | 0.99 | 0.91 |
| S.D. | .17 | 0.22 | 0.07 | 0.2 | 0.22 |
| Compression | | | | | |
| Mean | 0.91 | .94 | 0.95 | .91 | 0.91 |
| S.D. | 0.15 | 0.13 | 0.06 | 0.1 | 0.16 |
| Tension | | | | | |
| Mean | .87 | 0.95 | | 0.91 | 0.96 |
| S.D. | .16 | 0.22 | | 0.28 | 0.23 |

formance of the methods. Again all methods are seen to perform well. In the lower part of Table 2 the same treatment is given to the piles but grouped as either tension or compression. In Figure 4 the methods are compared again but using a common database of piles i.e. only those from sites were all methods could be used.

From the statistical analysis presented, it is seen that generally all the methods perform well. On average (excluding piles for which a method is at present not appropriate) all the methods are conservative. It is very difficult to draw conclusions on the relative performance of the methods as on average they all perform very similarly. For compression piles alone, the DMT 'compression pile' method gives clearly the most repeatable results and they also have very good accuracy. For the general methods, the observations are that the CPTU3 and the CPM method show the best repeatabilities but all are close. The CPM method appears to be on average the most conservative. There is however, very little difference between the methods.

The repeatability of all the methods is worse for tension piles than for compression piles. This may be because there are fewer sites with compression piles than with tension piles in this database or that the prediction of base suction effects has not been attempted for tension piles.

Comparisons with other methods of prediction (Table 3) are very encouraging, certainly the CPTU3 method appears to be equal to or generally better than other CPT methods listed. Equally the methods appear as good as or better than the API and Imperial College (Jardine and Chow, 1996) methods.

## 7 SUMMARY

New methods for predicting the ultimate load for axially loaded piles in clays have been proposed for the CPM, DMT, CPTU3 and MPM. All the methods have been shown to perform well. Based on the database of sites, no obvious difference can be seen to the performance of the methods in stiff or soft clay.

Generally, for all the compression piles the methods appear reasonable and there does not appear to be a consistent trend to the performance of the different methods relative to each other. The DMT method for compression piles only method does appear to out perform the others and this indicates that there may merit in developing methods specifically for compression piles.

Bearing in mind that it was not possible for all the compression piles to know calculated/measured against measured results for the shaft and point resistances, the comparisons that were possible indicate that the observations for shaft resistance are in line with those above for the whole pile. The calculations of point resistance from all the methods appear in general to be conservative.

For tension piles, overall, all the methods appear reasonable, though there are exceptions for some devices and some sites.

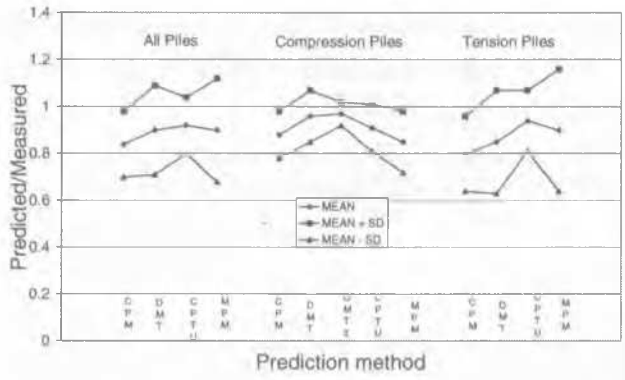


Figure 4 Relative performance of the methods

Across all the sites there does not appear to be a consistent trend to the performance of the methods relative to each other.

A general observation from all the figures for tension and compression piles is that the different methods show consistency. The variations in performance of the methods for a given site reflect the differences in measured pile behaviour.

From the analysis for the common database of piles, the repeatability of all the methods is worse for tension piles than for compression piles.

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Table 3. Statistical performance of some existing methods

| | Imperial College | API | CPT methods 1 | 2 |
|---|---|---|---|---|
| Mean | 1.01 | 0.98 | 0.8 | 1.03 |
| SD | 0.18 | 0.33 | 0.19 | 0.28 |

1. Almeida et al 1996, 2. De Ruiter & Beringen 1979

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