# Use of in situ tests in pile design

## Utilisation des essais in situ pour la conception des pieux

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SYNOPSIS: Modern methods of pile design often make great use of in situ test data. A total of 13 axial pile capacity design methods have been evaluated using the results from 8 full-scale pile load tests on six different piles. These methods, separated into direct and indirect approaches, used data obtained from the cone penetration test (CPT). Two methods of predicting the response of 3 of the piles to lateral loading were also evaluated using pressuremeter and flat dilatometer test data. The predicted behaviour of the piles is compared and discussed with the measured response.

## 1 INTRODUCTION

The design of driven piles to resist axial and lateral loads is a common geotechnical problem. The use of modern in situ test methods can often significantly improve the design of driven piles.

The use of in situ test results in geotechnical design may be split into the following two distinct approaches;

- DIRECT APPROACH, which provides the opportunity to pass directly from in situ measurements to the performance of foundations without the need to evaluate any intermediate soil parameters.
- INDIRECT APPROACH, which leads to design methods that require the evaluation of parameters such as, strength, stiffness and consolidation. These parameters are then applied to the solutions of boundary value problems.

The direct approach is frequently used in the evaluation of the settlement of shallow foundations in cohesionless deposits and to assess the ultimate and service limit states of piles subjected to both axial and lateral loads. The direct approach leads to empirical methods.

Although the indirect approach is basically more sound and rational than the direct approach, it suffers from the fact that it often requires the solutions of complex boundary value problems.

The results from eight full-scale axial pile load tests were used to evaluate six direct and seven indirect design methods using data from the cone penetration test (CPT).

Three of the piles were also laterally loaded and predictions of lateral load behaviour were made using both pressuremeter and flat dilatometer test data. The pressuremeter data were applied using a direct approach, whereas, the flat dilatometer test data were applied using a recently suggested indirect approach.

## 2 TEST SITE

The test piles were part of the studies associated with the recent construction of the Alex Fraser bridge and associated highway extensions near Vancouver, B.C., Canada. The site is located at the eastern tip of Lulu Island which is within the post-glacial Fraser River delta.

A summary of the soil profile at the test site to a depth of 75 m based on sampling and CPT is shown in Fig. 1. Below a surface layer of fill there is a deposit of organic silty clays to a depth of about 15 m that has been laid down in a quiescent swamp or marsh environment. Below this upper layer, a medium dense sand deposit, locally silty, prevails to a depth of 30 m. Underlying the sand, to a depth of up to 150 to 200 m, exists a normally consolidated clayey silt deposit containing thin sand layers (Blunden 1975). Below a depth of about 60 m the sand layers are more prevalent and thicker (up to 1 m thick). The CPT profile in Fig. 1 presents a clear picture of the stratigraphic detail at the test site.

Across the entire site, 2 to 4 m of non-homogeneous fill exists at the surface. For the purpose of facilitating in situ testing, making pile driving possible, and studying lateral pile behaviour, the fill material was removed in the general area of the test piles and replaced with clean river sand.

Six pipe piles were driven at the site. A summary of the pile geometries and measured capacities are given in Table 1. The five smaller piles were placed and tested under the supervision of University of British Columbia (UBC) personnel. The large pile was placed and tested under the supervision of the B.C. Ministry of Transportation and Highways (MOTH). Pile No. 1 had a larger diameter sleeve for the first 2 m to remove any frictional resistance in the upper sand fill.

The method by Davisson (1973) was used to determine failure loads. Fortunately, most of the piles derived a major part of their resistance from shaft friction and showed well defined plunging failures.

Full details of the testing program are given by Robertson et al (1985) and Davies (1987).

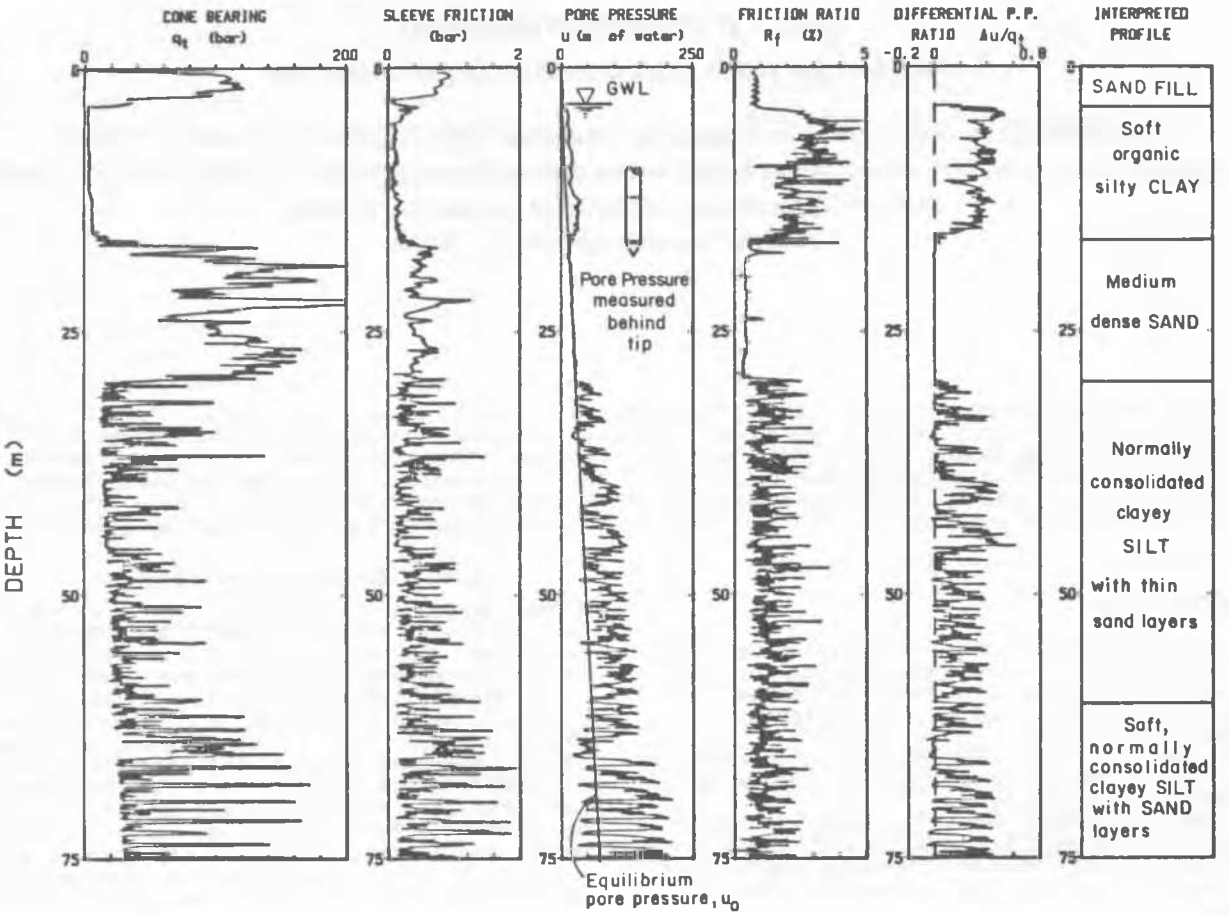

Figure 1. Soil profile for pile research site (1 bar = 100 kPa).

Table 1. Summary of pile geometries and axial capacities

| Pile/ Test No. | Length (m) | Diameter (m) | Wall Thickness (mm) | L/D | Open/ Closed Ended | Capacity (kN) (Davisson, 1973) |
|---|---|---|---|---|---|---|
| 1 | 14.3 | 0.324 | 9.5 | 44 | C | 170 |
| 2 | 13.7 | 0.324 | 9.5 | 42 | C | 220 |
| 3 | 16.8 | 0.324 | 9.5 | 52 | C | 610 |
| 4 | 23.2 | 0.324 | 9.5 | 72 | O | 1200 |
| 5 | 31.1 | 0.324 | 11.5 | 96 | C | 1070 |
| A | 67.0 | 0.915 | 19 | 73 | O | 7500 |
| B | 78.0 | 0.915 | 19 | 85 | O | 7000 |
| C | 94.0 | 0.915 | 19 | 103 | O | 8000 |

## 3 AXIAL CAPACITY

A summary of the thirteen methods used to predict the axial pile capacities is shown in Table 2. The first six methods are direct methods that use CPT data (tip resistance, $q_c$ and/or sleeve friction, $f_s$) in a direct manner with the use of empirical scaling factors. The scaling factors, in all cases, resemble the original work of de Beer (1963). The remaining seven methods are indirect methods that require intermediate correlations to predict soil parameters. Unlike the direct methods, most of the indirect methods were not formulated specifically for use with CPT data.

Table 3 summarizes the results of all the methods. Results from pile 1 have not been included in Table 2 because the predicted pile capacities included the shaft resistance in the upper sand fill which was not acting on pile 1.

Table 3 shows that both the direct and indirect methods provided reasonable predictions of the measured capacities for the small piles (piles 2 to 5). The direct methods, with the Zhou et al method to a lesser extent, also predicted the capacity of the larger piles quite satisfactorily. However, without exception, the indirect methods had predictions for large piles that were significantly in error and non-conservative when compared to the measured results. Since the indirect methods generally did reasonably well in predicting the capacity of the smaller piles, and since the piles are all in the same deltaic soil deposits, the results suggest that scale effects are extremely important for the large diameter piles when using indirect methods.

Table 2. Summary of axial capacity methods evaluated using CPT data.

| Direct Methods | References | Notes |
|---|---|---|
| 1. Schmertmann & Nottingham CPT | Schmertmann (1978) | Modified European |
| 2. de Ruiter & Beringer CPT | de Ruiter & Beringer (1979) | European (Fugro) ($q_c$ & $f_s$ used) |
| 3. Zhou et al CPT | Zhou et al (1982) | Chinese Railway Experience ($q_c$ & $f_s$ used) |
| 4. Van Mierlo & Koppejan CPT | Van Mierlo & Koppejan (1952) & Begemann et al (1982) | Original Dutch ($q_c$ only used) |
| 5. Laboratoire Central des Ponts et Chaussées CPT (LCPC) | LCPC-Bustamante & Gianeselli (1982) | French Method ($q_c$ only used) |
| 6. Belgian CPT | W.F. Van Impe (1986) | Belgian Method ($q_c$ only used) |
| **Indirect Methods** | **References** | **Notes** |
| 7. API RP2A | American Pet. Inst. (1980) | Offshore |
| 8. Dennis & Olson | Dennis & Olson (1983a & b) | Modified API |
| 9. Vijayvergiya & Focht | Vijayvergiya & Focht (1972) | "λ" Method |
| 10. Burland | Burland (1983) | "β" Method |
| 11. Janbu | Janbu (1976) | NIT |
| 12. Meyerhof Conventional | Meyerhof (1976) | Original Bearing Theory |
| 13. Flaate & Selnes | Flate & Selnes (1977) | NGI |

## 4 LATERAL PILE RESPONSE

The non-linear subgrade reaction method is widely used for the design of laterally loaded piles. This method replaces the soil reaction with a series of independent non-linear springs. The non-linear behaviour of the soil springs is represented by P-y curves, which relate soil reaction and pile deflection at points along the pile length. Most of the existing methods for obtaining P-y curves are highly empirical. Often little account is taken of the method of pile installation and the influence that this may have on the soil behaviour. Early methods to obtain P-y curves used empirical methods based on laboratory data (Matlock 1970).

Several methods have recently been proposed for the design of laterally loaded piles using pressuremeter data. Most of these methods make use of a Ménard type pressuremeter, and do not attempt to model the disturbance caused by a driven pile since the pressuremeter is placed in a prebored hole. However, it is possible to install the pressuremeter in a manner which models the disturbance caused during pile installation. For driven displacement piles, the pressuremeter can be pushed into the soil in a full-displacement manner. For cast-in-place or bored piles, a prebored or self-bored pressuremeter test can model the disturbance caused during pile installation. The method by Robertson et al (1983) uses the results in a direct approach from a pressuremeter pushed into the soil to model the installation of a driven displacement pile.

Recently a method has been suggested that uses data obtained from a flat dilatometer test (DMT) which is also pushed into the ground to obtain P-y curves (Robertson et al 1989).

Static monotonic lateral load tests were performed on three of the test piles. The pressuremeter and flat dilatometer methods proposed by Robertson et al 1983 and 1989, respectively, were evaluated.

A summary of the calculated and measured load deflection curves at the pile head is shown in the upper part of Figs. 2, 3 and 4 for three piles of different geometries. Also, calculated and measured pile deflections versus depth profiles are shown in the lower part of Figs. 2, 3 and 4 for one value of the lateral load.

A review of Figs. 2, 3 and 4 shows that both methods provide a good prediction of pile response, with the DMT method providing a slightly better prediction than the pressuremeter.

## 5 SUMMARY

Thirteen pile capacity methods were evaluated using CPT data for eight full-scale axial pile load tests. The piles were steel pipe piles driven into deltaic soil deposits. The length to diameter ratios for the piles ranged from 40 to 100 with measured axial capacities from 170 kN to 8,000 kN in soils that included

Table 3. Summary of predicted/measured axial pile capacity, %

| Pile | Direct Methods | | | | | | Indirect Methods | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| No. | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
| 2 | 48 | 94 | 110 | 49 | 95 | 67 | 75 | 58 | 127 | 104 | 126 | 98 | 134 |
| 3 | 97 | 135 | 135 | 133 | 125 | 104 | 158 | 122 | 158 | 148 | 232 | 120 | 170 |
| 4 | 100 | 100 | 99 | 102 | 88 | 137 | 113 | 76 | 92 | 88 | 135 | 110 | 95 |
| 5 | 86 | 99 | 129 | 74 | 96 | 153 | 114 | 77 | 107 | 102 | 114 | 129 | 98 |
| A | 86 | 103 | 141 | 73 | 80 | 101 | 156 | 141 | 174 | 206 | 165 | 181 | 174 |
| B | 113 | 114 | 177 | 91 | 105 | 130 | 223 | 204 | 223 | 267 | 226 | 252 | 231 |
| C | 126 | 118 | 192 | 94 | 109 | 140 | 247 | 214 | 231 | 286 | 248 | 285 | 234 |
| Average, % | 94 | 109 | 140 | 88 | 100 | 119 | 155 | 127 | 159 | 172 | 178 | 168 | 162 |
| Std. deviat. | 25 | 14 | 34 | 26 | 15 | 30 | 62 | 63 | 54 | 82 | 56 | 74 | 57 |

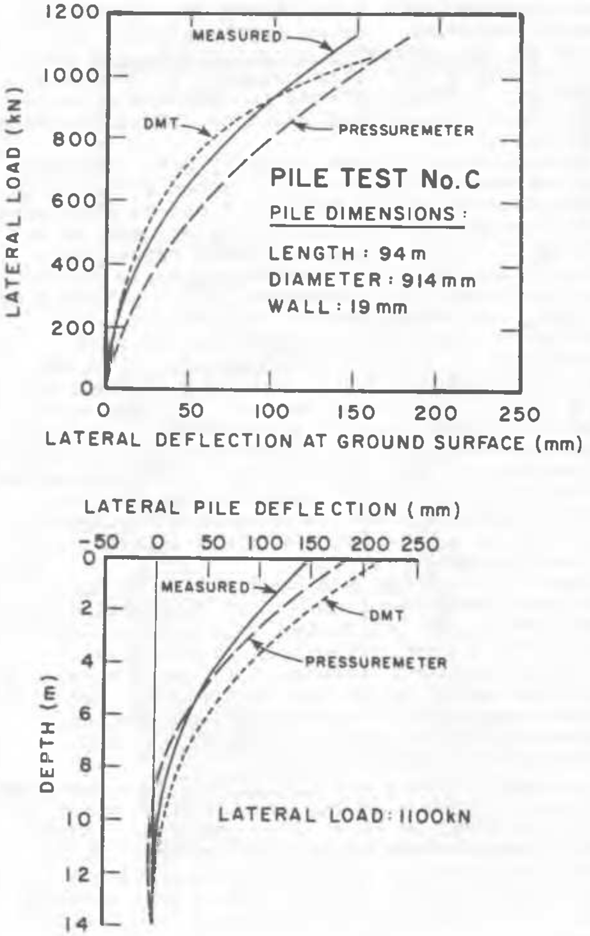

Figure 2. Predicted versus measured lateral pile behaviour - MOT pile No. C.

organic silt, sand and clay.

CPT data was used for the prediction of pile capacity for the thirteen methods evaluated. The direct methods, which incorporate CPT-pile scaling factors, provided the best predictions for the piles and methods evaluated. Based on the results of this study the following three direct methods are preferred:

1. LCPC CPT (Bustamante and Gianeselli, 1982)
2. de Ruiter and Beringer CPT (1979)
3. Schmertmann and Nottingham CPT (1978)

For the piles tested, the LCPC (French) method is shown to be the best method with a maximum error of about 25%. In addition, the LCPC does not directly require the CPT sleeve friction value other than to define soil type. This is a desirable feature since the cone bearing is generally obtained with more accuracy and confidence than the sleeve friction.

The results of this study indicate that indirect CPT methods to predict axial pile capacity may significantly overpredict the capacity of large diameter, long piles (L/D>75) supported in soft clayey soils.

Two methods were evaluated to predict the response of three piles that were monotonically laterally loaded. One method used data from a full-displacement pressuremeter test and the

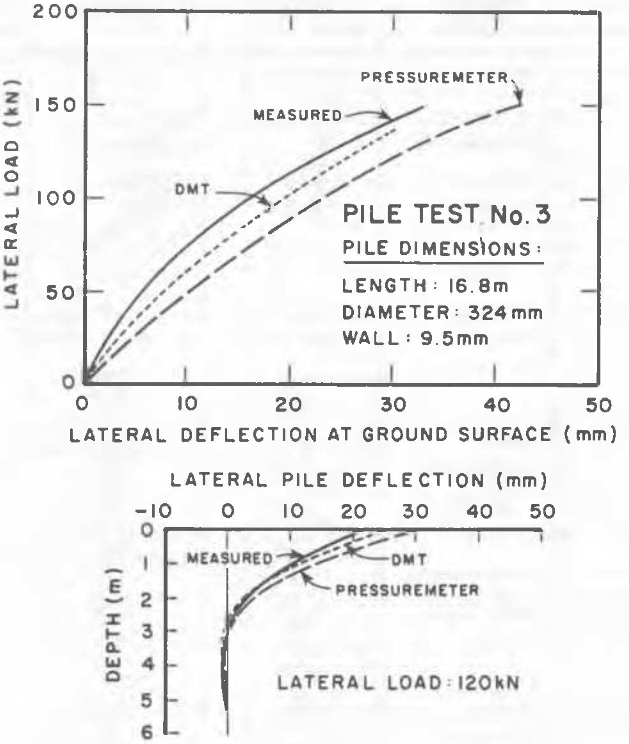

Figure 3. Predicted versus measured lateral pile behaviour - UBC pile No. 3.

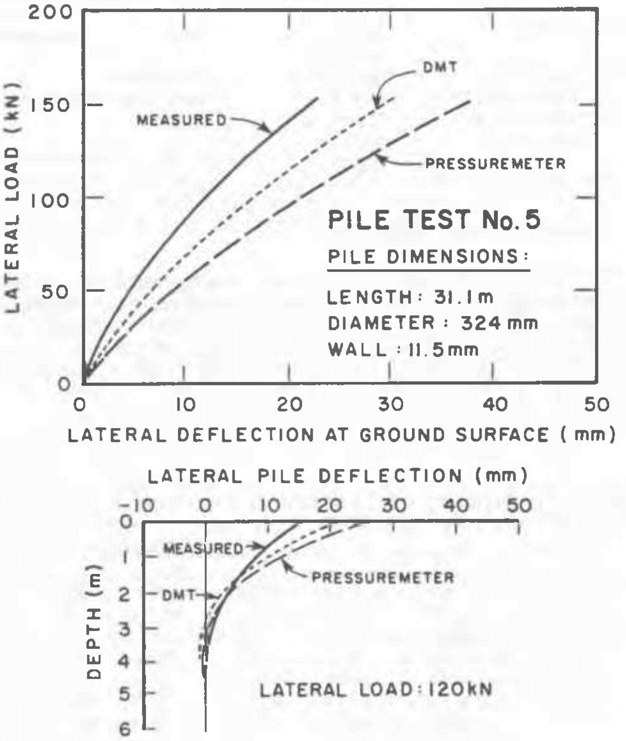

Figure 4. Predicted versus measured lateral pile behaviour - UBC pile No. 5.

other from a flat dilatometer test. Both methods provided reasonably good predictions of lateral pile behaviour for all three piles. The DMT method provided a slightly better prediction.

When driven piles are required to support axial and lateral loads in soft deltaic soils in situ tests such as the CPT and DMT, can be highly economical methods for providing extensive subsoil information to predict the pile response.

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