ASCE FOUNDATIONS Congress, JUNE 89
SM#135 ASCE SP23

AN EVALUATION OF PILE DESIGN IN FRASER RIVER DELTA USING IN-SITU TESTS

P.K. Robertson[1] M.ASCE, R.G. Campanella[2] M.ASCE,
M.P. Davies[3] and A. Sy[4]

ABSTRACT: Modern methods of pile design often take advantage of in-situ test data. Thirteen axial pile capacity design methods have been evaluated using the results from eight full-scale pile load tests on six different driven pipe piles. The design methods, separated into direct and indirect approaches, were evaluated using data from the Cone Penetration Test (CPT).

Pile driving records for continuous driving and redriving using a Pile Driving Analyzer (PDA) were also obtained on some of the piles. The analyses of the PDA data was reviewed based on the CPT results.

Two methods of predicting the response of three of the piles to lateral loading were evaluated using pressuremeter and flat dilatometer test data. This paper presents a review of the predicted behaviour of the piles based on in-situ tests compared with their measured response.

INTRODUCTION

The design of driven piles to resist axial and lateral loads is a common foundation engineering 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 foundation design may be divided into the following two distinct approaches;

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[1] - Prof., Dept. of Civil Eng., Univ. of Alberta, Edmonton, Alberta Canada, T6G 2G7 (formerly at University of British Columbia)

[2] - Prof., Dept. of Civil Eng., Univ. of British Columbia, Vancouver, B.C., Canada, V6T 1W5

[3] - Engineer, Klohn Leonoff, Cons. Eng., 10180 Shellbridge Way, Richmond, B.C., Canada, V6K 2W7

[4] - Graduate Student, Dept. of Civil Eng., Univ. of British Columbia, Vancouver, B.C., Canada, V6T 1W5

> 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 soil parameters such as, strength, stiffness and consolidation characteristics. These parameters are then applied to some analytical solution of design foundations.

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 axial loads. The direct approach generally leads to empirical methods in which quality is strictly linked to the number and quality of the case records upon which the approach has been established.

Although the indirect approach is basically more sound and rational than the direct approach, it suffers from the fact that it often requires compatible solutions of complex boundary value problems for the interpretation of the in-situ test and the analyses of the foundation problem.

The results from eight full-scale axial pile load tests have been used to evaluate six direct and seven indirect design methods using data from the Cone Penetration Test (CPT).

Pile driving records using strain gauges and accelerometers were also obtained on several piles for both continuous driving and redriving using a Pile Driving Analyzer (PDA).

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

This paper presents a review of predicted behaviour of the piles based on in-situ tests compared with their measured response. More detailed information is given by Robertson et al.; 1988, 1989 and Davies 1987.

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 75m based on sampling and CPT is shown in Figure 1. Beneath a surface layer of fill there is a deposit of organic silty clay to a depth of about 15m that was 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 30m. Underlying the sand, to a depth of up to about 150m, exists a normally consolidated clayey

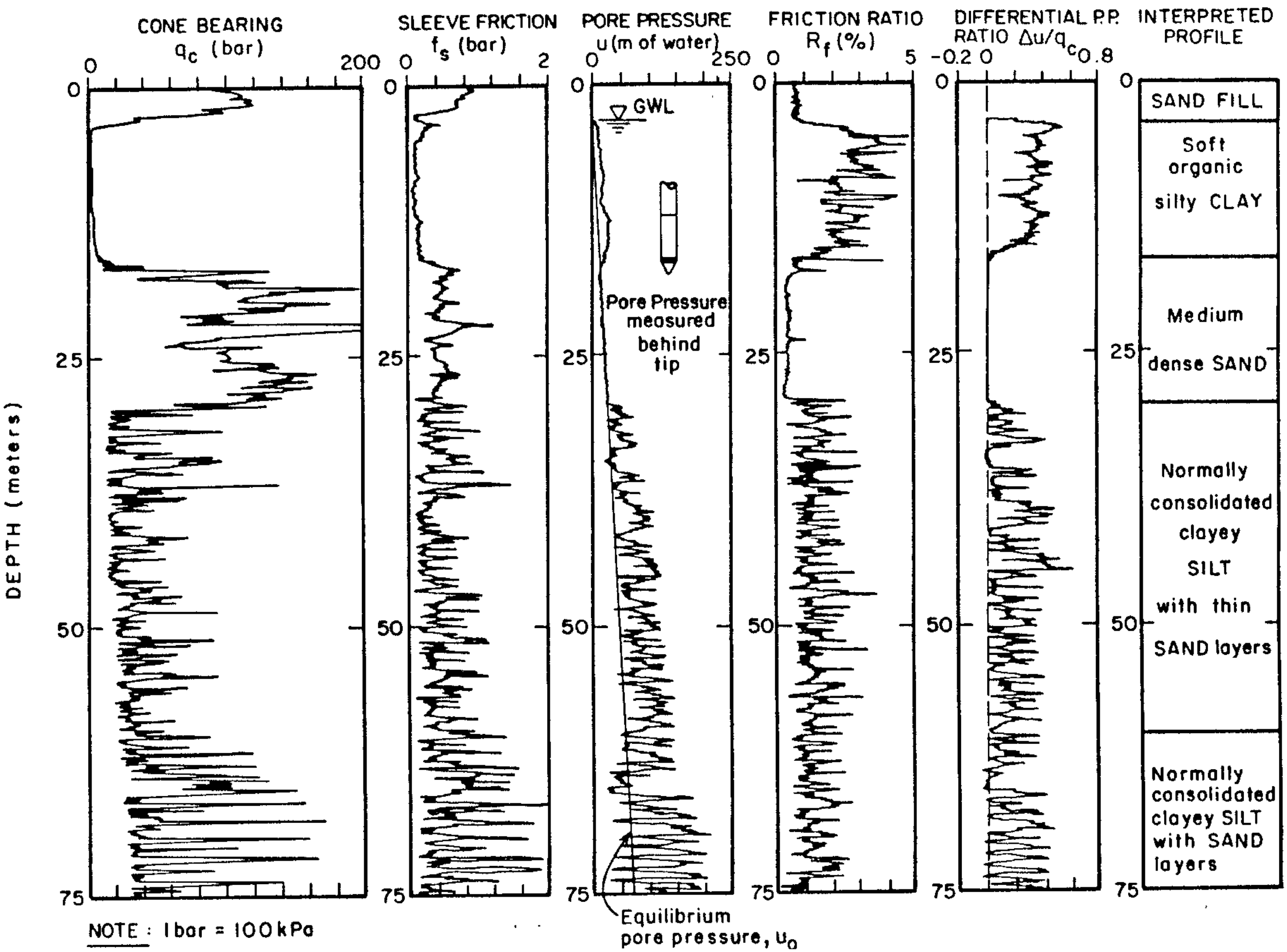


Figure 1. Summary of Soil Profile for Pile Research Site
(1 bar = 100 kPa)

silt deposit containing thin sand layers. Below a depth of about 60m the sand layers are more prevalent and thicker (up to 1m thick). The CPT profile in Figure 1 presents a clear picture of the stratigraphic detail at the test site. Although deltaic deposits are known to vary widely from location to location, the stratigraphic profile across the test site remains remarkably consistent.

Across the entire site, 2 to 4m 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 research piles. This material was replaced with clean river sand.

Six pipe piles were driven (four 324 mm dia., 9.5 mm wall thickness; one 324 mm dia., 11.5 mm thickness; one 915 mm dia., 19 mm thickness) at the site. A summary of pile geometries and measured capacities is 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.

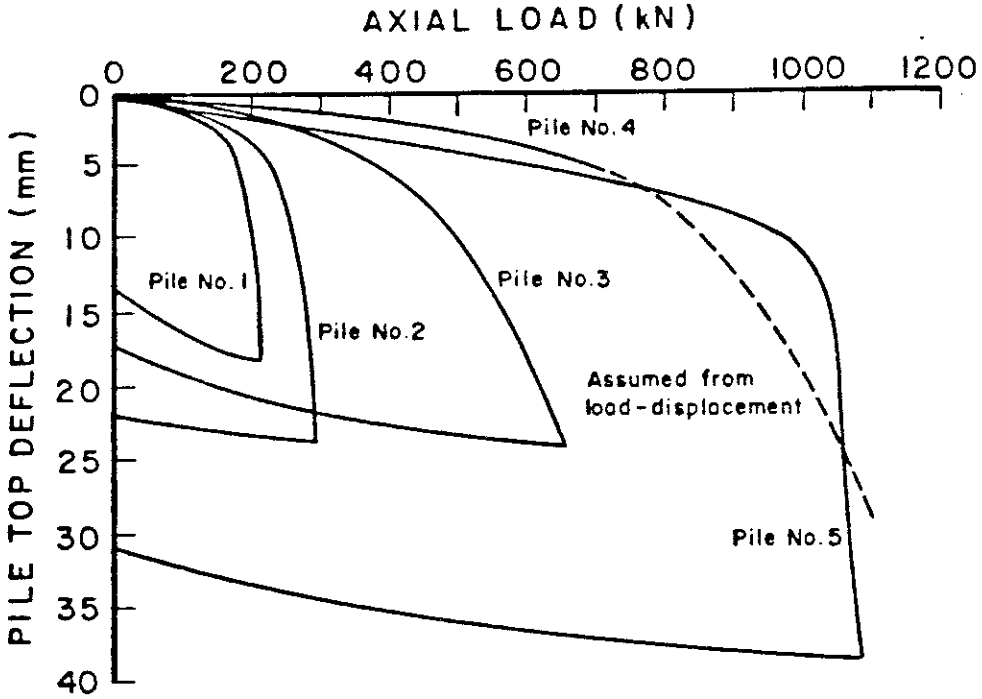
Table 1. Summary of pile geometries and measured capacities

Pile/Test No.	Length (m) (L)	Diameter (m) (D)	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

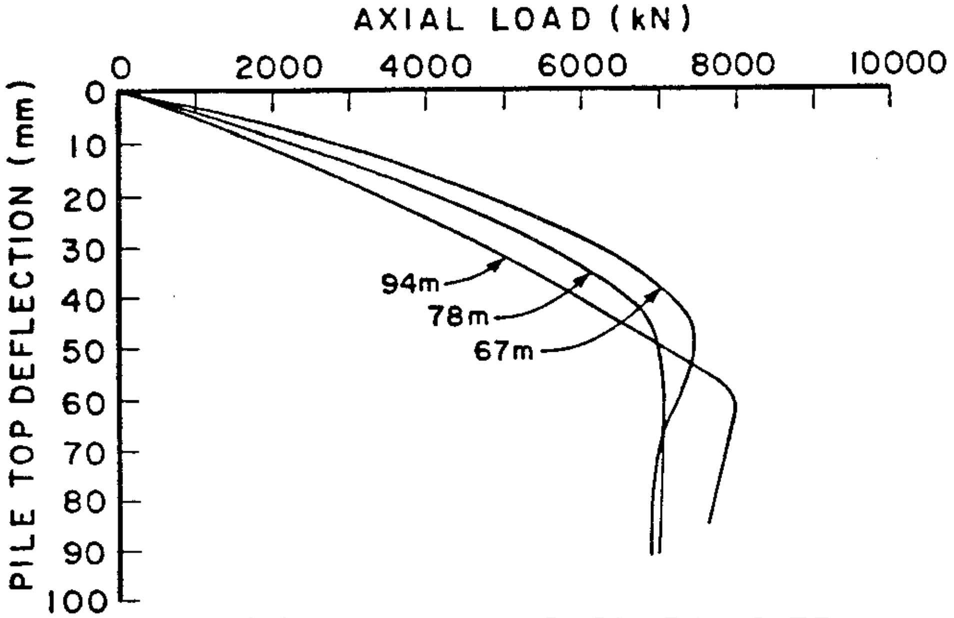
* O = open ended
C = closed ended

The 'Quick Load Test Method' of axial loading (similar to ASTM D1143-81 Section 5.6) was used with the axial load being applied in roughly 5% increments of the anticipated failure load. The 'Quick Load Test Method' was used to minimize time-dependent effects.

Figure 2(a) presents a summary of the load-displacement test results for the five smaller piles. Based on the telltale data piles 1, 2 and 5 are interpreted as predominantly shaft resistance piles whereas piles 3 and 4 had significantly larger contributions to their total capacity from end bearing. Pile No. 4 could not be loaded to failure, but the load-deflection diagram was based on the combined results of the other pile test results. Figure 2(b)



(a) UBC PILE RESEARCH SITE AXIAL LOAD TEST RESULTS



(b) MOTH PILE RESEARCH SITE

Figure 2. Summary of Axial Pile Load Test Results

presents a summary of the load-displacement results for the larger pile. The larger pile was tested at three depths (67, 78 and 94m). All three test results (Figure 2b) indicate that the larger pile has a large shaft resistance component. The reduction in measured load observed for the larger pile occurred because the hydraulic jacks were unable to sustain the load with rapid axial deflections. Although Pile No. 4 and the larger pile were installed open-ended, the soil plug inside the piles was longer than 85 percent of the pile length. During axial loading the piles appear to have behaved as closed-ended piles.

The method suggested 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, as shown in Figure 2.

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

AXIAL CAPACITY

A summary of the thirteen methods used to predict the axial pile capacities is shown in Table 2. The first six are direct methods that use the 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 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 and shows that both the direct and indirect methods generally provided reasonable predictions of the measured capacities for the small piles (piles 1 to 5). The direct methods, with the Zhou et al (1982) method to a lesser extent, also predicted the capacity of the larger pile quite satisfactorily. However, without exception, the indirect methods had predictions that were significantly in error and non-conservative when compared to the measured results for the large pile. 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 basic soil profile, the results suggest that scale effects are extremely important for the large diameter pile.

Dynamic Pile Measurements. Pile head accelerations and full bridge strain gauge data were recorded during pile driving. This information was recorded using a pile driving analyzer (PDA) operated by UBC and MOTH personnel.

After pile load testing, Pile No. 5 (324mm diameter, 31.1.m long) was given a few redriving blows with a large drop hammer and PDA data were collected under the supervision of an engineer from Goble, Raushe and Likins (GRL).

Table 2. Summary of Axial Capacity Methods Evaluated Using CPT Data

Direct Methods	References	Notes
1. Schmertmann and Nottingham CPT	Schmertmann (1978)	Modified European (q_c & f_s)
2. de Ruiter and Beringen CPT	de Ruiter and Beringen (1979)	European (Fugro) (q_c & f_s)
3. Zhou et al CPT	Zhou et al (1982)	Chinese Railway Experience (q_c & f_s)
4. Van Mierlo and Koppejan CPT	Van Mierlo and Koppejan (1952) and Begemann et al (1982)	Original Dutch (q_c only)
5. Laboratoire Central des Ponts et Chaussees CPT (LCPC)	Bustamante and Gianesalli (1982)	French Method (q_c only)
6. Belgian CPT	W.F. Van Impe (1986)	Belgian Method (q_c only)
Indirect Methods	**References**	**Notes**
7. API RP2A	American Pet. Inst. (1980)	Offshore Method
8. Dennis and Olson	Dennis and Olson (1983a & b)	Modified API
9. Vijayvergiya and Focht	Vijayvergiya and Focht (1972)	"λ" Method
10. Burland	Burland (1973)	"β" Method
11. Janbu	Janbu (1976)	NIT
12. Meyerhof Conventional	Meyerhof (1976)	Original Bearing Capacity Theory
13. Flaate and Selnes	Flaate and Selnes (1977)	NGI

Calculations of pile capacity for Pile No. 5 was made with the redriving PDA data using the Case Method (Rausche et al, 1985) and CAPWAP (Rausche, 1970).

The Case Method estimates the static pile capacity using a closed form solution to the one-dimensional wave equation. The dynamic component of soil resistance requires the evaluation of a damping constant, J_c, which is usually estimated empirically based on soil type. The suggested range of J_c values for a sand is 0.05 to 0.20 and for a silty clay or clayey silt is 0.4 to 0.7 (Rausche et al, 1985). Using a J_c value of 0.7 the Case Method predicts a capacity of 1903 kN compared with the measured capacity of 1070 kN (see Table 1). However, if a J_c value of 1.07 is used the Case Method predicts a capacity of 1080 kN. This clearly demonstrates the sensitivity of the Case Method to the estimated damping constant.

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

Pile	Direct Methods					
No.	1	2	3	4	5	6
1	50	98	89	37	88	60
2	48	94	110	49	95	67
3	97	135	135	133	125	104
4	100	100	99	102	88	137
5	86	99	129	74	96	153
A	86	103	141	73	80	101
B	113	114	177	91	105	130
C	126	118	192	94	109	140
Average, %	88	107	134	82	98	112
Std. deviat.	25	14	34	26	15	30

Pile	Indirect Methods						
No.	7	8	9	10	11	12	13
1	79	58	146	120	150	115	160
2	75	58	127	104	126	98	134
3	158	122	158	148	232	120	170
4	113	76	92	88	135	110	95
5	114	77	107	102	114	129	98
A	156	141	174	206	165	181	174
B	223	204	223	267	226	252	231
C	247	214	231	286	248	285	234
Average, %	146	189	157	165	175	161	162
Std. deviat.	62	63	54	82	56	74	57

The CAPWAP method requires a substantial computational effort to match the measured response of the pile head with a calculated response assuming a distribution of soil resistance and soil dynamic characteristics (quake and damping) along the pile. A preliminary CAPWAP analyses using a damping constant, J_c, of 0.7 produced a predicted capacity of 1646 kN (i.e. 50% overprediction). Unfortunately, CAPWAP analyses were not available using larger damping values.

The results of the redriving data obtained on Pile No. 5

illustrate the importance of evaluating the correct damping constant, J_c. In-situ testing methods, particularly the CPT, have the potential to improve the evaluation of the damping constant. The damping constant appears to be related to soil behaviour. The CPT data is also related to soil behaviour in that sands generally produce high cone resistance (q_c) and low friction ratio, R_f, where

$$R_f = \frac{f_s}{q_c} \times 100\% \qquad (1)$$

Clays generally produce low cone resistance and high friction ratio. Soil classification charts have been developed that relate soil behaviour type to q_c and R_f (Robertson and Campanella, 1983). Using the soil classification chart suggested by Robertson and Campanella (1983) and the damping constants determined from field measurements on 69 test piles (Rausche et al., 1985) a simple empirical correlation between J_c and the ratio q_c/R_f can be made, as shown on Figure 3. Included in Figure 3 is a recommended correlation between CPT data and J_c that will generally select a high value of J_c and hence tend to produce a conservatively low prediction of static capacity using the Case Method.

It is interesting to note that for Pile No. 5 the ratio of q_c/R_f through the organic silty clay (2m to 15m) and near the toe of the pile is in the range of 1 to 11 which yields a value of J_c between 0.8 and 1.8 using the proposed correlation in Figure 3.

To perform a wave equation analyses or CAPWAP a distribution of static shaft resistance is required. The CPT data provides an excellent means to evaluate the distribution of soil resistance along the pile.

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 been proposed for the design of laterally loaded piles using pressuremeter data (Baguelin et al., 1978; Baguelin, 1982; Briaud et al., 1983; and Robertson et al., 1985). Most of these methods make use of prebored pressuremeter results, using a Menard type pressuremeter, and do not attempt to directly model the disturbance caused by a driven pile since the pressuremeters are placed in a prebored hole. Robertson et al (1983) suggested that it is possible to install the pressuremeter in a manner which models the disturbance caused during pile

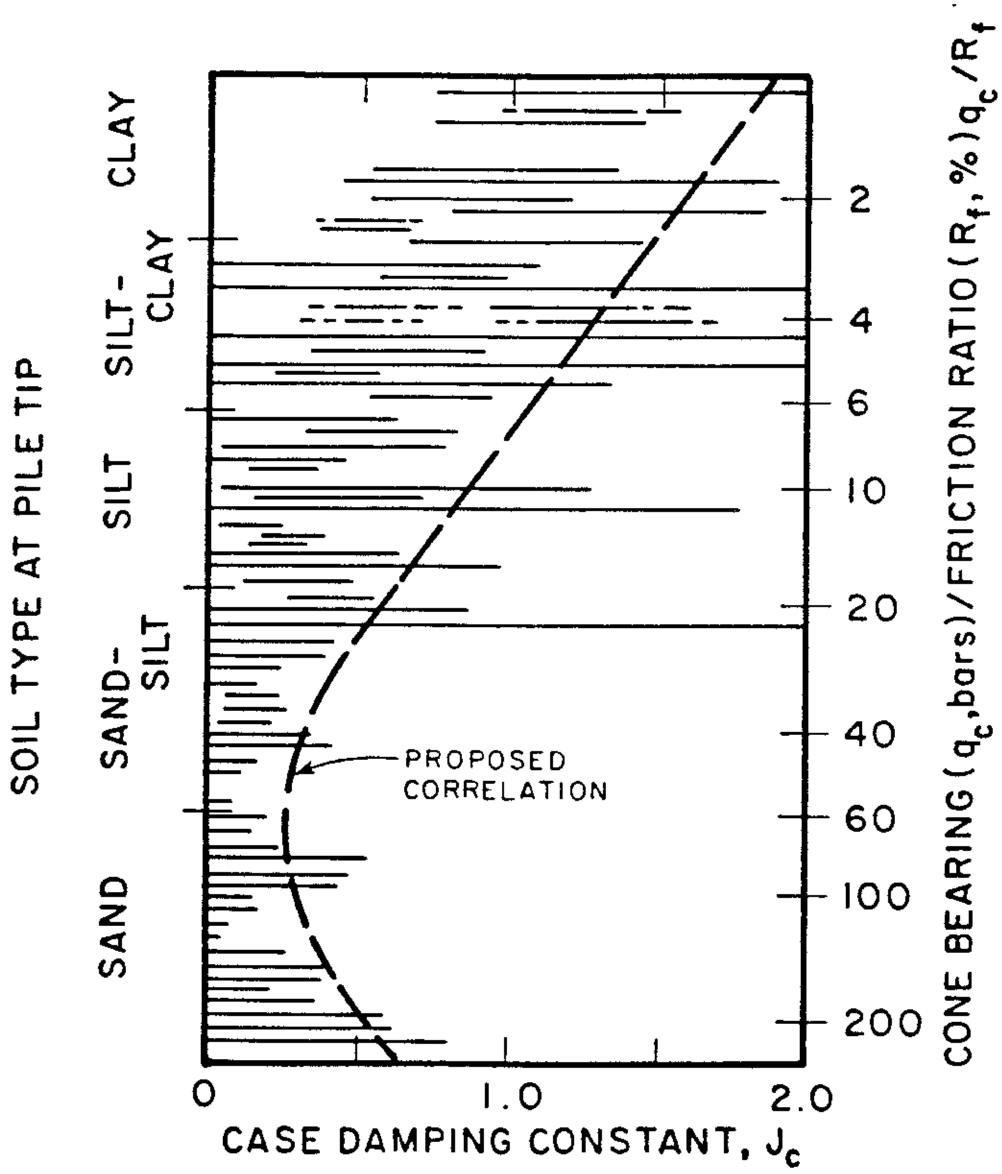


Figure 3. Proposed Correlation between CPT data and Case Method Damping Constant, J_c

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 depending on the exact method of pile installation.

Recently an indirect method has been suggested that uses data obtained from a flat dilatometer test (DMT) to obtain P-y curves (Robertson et al., 1989).

The response of three test piles to static monotonic lateral loads were also evaluated using full-displacement pressuremeter data with a direct method (Robertson et al 1983) and flat dilatometer data with an indirect method (Robertson et al. 1989). A summary of the calculated and measured load deflection curves at the pile head is shown in Figures 4, 5 and 6 for the three piles of different geometries. Also, calculated and measured profiles of pile deflections versus depth are shown in Figures 4, 5 and 6 for one value of lateral load.

A review of Figures 4, 5 and 6 shows that, for the displacement piles investigated, both methods provided a good prediction of pile response, with the DMT method providing a slightly better prediction than the pressuremeter method. Since the response of laterally loaded piles is generally controlled by the stiffness of the soil close to the ground surface, the DMT offers a promising method to obtain the required soil parameters in an economic manner. However, the method suggested by Robertson et al (1989) requires further field validation and is only possible in soils that can be penetrated by the DMT.

CONCLUSIONS

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 organic silt, sand and clay.

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

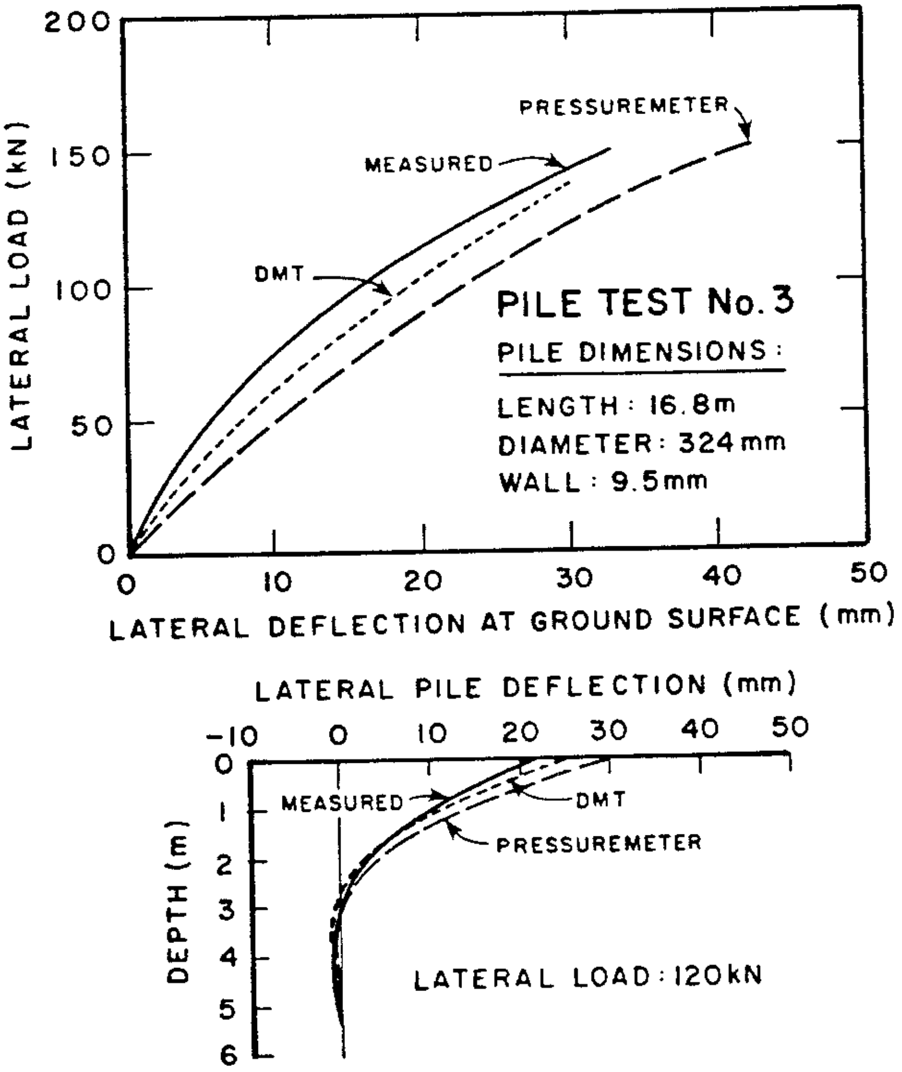


Figure 4. Summary of measured and predicted pile deflections for Pile No. 3

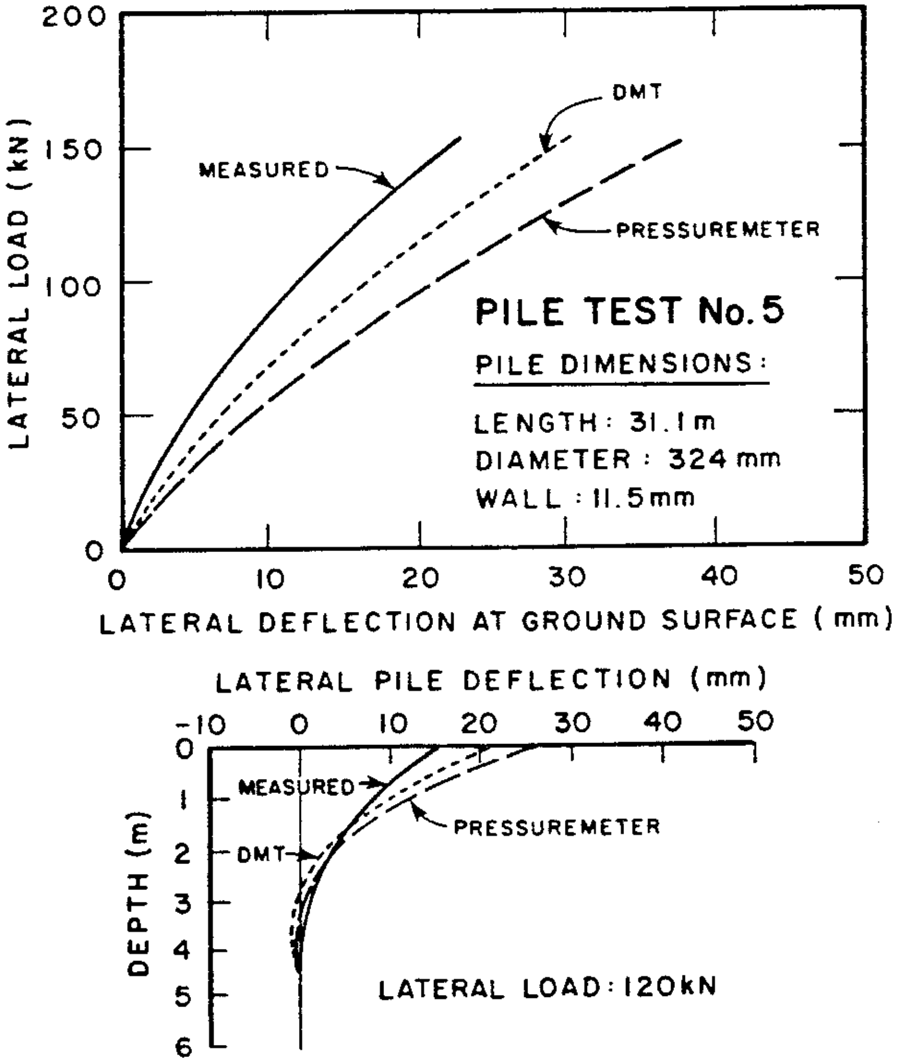


Figure 5. Summary of measured and predicted pile deflections for Pile No. 5

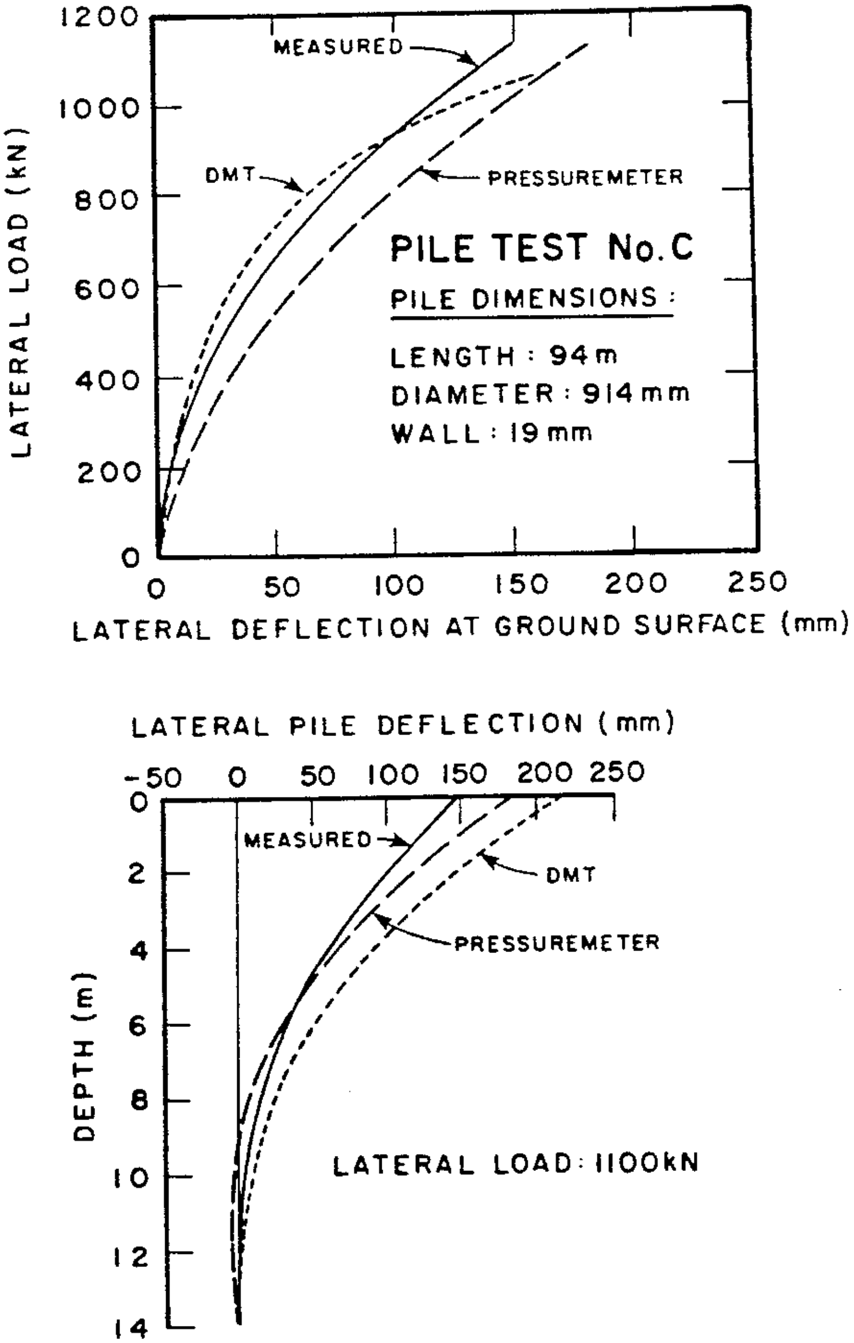


Figure 6. Summary of measured and predicted pile deflections for Pile No. C

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.

The limited experience in this study with dynamic measurements made during pile driving indicate that good prediction of static axial capacity can be obtained provided the correct value of damping constant is selected. An empirical correlation to evaluate damping constant from CPT data has been suggested.

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 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 than the pressuremeter method.

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 pile response.

ACKNOWLEDGMENTS

The assistance of the Natural Sciences and Engineering Research Council of Canada; Klohn Leonoff, Richmond; British Columbia Ministry of Transportation and Highways, in particular Mr. Don Fraser; Franki Canada, Richmond; members of the UBC In-situ Testing Group, and the technical staff of the Civil Engineering Department, University of British Columbia, is very much appreciated.

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