# Evaluation of shaft friction in sensitive clays from piezocone tests

## Evaluation du frottement latéral dans les argiles sensibles à l'aide du piézocône

S. Leroueil & M. Roy – *Department of Civil Engineering, Université Laval, Qué., Canada*
G. Martel – *Techmat, Jonquière, Qué., Canada*

ABSTRACT: Piles in clays have been tested to failure on six sites from the Province of Québec, Canada. The paper examines the mobilized skin friction in relation with the vane undrained shear strength and with parameters deduced from piezocone tests. The applicability to sensitive clays of existing methods to predict shaft friction is discussed.

RESUME: Des pieux dans l'argile ont été testés jusqu'à la rupture sur six sites de la province de Québec, Canada. Le frottement mobilisé a été examiné en relation avec la résistance au cisaillement non drainé mesurée au scissomètre et les paramètres de pénétration obtenus par essais au piézocône. L'applicabilité aux argiles sensibles des méthodes existantes permettant la prédiction du frottement latéral des pieux est discutée.

## 1 INTRODUCTION

The evaluation of skin friction along piles in clays is a complex problem which is still the focus of numerous researches. It has been shown that it is influenced by many factors such as the type of soil, in particular its overconsolidation ratio, the type of pile and the installation procedure, the distance to pile tip, the time to test loading and the loading procedure, in a manner which is not clear yet. However, practitioners need answers for their designs now, even if these answers are approximate.

Several semi-empirical methods have been developed for the design of piles, among which those using cone penetration test results. However, their use in sensitive Canadian clays has been limited, and it is the purpose of this paper to examine their capabilities in this geological context.

For that purpose, piezocone and vane shear test profiles have been established on six different sites from the Province of Québec, Canada. On three of these sites, piles have been tested to failure in the past, and the results have already been reported in literature; on five of the sites, short piles have been jacked and then tested to failure during the present study.

## 2 CPT METHODS TO PREDICT FRICTION ALONG PILES

Three approaches using cone penetration test (CPT) results to predict the unit skin friction mobilized at failure along piles in clay ($f_p$) are considered, i.e. those proposed by Schmertmann (1978), De Ruiter and Beringen (1979), and Bustamante and Gianeselli (1981, 1983).

Schmertmann (1978) suggested three methods for evaluating friction along piles. Two are directly derived from methods previously proposed by Tomlinson (1957) and by Vijayvergiya and Focht (1972) and use an undrained shear strength deduced from cone penetrometer tip resistance. The third method directly refers to the CPT sleeve friction $f_s$ measured during penetration, at least when the representative depth is larger than 8 pile diameters:

$$f_p = \alpha' f_s \qquad (1)$$

where $\alpha'$ would progressively decrease from 1.2 to about 0.3 when $f_s$ increases from 0 to 150 kPa.

According to De Ruiter and Beringen (1979), the unit skin friction can be defined as follows:

$$f_p = \alpha \, S_u \qquad (2)$$

where

- $\alpha$ is equal to 1.0 in normally consolidated clays and to 0.5 in overconsolidated clays.
- $S_u$ is the undrained shear strength of the clay, which can be estimated from the cone penetrometer tip resistance $q_c$ or the corrected tip resistance $q_T$ (Campanella et al., 1982):

$$S_u = (q_c - \sigma_{vo}) / N_k \qquad (3)$$

or

$$S_u = (q_T - \sigma_{vo}) / N_{kT} = q_{net} / N_{kT} \qquad (3')$$

where $\sigma_{vo}$ is the in situ vertical stress, and $N_k$ and $N_{kT}$ are cone factors. For Champlain sea clays, $N_{kT}$ varies from 11 to 18, but is usually between 11 and 15.

Bustamante and Gianeselli (1981, 1983a) proposed to evaluate $f_p$ as a fraction of the tip resistance:

$$f_p = q_c / \alpha'' \qquad (4)$$

where $\alpha''$ is a function of the type of soil, the type of pile and the pile installation procedure. There is also an upper limit to $f_p$.

Bustamante and Gianeselli (1983b) directly gave $f_p$ as a function of $q_c$ for different types of soil, types of pile and pile installation procedures.

It is worthnoting that these methods were developed fifteen years ago or more, when piezocone test results were not available. With the piezocone allowing pore pressure measurement just behind the tip, it becomes possible, and more logical, to use the corrected tip resistance $q_T$. This latter value is larger than $q_c$, in a manner which varies with the type of piezocone used, but which is usually significant in clays.

Almeida et al. (1996) proposed another method in which the unit skin friction $f_p$ would be directly related to the net tip resistance $q_{net} = q_T - \sigma_{vo}$.

$$f_p = q_{net} / k_1 \qquad (5)$$

In comparison with equations 2 and 3', it can be seen that $k_1$ is equal to $N_{kT} / \alpha$.

Almeida et al. (1996) have considered sites from Norway, United Kingdom and United States of America where instrumented piles jacked or driven in clay had been loaded up to failure. The clays were ranging from soft slightly overconsolidated to stiff heavily overconsolidated, and the $k_1$ values they obtained were varying between 15 and 46, with a tendency to increase with the ratio $q_{net} / \sigma'_{vo}$ or the overconsolidation ratio.

It comes out from all these approaches using CPT that $f_p$ has been related to the penetrometer sleeve friction $f_s$, the undrained shear strength $S_u$, possibly derived from the tip resistance, the tip resistance $q_T$ (or $q_c$) and the net tip resistance $q_{net}$. In the present paper, the friction mobilized along piles is directly correlated with these different parameters. Then, the results are compared with those inherent in the previously described methods.

## 3 SITES INVESTIGATED AND TESTED PILES

Six sites from the Champlain Sea basin, Canada, on which piles have been tested were considered in this study. These sites present the same geological history and the clay deposits are well documented with basic physical properties, Nilcon vane shear strength and piezocone profiles. The piezocone tests were performed at a rate of penetration of 30 cm/min. However, comparison with other tests realized at a rate of penetration of 2 cm/s shows that there is no significant difference in the considered clays. The main stratigraphic features of soil deposits and the main characteristics of the clay layers are summarized in Table 1. The plasticity index varies from 20 to 50; the liquidity index is generally larger than 1.0, which is typical of Champlain sea clays; the overconsolidation ratio ranges from 1.1 at Maskinongé to 5.2 at Mascouche; $N_{KT}$ values are between 11 and 14.5.

The main characteristics of the piles considered in this study are indicated in Table 2. In all cases, the pore pressures around the piles were fully dissipated before pile testing. None of the piles was instrumented for measuring skin friction locally. The unit shaft friction discussed here is thus an average value directly deduced from the maximum force measured in tension tests, or deduced from the difference between the maximum total load applied at failure in compression tests and an evaluated or measured end bearing capacity. As comparative tests performed in tension and in compression on the Louiseville site gave very similar results (see piles LOUI1 tested in compression and LOUI2 tested in tension in Table 2), the results obtained in both ways have not been differentiated.

On all sites except St-Alban, closed-ended steel piles (NW casings) with a diameter of 89 mm were jacked into the soil. These "casing" piles were short, with an embedded length in clay varying from 3.2 to 5.9 m. Also, in order to avoid the influence of the upper sand or weathered clay layer on the total shaft friction, a hole with a diameter larger than that of the pile was augered through these materials before installation of the "casing" piles. Except for one case at Louiseville (LOUI1), all the "casing" piles were tested in tension, with loads applied in increments equal to about 10 % of the expected load at failure and maintained during 5 min.

The pile testing program is briefly described hereunder for the different sites:

- Maskinongé: Five isolated piles, comprising two creosoted timber piles, two precast concrete piles and one closed-ended steel pipe pile were driven and then tested in compression at a constant rate of penetration of 0.35 mm/min. The test results are reported by Blanchet et al. (1980). These authors determined the average unit skin friction in clay, $f_{s\ pile}$, by substracting the friction in the upper coarse stratum from the total shaft friction. Only the piles having a constant section are considered here. One additional "casing" pile was jacked and tested in tension in the present study.
- Batiscan: Six isolated piles, comprising four timber piles, one HP steel pile and one precast concrete pile were driven and then tested in compression 4 months later at a constant rate of penetration of about 0.4 mm/min. The test results are presented by Roy and Tanguay (1989). Only the piles having a constant section are considered here. One additional "casing" pile was jacked and tested in tension in the present study.
- St-Alban: One closed-ended steel pile was jacked and then tested in compression two years later (Konrad and Roy, 1987).
- Berthierville and Mascouche: One "casing" pile was jacked and tested in tension on these two sites.
- Louiseville: Three "casing" piles were jacked in the present study. The first one (LOUI1) was tested in compression whereas the two others (LOUI2 and LOUI3) were tested in tension.

## 4 TEST RESULTS AND DISCUSSION

Initial remark: On the Batiscan site, three piles have been installed. There is a "casing" pile embedded between 6.4 and 12.3 m, thus entirely in clay. The measured average unit skin friction is of 30.2 kPa and correlates well with the values obtained on the other sites. For the two other piles embedded from 1.5 to 13.5 m, Roy and Tanguay (1989) estimated the skin friction in clay by substracting from the total peak load the estimated point bearing capacity and friction in the upper fine sand layer. These authors reported a very small skin friction in clay of 10.2 kPa, which has not found clear explanations. So, these results have been plotted on the figures but have not been considered in the correlations.

The CPT or piezocone friction measured just behind the tip or several diameters behind the tip is very low in sensitive clays. At a distance between 5 and 8.75 diameters behind the tip, the measured values have been found between 3.7 and 9.2 kPa in all clay deposits except in the stiff Mascouche clay where an average value of 16 kPa was measured between 4 and 8 m. For such values and according to Schmertmann (1978), $\alpha'$ values (Eq. 1) would be between 1.0 and 1.2. In fact, the friction mobilized along piles is 2 to 7 times larger than the CPT or piezocone unit friction. The approach based on this friction is thus not valid for sensitive clays.

Figure 1 shows the average skin friction along piles $f_{s\ pile}$ as a function of the vane undrained shear strength. With the exception of the 2 pile test results obtained at Batiscan, the correlation is quite good and can be expressed as:

$$f_{s\ pile} = 0.78\ \tau_{fuv} \tag{6}$$

It is worthnoting, however, that the 37.5 m long precast concrete pile gives an average skin friction equal to 51% of the vane undrained shear strength, which could indicate a depth effect.

Table 1: Geotechnical characteristics of the investigated sites

| Sites | Stratigraphy | $I_P$ | $I_L$ | OCR | $q_T$ (kPa) | $N_{KT}$ |
|---|---|---|---|---|---|---|
| **Maskinongé:** | 0 - 4 m, clay and silt<br>4 - 6 m, coarse sand<br>6 - 15 m, strat. silty clay<br>> 15 m, silty clay | 30<br>50 | 1.15<br>0.8 | 1.2<br>1.1 | 420 - 710<br>710 - 1500 (35 m) | 11.5<br>11.5 |
| **Batiscan:** | 0 - 5 m, fine sand<br>> 5 m, clay | 26 | 2.6 → 1.5 | 1.35 | 480 - 870 (15 m) | 14.5 |
| **St-Alban:** | 0 - 1.5 m, clay crust<br>1.5 - 9.5 m, silty clay | 23 | 2.3 | 2.2 | 120 - 550 | 11 |
| **Berthierville:** | 0 - 2.3 m, sand<br>2.3 - 5.5 m, silty clay<br>5.5 - 9.2 m, sand | 20 | 1.8 | 1.2 | 200 - 300 | 11 |
| **Louiseville:** | 0 - 1.8 m, clay crust<br>> 1.8 m, clay | 43 | 1.5 → 1.0 | 4.7 → 2.5 | 200 - 1200 (20 m) | 13.5 |
| **Mascouche:** | 0 - 2.2 m, clay crust<br>2.2 - 9 m, silty clay | 37 | 1.1 | 5.2 | 930 (4 m) - 1500 (8 m) | 13.5 |

Table 2: Main characteristics of the considered piles

| Sites | Piles | Diameter (mm) | Depth (m) | Average skin friction (kPa) |
|---|---|---|---|---|
| **Maskinongé** | MASK1, « casing » pile | 89 | 6.4 - 12.3 | 18.1 |
| | MASK3, precast concrete pile | 219* | 0 - 23.8 | 31.6 |
| | MASK4, steel pipe pile | 219 | 0 - 23.8 | 27.9 |
| | MASK5, precast concrete pile | 219* | 0 - 37.5 | 27.2 |
| **Batiscan** | BATI11, « casing » pile | 89 | 6.4 - 12.3 | 30.2 |
| | BATI1, HP steel pile | 203† | 1.5 - 13.5 | 10.2 |
| | BATI9, precast concrete pile | 300* | 1.5 - 13.5 | 10.2 |
| **St-Alban** | SALB1, steel pipe pile | 220 | 1.3 - 7.6 | 18.0 |
| **Berthierville** | BERT1, « casing » pile | 89 | 2.3 - 5.5 | 13.9 |
| **Louiseville** | LOUI1, « casing » pile | 89 | 2.8 - 6.45 | 25.9 |
| | LOUI2, « casing » pile | 89 | 2.8 - 6.45 | 28.4 |
| | LOUI3, « casing » pile | 89 | 6.5 - 10 | 32.1 |
| **Mascouche** | MASC1, « casing » pile | 89 | 4.0 - 8 | 76.8 |

*Distance between parallel faces of hexagonal pile

† Distance between faces of HP pile

The $\alpha$ value of 0.78 deduced from Fig. 1 is between the values of 1.0 and 0.5 proposed by De Ruiter and Beringen (1979) for normally consolidated and overconsolidated clays respectively. However, present data do not show any effect of the over-consolidation ratio on $\alpha$. In particular, the pile installed in the Mascouche clay having an overconsolidation ratio of 5.2 gives an $\alpha$ value of 0.90.

Figure 2 shows the average skin friction along piles $f_{s\ pile}$ as a function of $q_{net}$. The correlation presents a quality very similar to that shown in Fig. 1 and can be expressed as:

$$f_{s\ pile} = q_{net} / 17 \qquad (7)$$

thus with an average $k_1$ value equal to 17 (Eq. 5). Combined with the $\alpha$ value of 0.78 (Eq. 6), this $k_1$ value would correspond to a $N_{kT}$ value of 13.3, a typical value for Champlain Sea clays.

The $k_1$ values obtained in this study vary from 10 to 27, and are thus in the lower range of the values obtained by Almeida et al. (1996). A detailed examination of the data indicates an increase of $k_1$ with plasticity index (Fig. 3). However, the number of test results is too limited to draw a definite conclusion.

$f_{s\ pile}$ is plotted as a function of $q_T$ in Fig. 4. The correlation is not as good as those established with $\tau_{fuv}$ (Fig. 1) and $q_{net}$ (Fig. 2). This indicates that the Bustamante and Gianeselli (1981, 1983) approach could possibly be improved if $q_{net}$ would be used in place of $q_c$ or $q_T$. The $\alpha$" values (based on $q_T$) range from 13 to 39,

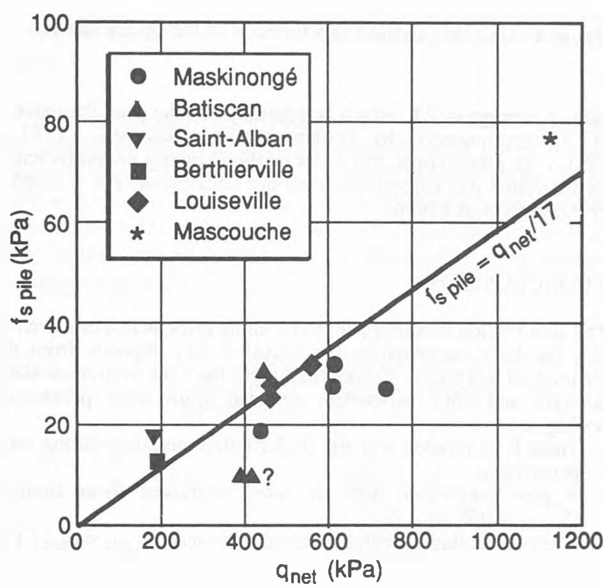

Figure 2 : Unit skin friction as a function of the net tip resistance

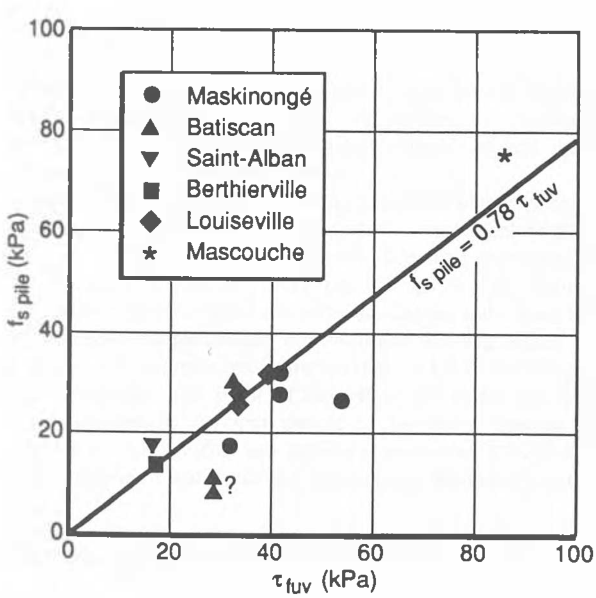

Figure 1 : Unit skin friction as a function of the vane shear strength

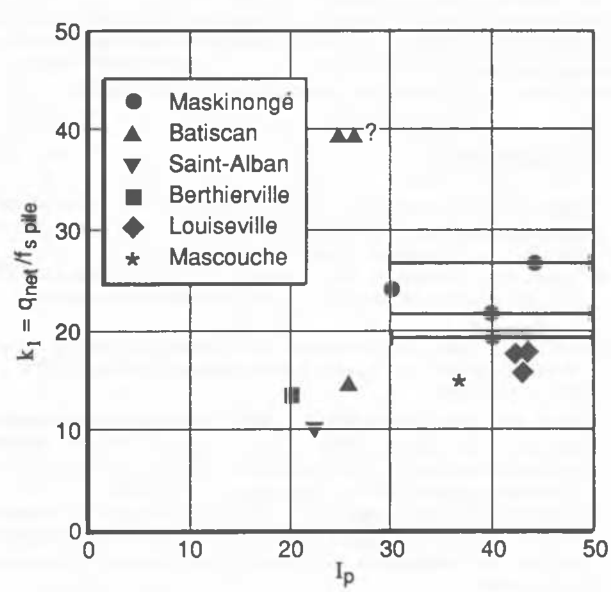

Figure 3 : $k_1$ ($q_{net}/f_{s\ pile}$) as a function of the plasticity index

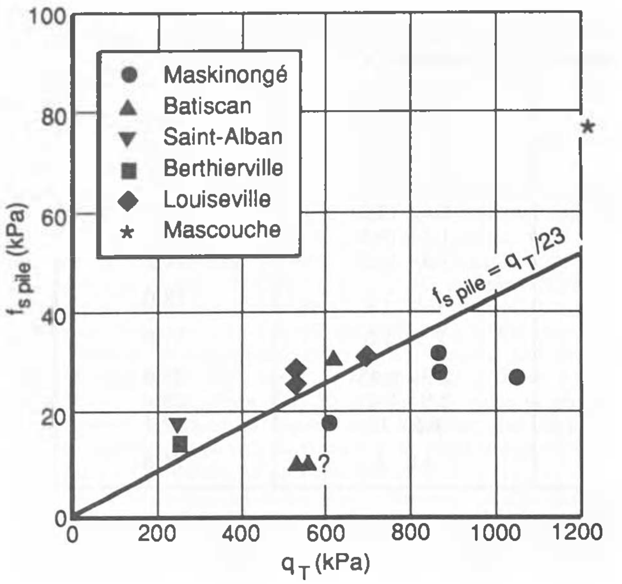


**Figure 4** : Unit skin friction as a function of the tip resistance

with an average of 23, which is generally smaller than the value of 30 recommended by Bustamante and Gianeselli (1981, 1983a). In other words, this latter method slightly underpredicts the measured pile capacities. A similar conclusion was reached by Almeida et al. (1996).

## 5 CONCLUSIONS

The skin friction mobilized at failure along piles jacked or driven in clay has been measured in six sensitive clay deposits from the Champlain Sea basin. Correlations with the vane undrained shear strength and with parameters deduced from cone penetration testing show:

- There is no relation with the shaft friction measured during cone penetration.
- A good correlation with the vane undrained shear strength ($f_{s\ pile} = 0.78\ \tau_{fuv}$ ).
- A good correlation with the net tip resistance ($f_{s\ pile} = q_{net}$ / 17).

## 6 ACKNOWLEDGMENTS

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