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Side Friction of Piles in Clay

Le Frottement Latéral des Pieux dans Sols Argileux

K. FLAATE Norwegian Road Research Laboratory,
P SELNES Norwegian Geotechnical Institute, Norway

SYNOPSIS Extensive deposits of soft marine clays in Norway has led to widespread use of friction piles. These are normally slender piles of timber and, to a lesser extent, precast concrete. The tip area is small compared to the pile surface, and this means that side friction determines the magnitude of the bearing capacity. The basis for the investigation is a large amount of data from which one have selected piles with the necessary data about load tests and routine soil investigations. The study concludes that the best estimate of side friction is obtained by an effective stress analysis. A formula for side friction which also takes the overconsolidation ratio into account seems to give the best fit to the test data.

INTRODUCTION

Methods for estimating side friction have been of concern to many investigators over the years. Fellenius (1938) presented the result of load tests on long steel pipes and compared the side friction with the undrained strength. He also pointed out that the frictional resistance was not mobilized at great depths. Skaven-Haug (1940) developed a formula where the remolded strength and the fineness number were taken into account in addition to the undrained shear strength.

Several authors have compared the measured side friction with the undrained shear strength, and found a fair correlation for soft clays. (Bjerrum 1953, Fellenius 1955, Bergfelt 1957). Tomlinson (1957) and Woodward et al. (1961) showed that the side friction as a proportion of undrained strength, decreased with increasing strength.

Nilsson (1965) suggested to take the varying degree of mobilization with depth into account. Flaate (1968) indicated in addition a dependence of the plasticity of the clay. The use of effective stresses was advocated by Zeevaert (1959), Eide et al. (1961) and presented by Chandler (1966) and Burland (1973).

This study is limited to driven piles in soft to medium clays. An attempt is made to correlate the data from routine soil investigations with the side friction as actually observed in load test.

DETERMINING BEARING CAPACITY

The bearing capacity normally referred to is capacity as determined by load test on a single pile. This capacity is in clay

strongly time dependent as shown in Fig. 1. The ultimate capacity is normally reached within 3 months but considerably longer time may be needed if driven in a large group.

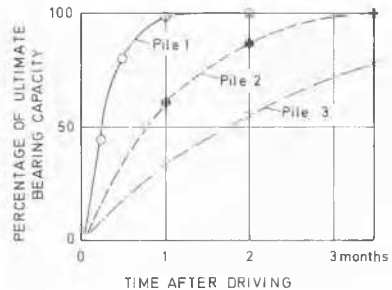


Fig. 1 Variation of bearing capacity of piles in clay with time after driving.

This shows the importance of determining the capacity in a consistent way. The time increase will not be discussed herein. The capacity has been taken as the ultimate or near ultimate capacity after a study of the time increase curve for each pile.

The bearing capacity (Q_u) consists of two parts, the total side friction (Q_s) and the total point resistance (Q_p) Fig. 2. The side friction (f_s) can be computed as the bearing capacity minus the point resistance divided by the surface area of the pile. This approach gives an average value for the side friction acting along the pile.

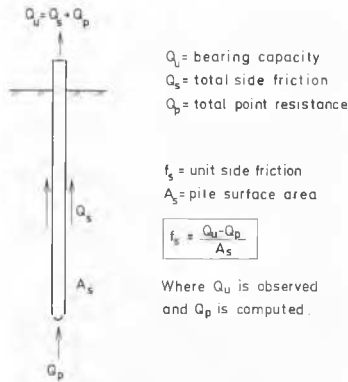


Fig. 2 Computing side friction from load tests.

SIDE FRICTION IN CLAY

Previous work

Expressions for side friction based on undrained shear strength (s_u) have been widely used, generally in the form of:

$$f_s = \alpha \cdot s_u \quad (1)$$

where the range in values for α may be from 0.3 to more than 1.0. Values for α may be based on undrained shear strength, plasticity index, pile material, method of installation and α .

Around 1960 several authors (Zeevaert 1959, Eide et al. 1961, Chandler 1966) proposed to use effective stresses to determine the side friction, expressed in the following form:

$$f_s = K \cdot \text{tg} \phi \cdot p'_v \quad (2)$$

where:

K is an earth pressure coefficient
 ϕ is the effective friction angle
 p'_v is the effective vertical stress

Burland (1973) proposed to use

$$f_s = \beta p'_v \quad (3)$$

The range in β -value found from pile test data were 0,25 to 0,4 with an average of $\beta = 0,32$.

Vijavergiya and Focht (1973) included the undrained shear strength in their expression:

$$f_s = \lambda (p'_v + 2 s_u) \quad (4)$$

where λ is a function of length.

Janbu (1976) based his theory on effective stress parameters including cohesion and also

took the effect of the mobilized friction into account:

$$f_s = S_v (p'_v + a) \quad (5)$$

where:

$$a = c/\text{tg} \phi \text{ (attraction)}$$

and S_v is a function of friction angle and length.

The effects of pile driving

Pile driving creates a remoulded zone varying from "complete" disturbance near the pile to undisturbed soil some distance away. Some investigations (Cummings et al. 1950, Skrede 1967) indicate that the disturbed zone extends to about one diameter from the pile surface. This will of course vary with soil and piling conditions. The strength and the sensitivity are believed to be important factors in this matter.

Increased horizontal stresses are set up against the pile shaft. (Seed and Reese, 1955). Excess pore pressures come close to the total horizontal stresses (Koizumi and Ito 1967) with observed average values in the order of $(5-7) \cdot s_u$. The subsequent dissipation of pore water decreases the water content and increases the undrained shear strength near the pile. The long term creep may restore the original stress conditions in the ground. Changes in undrained strength and water content are illustrated in Fig. 3.

The soil in the zone near the pile will be overconsolidated, even if the original soil was normally consolidated and original stress conditions are restored. Flaate (1972) have shown that the side friction is not equal to the undrained shear strength at or near the pile surface. The undrained strength do not seem to determine the side friction and this fact suggests the problem to be treated by an effective stress analysis.

An effective stress formula

The side friction of the pile may be governed by the drained strength of the clay near the pile surface. Bjerrum (1973) proposes the following expression for the side friction based on Hvorslev's parameters, ϕ_e and x .

$$f_s = \nu_t (p'_h \cdot \text{tg} \phi_e \cdot D_M + x \cdot p'_e) \quad (6)$$

where ν_t is a coefficient for the time rate effects, p'_h is the effective horizontal stress, D_M is a mobilization factor for the frictional resistance and p'_e equivalent consolidation pressure.

Assuming that original ground stresses are restored in the soil, that the equivalent consolidation pressure is near the maximum pore pressures set up due to the driving and that the coefficient of mobilized friction depend on the pile length L , eq. 6 may be written:

$$f_s = \mu_L \cdot \nu_t (K' p'_v \text{tg}\phi_e + x(K' p'_v + 5' s_u)) \quad (7)$$

where μ_L is a function of pile length and K is earth pressure coefficient.

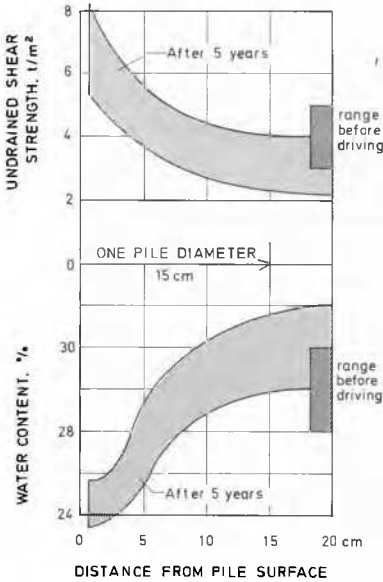


Fig. 3 Change in undrained shear strength and water content near the surface of a timber pile (Skrede, 1967)

The parameters in this expression are, however, seldom available from routine soil testing, and the equation must be simplified in order to have any practical applications.

The soil parameters $K \text{tg}\phi$, K_e and x may be related to plasticity index I_p as shown in Fig. 4. The earth pressure coefficient for OC-clays, K , may be expressed by the earth pressure coefficient for NC clays, K_e , and the overconsolidation ratio, R_o , (Meyerhof 1976):

$$K = \sqrt{R_o} \cdot K_o \quad (8)$$

The reduction in strength with decreased rate of loading is mainly associated with the cohesion part of the strength (Bjerrum 1973). Substituting the above relationships with x reduced 30% due to time rate effects into eq (7) gives approximately the following expression:

$$f_s = \mu_L ((0,3-0,001 I_p) \sqrt{R_o} p'_v + 0,008 I_p s_u) \quad (9)$$

This expression contains parameters that are generally obtained in routine soil testing, and the side friction of piles in clay may be computed from this equation.

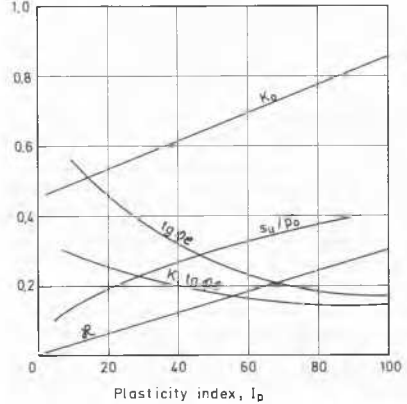


Fig. 4 Relations between plasticity index and various soil properties (data from Bjerrum, 1954 and 1973)

A further simplification is, however, obtained by substituting p'_v for s_u by the use of the (s_u/p_o) relation shown in figure 4 to give:

$$f_s = \mu_L (0,3 - 0,5) \cdot \sqrt{R_o} p'_v \quad (10)$$

where the values increase with increased plasticity of the clay.

A reduction in mobilized side friction with increased pile length has been proposed by several authors f.i. Nilsson (1965), Vijavergiya and Focht (1973), Janbu (1976) and Meyerhof (1976). The following function seems to give reasonable agreement with proposed values:

$$\mu_L = (L + 20)/(2L + 20) \quad (11)$$

CORRELATION WITH OBSERVED DATA

The basic data for this investigation comes from full scale load tests on piles and the corresponding soil investigations. In order to have a uniform set of data certain requirements to the amount and quality of the information must be set on beforehand. Starting out with about 200 cases, mainly from Flaate (1968), only 44 have been used.

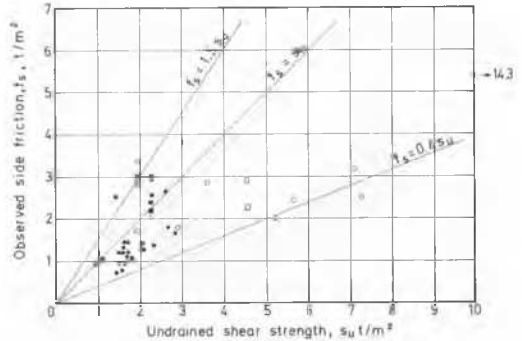
The data for each pile, soil properties and the results from load tests are given in Table 1. The measured average side friction is obtained by dividing the total bearing capacity minus computed tip resistance with the surface of the pile. This observed side friction is in the following compared with various formulas for side friction.

The soil data available allows the following expressions to be compared with observed values:

- A: $f_s = \alpha \cdot s_u$
- B: $f_s = \beta \cdot p'_v = 0.32 p'_v$ (Burland, 1973)
- C: $f_s = \lambda (p_v + 2 \cdot s_u)$ (Vijayvergiya and Focht)
- D: $f_s = \mu_L \cdot 0,4 \cdot \sqrt{p'_v}$ (present paper, eq. 10 and 11)
- E: $f_s = \mu_L ((0,3 - 0.001 I_p) \cdot \sqrt{p'_v} + 0.008 I_p \cdot s_u)$ (present paper, eq. 9 and 11)

In Fig. 5 are the observed side friction values plotted against undrained shear strength (formula A). The range in α -values is quite large with $\alpha = 0,5 - 1,5$ for NC-clay and $\alpha = 0,4 - 0,8$ for OC-clay. The data do not seem to indicate any significant effect of pile material.

In Fig. 6 are the values plotted against effective vertical stress. The correlation is considerably better than for the undrained shear strength and the values for β (formula B) falls generally between 0,2 - 0,4 for normally consolidated clays. The data indicates higher β -values for OC-clays, and no significant effect of pile material.



- Legend:
 - Timber, NC-clay
 - spliced NC-clay
 - OC-clay
 - Concrete, NC-clay
 - OC-clay
 - + Steel, NC-clay
 - * OC-clay

Fig. 5 Observed side friction versus undrained shear strength.

No.	Length (m)	Surface area (m²)	Tip diameter (m)	Pile type	Unit weight (t/m)	Water content (%)	Plasticity index	Mean eff. vert. press. (t/m²)	Mean undr. shear strength (t/m²)	Stiffness	Observed bearing cap. (tons)	Computed tip resistance (tons)	Side friction (t/m²)	Def. number (Flaabe 1968)
1	14.1	14.8	15.0	Timber NC	2.0	33.	12.	9.6	2.6	7.	40.0	6.3	1.2	1.09
2	13.0	10.3	15.0	"	1.8	34.	19.	10.2	1.5	7.	27.0	3.2	1.17	
3	11.7	11.1	20.0	"	2.0	32.	14.	5.4	2.3	5.	16.0	1.0	1.4	2.10
4	14.6	11.7	16.0	"	1.9	43.	9.	6.7	2.9	3.	20.0	0.9	1.6	2.22
5	11.6	9.2	17.5	"	1.9	43.	9.	5.7	2.7	3.	17.0	0.8	1.8	2.23
6	17.5	8.8	14.3	"	1.6	62.	43.	8.7	2.3	6.	23.0	3	2.6	3.10
7	14.4	8.5	15.6	"	1.6	62.	43.	8.5	2.3	6.	26.0	3	2.6	3.14
8	15.0	9.0	15.3	"	1.6	62.	44.	8.6	2.3	6.	27.0	3	3.0	3.15
9	11.9	6.0	15.9	"	1.3	145.	98.	4.4	1.6	6.	8.0	4.4	1.3	5.02
10	13.8	7.7	15.0	"	1.3	145.	98.	4.6	1.6	6.	11.5	3	1.5	5.03
11	15.9	9.9	15.0	"	1.3	145.	98.	4.9	1.7	6.	12.5	3	1.2	5.04
12	17.3	10.8	14.0	"	1.3	145.	98.	5.1	1.7	6.	12.5	3	1.1	5.05
13	8.1	4.5	13.5	"	1.7	73.	46.	3.7	1.3	6.	5.0 ¹⁾	4	1.1	5.06
14	9.6	7.3	19.2	"	1.7	70.	45.	4.2	1.5	6.	9.8	5	1.3	5.07
15	11.5	7.8	15.6	"	1.7	68.	42.	4.6	1.6	6.	10.0	4	1.2	5.08
16	11.6	7.5	14.7	"	1.7	68.	42.	4.6	1.6	6.	11.0	4	1.4	5.09
17	12.7	9.2	16.7	"	1.7	68.	42.	4.8	1.7	6.	14.5	5	1.5	5.10
18	7.7	4.9	16.5	"	1.6	78.	45.	3.2	1.5	6.	5.0 ¹⁾	4	1.9	5.12
19	9.4	5.5	13.8	"	1.6	78.	45.	3.7	1.6	6.	5.5	3	1.9	5.13
20	8.0	4.1	13.5	"	1.4	100.	61.	2.7	1.9	9.	4.0	1	1.9	5.16
21	10.0	5.9	13.5	"	1.5 ²⁾	90.	54.	3.3	1.0	-	7.0	2	1.2	5.17
22	12.0	8.7	15.5	"	1.5 ²⁾	80.	47.	3.9	1.7	-	9.0	3	1.0	5.18
23	13.8	10.4	19.0	"	1.4 ¹⁾	108.	69.	2.7	2.1	8.	14.0	8	1.3	6.05
24	10.2	7.7	22.0	"	1.4 ¹⁾	120.	76.	1.9	1.5	9.	7.0	1	1.8	6.08
25	14.1	12.0	23.5	"	1.4 ¹⁾	108.	69.	2.8	2.1	8.	18.0	1.3	1.4	6.08
26	10.1	7.9	19.0	"	1.4	120.	76.	1.8	1.5	9.	6.3	0.8	1.7	6.09
27	24.2	16.1	15.0	" spliced	1.9	34.	16.	14.5	2.0	6.	45.0	6	2.8	1.18
28	24.2	16.8	15.0	"	1.9	34.	16.	14.6	1.9	6.	50.0 ³⁾	6	2.9	1.19
29	24.2	17.9	15.0	"	1.9	34.	16.	14.7	1.9	6.	55.0 ³⁾	6	3.0	1.20
30	24.2	17.7	15.0	"	1.9	34.	16.	14.6	1.9	6.	60.0 ³⁾	6	3.4	1.21
31	17.1	14.2	15.0	Timber OC	2.0	27.	12.	10.9	5.7	5.	35.0	0.8	2.4	1.06
32	12.7	11.8	23.2	"	1.7	61.	20.	3.8	1.9	16.	21.0	7	1.7	2.12
33	15.5	12.3	17.5	"	2.0	27.	12.	8.0	7.2	3.	45.0	1.9	3.5	2.15
34	11.5	8.4	17.5	"	2.0	27.	13.	6.3	7.2	3.	23.0	1.7	2.5	2.16
35	10.0	8.9	23.0	"	2.0	26.	8.	4.7	5.2	4.	20.0	2.2	2.0	2.17
36	10.0	6.9	17.0	"	1.9	31.	14.	8.2	3.6	4.	20.0	6	2.8	2.18
37	9.4	9.8	29.3	"	1.7	53.	31.	5.2	2.9	11.	19.5	2.1	1.8	2.21
38	14.3	10.6	26.0	Concrete NC	1.6	62.	34.	8.9	2.2	-	26.0	1.0	2.4	7.10
39	14.3	10.6	26.0	"	1.6	62.	34.	8.9	2.2	-	24.0	1.0	2.2	7.11
40	22.5	33.2	47.0	Concrete OC	1.8 ¹⁾	43.	27.	6.0	4.5	-	88.0	11.7	2.3	8.13
41	22.5	33.2	47.0	"	1.8 ²⁾	43.	27.	6.0	4.5	-	109.0	11.7	2.9	8.14
42	13.4	10.2	27.0	Steel NC	1.6	60.	32.	8.1	2.2	-	21.0	3	2.0	10.01
43	13.5	12.9	30.5	Steel OC	2.1 ¹⁾	18.	14.	14.1	14.3	-	71.0	7	5.4	10.04
44	5.5	5.2	30.0	"	1.5	100.	45.	4.4	3.0	-	22.0	2.2	3.8	10.16

Table 3. Pile and soil data and results from load tests

1) Computed from pile taper 1 cm/m
 2) Computed
 $Y = 2.6 + 0.026W$
 $Y = 1.0 + 0.026W$
 3) Computed
 $I_p = 0.73 (W_L - 16)$
 4) Computed
 $I_p = 0.73 (W - 16)$
 5) Extrapolated value using same rate of increase in bearing capacity with time as nearby piles

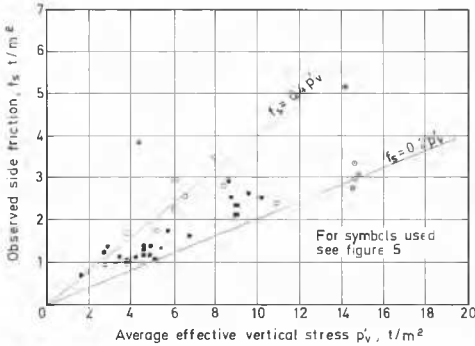


Fig. 6 Observed side friction versus effective vertical stress.

If the effective stress for OC-clays are increased by a factor $\sqrt{R_0}$ (eq.8), the values both for OC and NC-clays will generally fall within the range 0,2 - 0,4 for β as shown in Fig. 7.

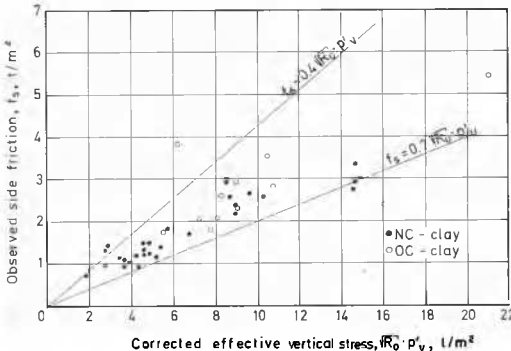


Fig. 7 Observed side friction versus adjusted effective vertical stress.

The quotient of calculated to observed side friction have been established for the various formulas (A to E). The results are illustrated in Fig. 8 in the form of frequency curves. This presentation gives a picture of the merits of the various methods for estimating side friction in clay.

CONCLUSIONS

The conclusions are based on the results of load tests on driven piles and theoretical considerations.

1. Formulas based on effective stress analysis give better estimate of average skin friction than estimates on the basis of undrained shear strength.
2. A formula which is applicable to both overconsolidated and normally consolidated

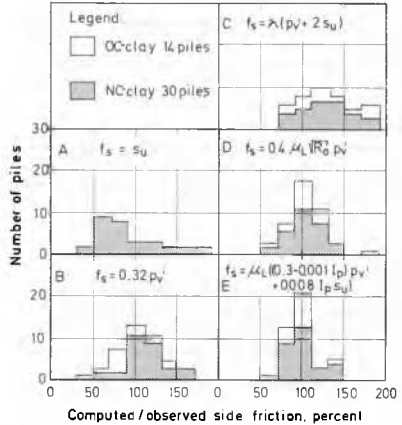


Fig. 8 Frequency curves for the quotient of calculated to observed side friction for various formulas.

ted clays is presented.

3. The magnitude of the side friction does not seem to depend on the pile material.

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