TECHNICAL NOTE

DEVELOPMENT OF THE FRICTION METER FOR EVALUATING THE SKIN FRICTION OF A PILE

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ABSTRACT

A device was developed for evaluating the skin friction of a pile, which is named "Friction Meter". The main features of this device are that it is possible to evaluate various factors affecting the skin friction of a pile and it can easily be used in routine soil investigations. Results of a series of the friction meter test conducted on mud stone, very dense sand and hard clay are reported. Further, a comparison of the skin friction evaluated from the friction meter test and load test on actual piles is presented for a hard clay. It is demonstrated that the skin friction values determined from the friction meter test showed good agreement with the values obtained from load test.

Key words : bearing capacity, engineering development, friction, piles, special shear test, test equipment (IGC : E 6)

INTRODUCTION

Evaluation of the amount of skin friction for a pile has been recognized as an important problem in geotechnical engineering and extensive research has been devoted to this subject. Based on theoretical and experimental studies related to this problem, various methods for predicting the skin friction of a pile have been proposed and practiced. It can be said, however, that the accuracy of the methods currently practiced is not adequate, particularly for dense sand and hard clay.

There is no question, that the skin friction of a pile can accurately be determined from the results of a performed load test on an

actual pile. The cost of such a test is considerable. In addition, it is sometimes difficult to determine the amount of skin friction accurately even from a load test because the test is often completed before the ultimate load is reached when the bearing capacity requirement considered in the design has been satisfied.

The development of a procedure for more accurate evaluation of skin friction of pile is considered an urgent task from both technical and economical points of view. For this reason, the authors recently developed a device for evaluating the skin friction of a pile and have carried out a number of in-situ tests at two sites where load tests on actual piles have also been carried out. It is possi-

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ble to compare the skin friction evaluated from the test results using this device with those from actual pile load tests.

This paper first describes the features of the friction meter as well as the operation and evaluation of the skin friction values. The results of the friction meter tests are presented for Pleistocene sand and clay, and Tertiary mud stone. In addition, a comparison of the skin friction obtained from the friction meter test and load test on actual piles is presented for a Pleistocene hard clay.

FEATURES OF THE FRICTION METER AND ITS PRACTICAL USE

In developing the friction meter (hereafter called F.M), the three points described below were considered.

1) The F.M should be a portable unit which can easily be used practically in routine soil investigations.

2) The actual pile driving method can be simulated to a certain extent.

3) The effect of the roughness of pile surface on skin friction can be evaluated.

Based on these three requirements, the friction meter shown schematically in Fig.1 was developed. The features and actual method of operation of the device are explained below.

1) The F.M is 100 mm in diameter and is made of stainless steel. It consists of three part, ①drive shoe 10 cm long, ②measurement sleeve 10 cm long and ③upper part 60 cm long.

2) Hole is advanced by drilling with casing $\phi=116$ mm to a proposed depth. Drilling with $\phi=76$ mm - 86 mm is continued as a pre-drilled hole to a depth of 50 cm to 100 cm below the bottom of the $\phi=116$ mm hole (see Fig.1).

3) The F.M is forced to penetrate into the ground either statically (for soft clay) or dynamically (for sand and hard clay) following the pre-drilled hole to a depth of 30 cm (see Fig.1).

4) The measurement sleeve is rotated through the torque ring placed at the top of

Fig. 1. Schematic diagram of the friction meter developed for evaluating the skin friction of a pile

the casing pipe (see Fig.1). The F.M does not require a large installation but can easily be used in routine soil investigation.

5) Both the torque required for rotation and the angle of rotation are measured.

6) The static penetration method for soft clay following the pre-drilled hole minimizes the disturbance of the clay and permits the evaluation of the shear strength restoration with time after pile driving.

7) The dynamic penetration method for sand and hard clay also following the pre-drilled hole could simulate the actual pile driving installation for these types of soils to a certain extent.

8) Since it is possible to modify the measurement sleeve with a different roughness, the effect of roughness of the pile surface on skin friction can be evaluated.

Kishida (1979) conducted a detailed study on the frictional resistance between sand and metal surface, and found that the frictional

Fig. 2. Change of frictional coefficient between sand and metal surface with change of the roughness of metal surface (after Yoshimi and Kishida, 1981)

Fig. 3. Schematic plot showing the value of R_{max} of metal surface

Fig. 4. Idealized plot showing the shear stress and angle of rotation obtained from the F.M test

resistance is greatly dependent of the roughness of metal surface. Fig. 2 indicates a test

result obtained from a ring torsion shear test conducted on Toyoura Standard sand (Yoshimi and Kishida, 1981). The value of R_{max} in the figure is defined as the maximum difference of level of the metal surface for a distance of 2.5 mm as shown in Fig. 3. It can be observed that the frictional coefficient greatly depends on the values of R_{max} irrespective of the relative density of sand.

Shear stress and angle of rotation, $\tau - \theta$ relationship is obtained from the F.M test as presented in Fig. 4. The shear stress from the F.M test is designated with the symbol, $\tau_{(F,M)}$ in this paper. Since the measured angle of rotation $\theta_{(m)}$ includes torsion of the drill rod, a correction is required in order to obtain the angle of rotation of the measurement sleeve itself. The rotation angle induced by torsion of the drill rod can be obtained using Eq. (1) and the rotation angle of the measurement sleeve is then computed by subtracting this angle calculated by Eq. (1) from the measured value.

$$\theta_r = \frac{32 \cdot M \cdot l \cdot 180^\circ}{G(d_1^4 - d_2^4)} \quad (1)$$

where θ_r = angle of rotation induced by torsion of the drill rod

M = moment required for rotation

l = length from the measurement sleeve to the torque ring

d_1 = outside diameter of the drill rod

d_2 = inside diameter of the drill rod

G = shear modulus of the drill rod

The angle of rotation of the measurement sleeve, $\theta_{(F,M)}$ is then obtained as shown in Fig. 4.

The value of $\tau_{(F,M)}$ obtained from the F.M test should be corrected for the difference in roughness of the actual pile and the measurement sleeve. In order to obtain the adjustment for the effect of roughness of pile surface on skin friction, a direct shear apparatus, where a specimen is sheared on metal surface with different roughness properties, was used. The value of this adjustment, which is designated with the symbol μ_R , is given by Eq. (2).

$$\mu_R = \tau_{(R_{max}=pile)} / \tau_{(R_{max}=F.M)} \quad (2)$$

Fig. 5. Soil conditions at the test sites

Fig. 6. $\tau_{(F.M)p}$ values obtained from the F.M test at the two sites plotted versus depth.

The shear stress acting between pile and soil, which is designated with the symbol of $\tau_{(pile)}$, is obtained using Eq. (3).

$$\tau_{(pile)} = \tau_{(F.M)} \times \mu_R \quad (3)$$

IN-SITU TEST RESULTS

A series of F.M tests were conducted for Pleistocene dense sand and hard clay, and Tertiary mud stone at two sites where the soil conditions are as indicated in Fig. 5.

The upper 5 m to 7 m of both sites consists of alluvial sand. Below the alluvial sand, a Tertiary mud stone with unconfined compressive strength, q_u of about 2000 kN/m² was found at Site A, while Pleistocene dense sand with N values more than 50 and hard clay with q_u from 200 to 600 kN/m² was found at Site B. The values of peak $\tau_{(F.M)}$, designated with the symbol $\tau_{(F.M)p}$, for each of the layers at the two sites are shown in Fig. 6.

Fig. 7. Representative $\tau_{(F,M)}$ versus θ curves for each layer at the two sites

1) The values of $\tau_{(F,M)p}$ of mud stone mostly indicated the values more than 200 kN/m² but some lower $\tau_{(F,M)v}$ values ranging from 60 to 140 kN/m² were obtained for the upper part. It was found from the observation of core sample that these lower values are corresponding to the cracked zone existing in the mud stone.

2) The values of $\tau_{(F,M)p}$ of dense sand measured by $R_{max}=430 \mu\text{m}$ exceeded 250 kN/m² which is the strength corresponding to the maximum capacity of the torque ring, but the values measured by $R_{max}=2 \mu\text{m}$ ranged from 60 to 110 kN/m² increasing with depth. This phenomenon demonstrates the importance to consider the effect of roughness of pile surface in evaluating the skin friction.

3) The values of $\tau_{(F,M)p}$ of hard clay measured by $R_{max}=430 \mu\text{m}$ mostly ranged from 150 to 200 kN/m². In spite of the considerable difference in q_u values between hard clay ($q_u=200-600 \text{ kN/m}^2$) and mud stone ($q_u=2000 \text{ kN/m}^2$), the values of $\tau_{(F,M)v}$ for both

layers were similar. This phenomenon would be important in predicting the skin friction of pile installed into such layers.

Fig. 7 indicates the representative $\tau_{(F,M)} - \theta_{(F,M)}$ curves of each layer measured by $R_{max}=2 \mu\text{m}$ and $430 \mu\text{m}$.

1) The values of $\tau_{(F,M)}$ of mud stone and hard clay measured by $R_{max}=430 \mu\text{m}$ rapidly decreased after reaching a peak. This phenomenon is consistent with the stress-strain behaviour of the cemented structure of these two materials. However, $\tau_{(F,M)} - \theta_{(F,M)}$ curve for hard clay measured by $R_{max}=2 \mu\text{m}$ did not show this phenomenon.

2) The $\tau_{(F,M)} - \theta_{(F,M)}$ curve of dense sand measured by $R_{max}=2 \mu\text{m}$ indicated the stick-slip behaviour. Kishida (1979), and Yoshimi and Kishida (1981) also reported such behaviour in a series of ring torsion shear tests on sand where R_{max} value is equal to or less than $5 \mu\text{m}$.

ULTIMATE SKIN FRICTION OF TEST PILES DETERMINED FROM LOAD TEST

Three tension (pull-out) tests were conducted on steel piles with $\phi=400 \text{ mm}$ and $R_{max}=40 \mu\text{m}$ driven into hard clay at Site A. In these tests an outer casing 500 mm in diameter was first driven to a certain depth and then soils in the casing were removed to eliminate the skin friction of the overlying deposits. After the casing was installed, the piles were driven to the proposed depth as shown in Fig. 8. Any equipment such as strain gage was not used but only the load required for complete pull-out was measured. Thus the bearing capacity obtained from the test represents the ultimate skin friction designated with the symbol, $Q_{s,f}$ of the hard clay alone. The values of $Q_{s,f}$ obtained from load test for three test piles, A_1-1 , A_1-2 and B_1-1 were as follows.

$$\begin{aligned} Q_{s,f} &= 1600 \text{ kN} \quad (A_1-1) \\ &= 2800 \quad (A_1-2) \\ &= 1950 \quad (B_1-1) \end{aligned}$$

Fig. 8. Schematic plot showing soil conditions and dimensions for each test pile

ULTIMATE SKIN FRICTION OF TEST PILES DETERMINED FROM THE FRICTION METER TEST

In order to obtain the value of $Q_{s,f}$ based on the F.M test, the values of $\tau_{(F.M)p}$ and μ_R must be determined. The average of $\tau_{(F.M)p}$ for the hard clay measured by $R_{max}=430\mu m$ was first determined and a value of 165 kN/m^2 was obtained. As shown in Fig. 8, on the other hand, soil conditions above the hard clay at the A₁-1, A₁-2 and B₁-1 pile locations are different. Since the hard clay is in a considerably overconsolidated state due to cementation, it is judged that this difference in soil conditions is insignificant. The average value of 165 kN/m^2 obtained at the B₁-1 pile location was used for the other two piles as well.

A series of direct shear test, where specimens from the hard clay were sheared on metals with different roughness, was carried out in order to determine the value of μ_R . In this test, representative sample from the hard clay is first remoulded to a liquid condition and

Fig. 9. τ_f values for hard clay plotted versus R_{max} obtained from a series of direct shear tests

Table 1. Comparison of $Q_{s,f}$ values from the F.M test and load test

Pile No.	Length	$Q_{s,f}$	
		F.M Test	Load Test
A ₁ -1	9m	1590 kN	1600 kN
A ₁ -2	18	3170	2800
B ₁ -1	12.5	2200	1950

placed in the apparatus. After consolidating at a stress of 100 kN/m^2 , the sample was subjected to shear under undrained condition. A remoulded sample was used for the following reasons.

1) Homogeneous sample can be obtained using this operation, whereas it would be difficult to obtain homogeneous sample with undisturbed sampling method, particularly for such a hard clay.

2) Frictional resistance between sand and metal surface is very much dependent of the roughness of metal surface irrespective of the relative density as shown in Fig. 2. The value of μ_R is, therefore, little dependent of the state of the soil such as normally consolidated or overconsolidated.

Direct shear test results conducted on hard clay are presented in Fig. 9 and the value of μ_R can be obtained as follows.

$$\mu_R = \tau_{(R_{max}=pile)} / \tau_{(R_{max}=F.M)} = 0.22 / 0.26 = 0.85$$

The value of $Q_{s,f}$ of a pile from the F.M test is given by Eq. (4).

$$Q_{s,f} = \Psi \cdot l \cdot \tau_{(F.M)p} \cdot \mu_R \quad (4)$$

where Ψ = perimeter of pile and l = length of pile

Using $\tau_{(F.M)p} = 165 \text{ kN/m}^2$, $\mu_R = 0.85$, $\Psi = 1.26$ m and length of each test pile into the hard clay, the values of $Q_{s,f}$ for each of test piles can be obtained and are summarized in Table 1 together with $Q_{s,f}$ values determined from load test. As indicated in the table, the values of $Q_{s,f}$ determined from the F.M test showed good agreement with the values from load test on actual piles.

CONCLUSION

Features of the friction meter developed for evaluating the skin friction of pile and field measurement results on various soil types were reported. A comparison of skin friction evaluated from the F.M test and load test was also made. Although there are some problems to be solved in application of the F.M test, the following conclusions can be made based on this study.

- 1) It was confirmed that the F.M can be used for hard soils such as mud stone, dense sand and hard clay using routine drilling machine without trouble in operation and/or damage of the device.
- 2) The roughness of pile surface should be taken into account in evaluating the skin friction of a pile.
- 3) The ultimate skin friction of three test piles, driven into a hard clay, evaluated from the F.M test showed good agreement with

the values from load test when the $\tau_{(F.M)p}$ value measured by the F.M is corrected for the difference in roughness between the actual pile and the measurement sleeve of the F.M.

NOTATION

$Q_{s,f}$ = ultimate skin friction

$R_{\max}$ = maximum difference of level in a distance of 2.5 mm

$\tau_{(F.M)}$ = shear stress obtained from the F.M test

$\tau_{(F.M)p}$ = peak shear stress obtained from the F.M test

$\tau_{(pile)}$ = shear stress mobilized between pile and soil
 θ = angle of rotation

$\theta_{(F.M)}$ = angle of rotation of the measurement sleeve of the F.M

$\theta_{(m)}$ = angle of rotation measured

$\theta_{(r)}$ = angle of rotation induced by torsion of the drill rod

μ_R = correction coefficient for the roughness of pile surface

REFERENCES

- 1) Kishida, T. (1979): "Fundamental studies of frictional resistance between sand and metal surface," Doctoral Dissertation, Tokyo Institute of Technology (in Japanese).
- 2) Yoshimi, Y. and Kishida, T. (1981): "A ring torsion apparatus for evaluating friction between soil and metal surface," Geotechnical Testing Journal, Vol. 4, No. 4, pp. 145-152.