Pile Load Test Data Interpretation and Design Verification for HSR Project in Taiwan

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Abstract: Construction of the southern section of Taiwan High Speed Rail Link will involve the construction of a large number of piles. The behaviour of the piles must be understood. At an early stage in the project, some static pile load tests were conducted at Taipao, Chiayi to investigate the ultimate capacity of piles when formed in the alluvium materials of the southwest plain in Taiwan. At later stages in the project, a number of pile load tests were carried out with the loads applied using Osterberg load cells (O-cells). The pile O-cell tests were performed in Contract C270 through the length of the contract. Some of the pile tests were carried out at a location about 2km north of Taipao. Using data from these pile load tests, the paper will explore and discuss the pile capacities of piles installed in soft ground using the construction methods used during the construction of C270. The effects of pile size, base grouting and the variations possible in the elastic modulus of concrete will be considered. Based on the pile load test results at Taipao and in Contract C270, it was found that the percentage of the load carried in end bearing approximately 22% to 24% of the ultimate capacity. The variation in the value of the elastic modulus of the concrete can give a 16% to 25% variation in the calculated shaft friction force along the pile. For the piles tested using the O-cell system, it is concluded that some of the inconsistent calculated values of the unit shaft friction results close to the O-cells may be a result of soil disturbance resulting from soil movements as the O-cell is opened during the tests.

1 INTRODUCTION

To enable the rapid development of urban areas in the western part of Taiwan, a high-speed rail link is being constructed from Panchiao, Taipei County, in the north to Tzoying Kaohsiung City in the south. Total route length of the Taiwan High Speed Rail Link (THSRL) is 345 km. It will have six stations including Panchiao, Taoyuan, Hsinchu, Taichung, Chiayi, Tainan and Tzoying. The railway runs on viaducts for much of the route south of Paguashan tunnel. Along the southern section of the route, the main type of soil is Alluvium. To support the structures, a large number of piles have been installed. Pile load tests are an essential part of the design process to confirm estimates of the ultimate pile capacity. This paper will consider the results from pile tests carried out by BOTHSR prior to inviting tenders for the construction and some of the pile tests carried out by the Contractor to validate the designs. The early pile tests were carried out at the depot site at Taipao, which is close to the route in contract C270.

2 THE SITE

Contract C270 (THSRL chainage of 207km+015 to 249km+ 814) is located between Hsichou, Changhwa County and Taipao, Chiayi County and is 42.799 km long. The geology along this section is alluvial deposits, consisting of sands, silts and clay with occasional layers of gravel. In some sections, there is a thin covering of made ground. The whole of the area is seismically very active with the Meishan Fault close to the route between ch 241+606 to 245+415.

The depth of the alluvium exceeds 100m. Underlying solid basement was not penetrated in any of the boreholes sunk during the ground investigations.

The soil types encountered in contract C270 are predominantly either loose to medium dense deposits of soft to firm silty sands or firm to stiff silty clays to depths of about 30m below ground level. From 30 m to 50 m, the density of the soils increases and the soils are generally medium dense, with a few results recorded as dense, cohesionless material. In this depth zone, clays would be described as being generally firm to stiff, occasionally very stiff. At depths greater than 50m below ground level the soils are mainly medium dense to dense with a greater proportion being described as very dense below 60m.

The sequence of the soil layers along the route is variable. The soils can be described collectively as alluvium, of generally low plasticity (where cohesive), and generally with strength and density increasing linearly with depth.

Groundwater was encountered between 2.7 and 4.3m below ground level during the ground investigation. The ground water level can vary locally due to abstractions for irrigation.

3 EARLY PILE LOAD TESTS (BOTHSR)

In 1996, to provide information and an understanding of the optimum design for structural foundations for the THSRL, the Taiwan High Speed Rail Bureau (BOTHSR), initiated a research contract before the tenders were invited for design and construction . Piles were constructed using both reverse circulation drilling (RCD) and the casing oscillator method (OCM) at the provisional site of the Taipao Depot (THSRL chainage 251km+200). Three key aspects were considered in this study (Taiwan High Speed Rail Bureau, 1997):

(1) A review of the design criteria
(2) Identification of problems of foundation analysis and construction
(3) The effects of soil liquefaction and soil improvement

The Taipao Depot is located next to the southern end of contract C270; the ground profile is similar to the soils along Contract C270. The test results from Taipao Depot will be compared with pile tests carried out by the contractor for section C270.

4 C270 TEST PILES LOADED USING OSTERBERG CELL

The primary objectives of the C270 pile load tests were to verify design assumptions given in the Design Manual (FaberMaunsell Ltd, 2000) and where possible to optimise pile design by analysing the distribution of forces within the pile during loading. Details of the test piles constructed during this programme are given in the reports prepared by the sub-contractor LOADTEST (2000a, 2000b, 2000c, 2000d & 2000e), all of the test piles were loaded using Osterberg in-shaft load cells (O-cells). A schematic section of a test pile is shown in Fig. 1. The tests were carried out with three loading stages. In the first stage, the lower O-cell is expanded to assess the combined end bearing and shaft friction below the O-cell. In the second stage, after unloading the lower O-cell, the upper O-cell is pressurised to assess the shaft friction characteristic of the pile between the two O-cell assemblies by using the upper shaft friction as the reaction, the lower O-cell is left free to drain. During the last stage, after closing the lower O-cell, the upper O-cell is loaded to assess the friction characteristics of the pile above the upper O-cell assembly by using the combined middle and lower shaft friction and the end bearing as the reaction.

5 EVALUATION OF PILE CAPACITY

After reviewing data from pile load tests at the Taipao Depot and the eight O-cell test piles constructed in Contract C270 during the design stage, data from four of the tests, which are considered representative of the soil conditions encountered in the area of C270, have been selected for this comparison. To eliminate the influence of different construction methods on the analysis, only test piles at Taipao Depot constructed by the RCD method have been considered. Some differences may, however, still pertain due to the use of different drilling muds and the different lengths of the piles. Although the piles are of different lengths, the soils at the pile toe and over upper portions of the shaft are similar. Results selected for this comparison are from Pile B4 and B7 at Taipao Depot and piles 270-05 and 270-07 from the contractor's test pile programme. During the construction of test pile B7, the base was grouted to maximise the base resistance. Details of the test piles are presented in Table 1.

Table 1 . Details of test piles.

Test pile number	B4	B7	270-05	270-07
Location	Taipao		Main Site	
Pile diameter (m)	1.5	1.5	2	2
Pile length (m)	34.7	34.7	57.1	63.4

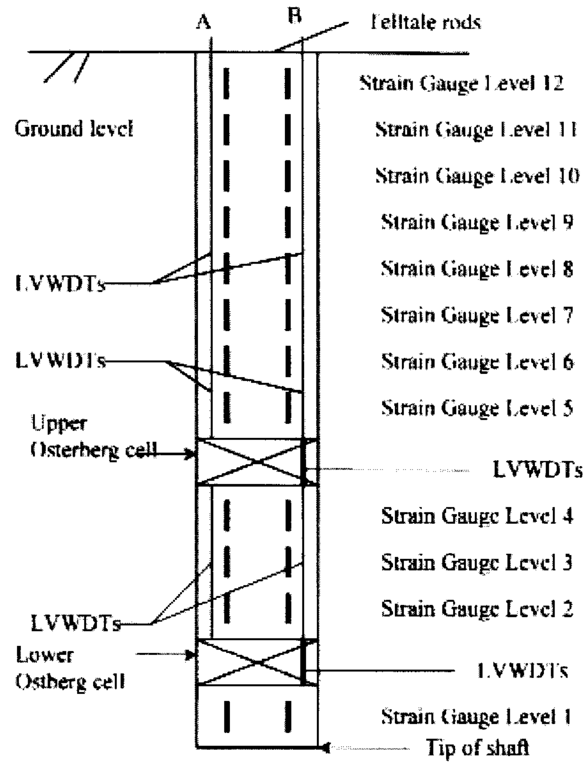

Fig. 1. Schematic section of a test pile.

In a conventional pile load test, skin friction force along the shaft (P) is defined by:

$$P = \varepsilon \times E_s \times A_s + \varepsilon \times E_c \times A_c \qquad (1)$$

ε: strain measured from strain gauge on pile shaft
E_s: elastic modulus of reinforcement
E_c: elastic modulus of concrete
A_c: area of cross section of concrete
A_s: area of cross section of reinforcement

E_s is taken as 2.04×10^5 MPa and E_c is interpreted in

$$E_c = 15{,}000 \times \sqrt{f_c'} \qquad (2)$$

in which f_c' is the unconfined compressive strength of concrete. E_c is equal to 2.5×10^4 MPa for a value of f_c' = 28 MPa. Figure 2 shows the friction force along the pile shaft interpreted from strain gauges when the maximum top load, (1375 tonnes) is applied to pile B4 and B7 using a conventional top loading static system.

A strain gauge was installed in the pile 40 cm above the pile toe (34.3 m below ground level) to provide data for an estimate of the end bearing resistance of the pile. The results from pile test B4 show the measured load from this strain gauge to be 3319 kN when 13,750 kN was applied to the pile head. In contrast, the base load measured in pile B7 was only 613 kN when 13,000 kN is applied to the pile head.

Considering the results of the O-cell tests, the unit shaft friction force (P) is determined by

$$P = \varepsilon \times E_{mix} \times A \qquad (3)$$

ε: strain measured from strain gauges in pile shaft at one level.
E_{mix}: weighted pile modulus
A: area of cross section of pile

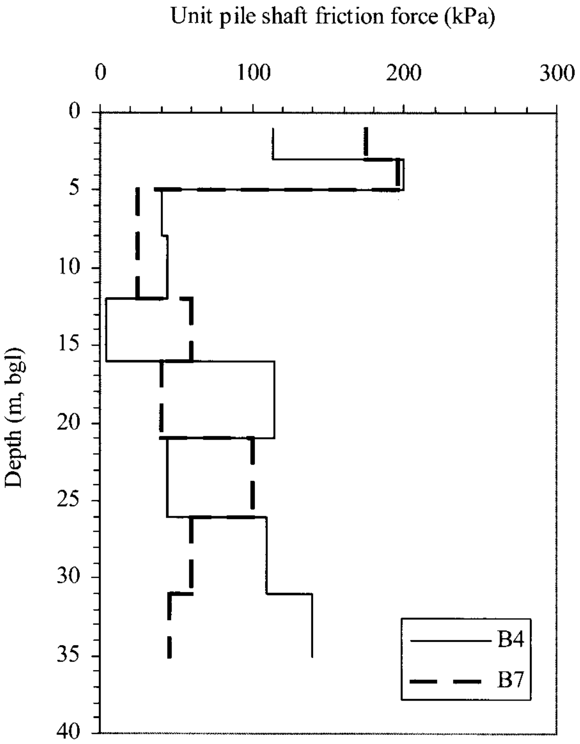

Fig. 2. Friction force along the shaft Test B4 and B7.

Figure 3 presents the measured unit shaft friction force along the pile taken from the strain gauges in piles P270-05 and P270-07 tested using the double O-cell test.

The load is applied to the lower O-cell directly in the first stage test. Lower side shear force can be calculated from the strain gauges and it is possible to separate end bearing and shaft friction. Test results show that load carried in end bearing is 6.25MN for Pile P270-05 and 8.65MN for Pile P270-07.

6 DISCUSSION

The Taiwanese Building Code (TBC, 2001) recommends that the unit shaft friction resistance (f_s) of piles in sand can be estimated using the Standard Penetration Test results (SPT N) as:

$$f_s = 1.96N \qquad \text{(units: kPa)} \qquad (4)$$

Based on the data from the conventional top loaded pile load tests at Taipao Depot, BOTHSR suggested that the relationship between shaft friction force (f_s) and SPT N value could be:

for sandy soils

$$f_s = 4.7N + 105.84 \qquad \text{(units: kPa)} \qquad (5)$$

for silty and clayey soils

$$f_s = 4.7N \qquad \text{(units: kPa)} \qquad (6)$$

Based on the pile tests in the soft alluvium in south Taiwan, FaberMaunsell (2000) suggested that f_s could be

for sands and gravels

$$f_s = 3.3N \qquad \text{(units: kPa)} \qquad (7)$$

with a maximum value of 165kPa or N<50

for silt and clay of N≤ 4

$$f_s = 6.25N \qquad \text{(units: kPa)} \qquad (8)$$

with a maximum value of 150kPa or N<24

and for silt and clay of N>4

$$f_s = 1.31N + 26 \qquad \text{(units: kPa)} \qquad (9)$$

Taking a typical common ground profile, the friction force along the pile shaft is calculated from Eqs. (5) to (9). Figs. 4 & 5 show the shaft friction force interpreted from the different equations. The estimation from Eqs. (7) to (9) are close to pile load test results carried out by the contractor.

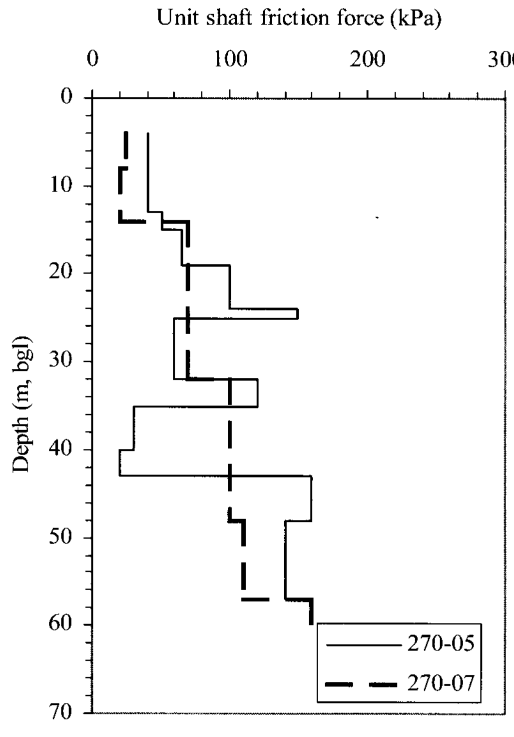

Fig. 3. Friction force along the shaft from the O-cell tests.

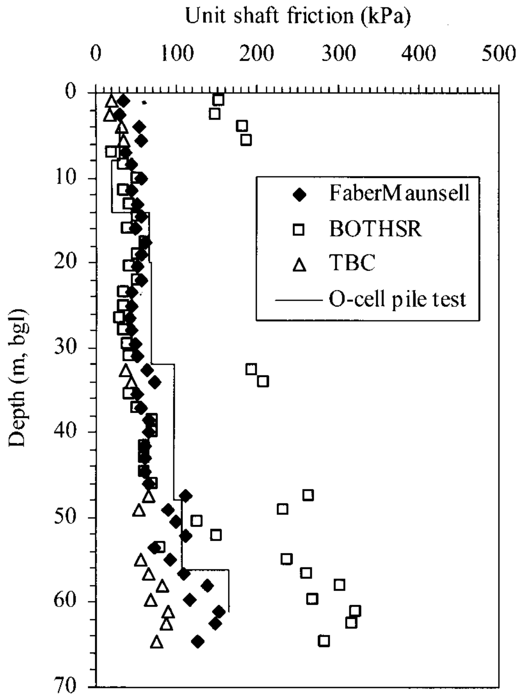

Fig. 4. Shaft friction based on the ground profile at Pier 7-570 in contract C270.

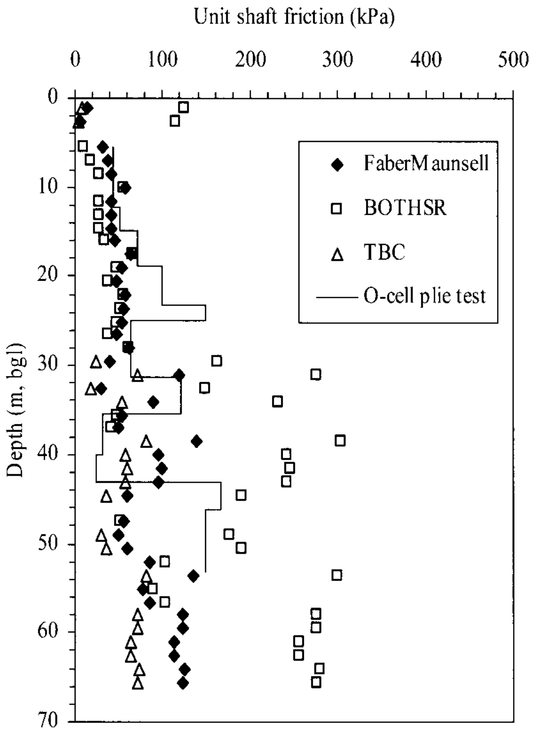

Fig. 5. Shaft friction force based on the ground profile at Pier 7-621 at contract C270.

Considering different sizes of test piles installed on site, a similar relationship between f_s and SPT N in sandy soils is found by TBC, BOTHSR and FaberMaunsell. In this study it is seen that the pile diameter, in the range 1.5m to 2.0m, does not affect the unit values of shaft friction (f_s). Variations noted are a function of the strain gauges in the test piles and possibly the effects of different drilling muds used during construction.

End bearing and shaft friction of the piles has been estimated from the pile load tests. Table 2 lists the shaft friction, end bearing and the ratio of end bearing to ultimate pile capacity as a percentage for the pile load tests.

Table 2. Shaft friction, end bearing and ratio of end bearing to ultimate pile capacity.

Test pile	B4	B7	P270-05	P270- 07
Shaft friction force (MN)	13.75	13.00	21.50	30.00
End bearing (MN)	3.32	0.61	6.25	8.65
Ratio of end bearing to ultimate pile capacity (%)	24.1	4.72	22.5	22.4

It can be seen that the shaft friction is the most significant element in the pile capacity for the piles installed in the local soft alluvial soils. The ratio of end bearing to ultimate pile capacity varies from 22.4% to 24.1%. The end bearing and the base grouting at test pile B7 does not seem to have induced a significant increase in the end bearing resistance, this is consistent with the suggestion of BOTHSR (1997). However, there may be other reasons, which are not obvious from the BOTHSR report to explain this result.

During the interpretation of shaft friction along the pile using the strain gauges, an elastic modulus of concrete must be assumed. For test pile P270-05, at the time of testing, the concrete unconfined compressive strength was reported to be 37.1 MPa, using the relationship for the elastic modulus of the concrete (E_c) as defined:

$$E_c = 57000 \times \sqrt{f_c'} \qquad \text{(where } f_c' \text{ is in psi)} \qquad (10)$$

Combined with the area of reinforcing steel, a weighted pile modulus of 28,800 MPa is determined. Hsiung (2002) reported that the elastic modulus of concrete may be expressed as (BS8110, 1985)

$$E_{c,28} = K_{0ag} + 0.2 \times f_{cu,28} \qquad (11)$$

where $E_{c,28}$ is the elastic modulus of concrete at 28 days. $f_{cu,28}$ is the characteristic cube strength at 28 days (in MPa). K_{0ag} is a constant related to the aggregate material used for concrete, varying from 14 to 26 GPa. The test was carried out 27- 29 days after pile construction. Thus, 37.1MPa of $f_{cu,28}$ is used in Eq. (11). From Eq. (11), the elastic modulus of concrete at 28 days ($E_{c,28}$) was calculated with a possible range of $E_{c,28}$ from 21.4 to 33.4 GPa depending on aggregate type, as shown in Fig. 6. The weighted pile elastic modulus varies in the range 21.5 to 33.5 GPa.

Shaft friction along the pile can be re-calculated using the weighted pile elastic modulus and the results are shown in Figs. 7 & 8. The variation of elastic modulus of concrete induces 16-25% change of skin friction force along the pile.

As indicated in Fig. 3, it is seen that shaft force measured by reference to the strain gauge in the pile close to an O-cell in Pile P270-05 is not in agreement with the range of values expected. The disturbance of the soils close to the O-cell caused by a flow of soil during the opening of the O-cell is considered to be one possible reason for this observation

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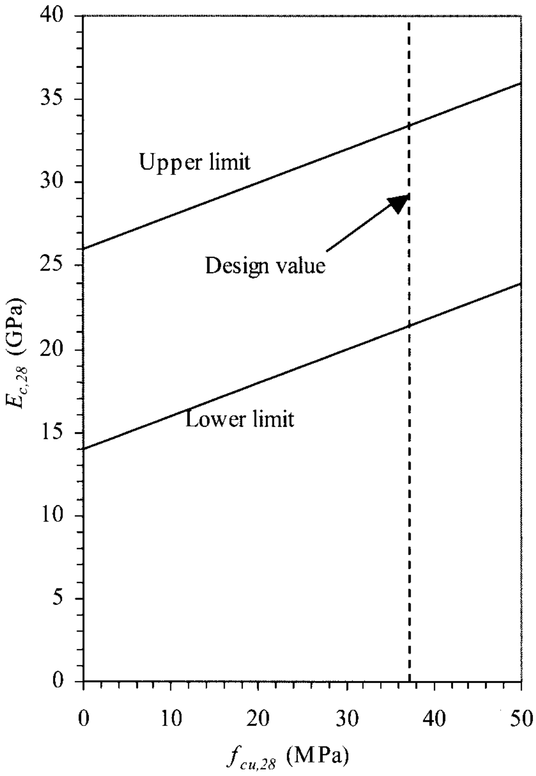

Fig. 6. Variation of elastic modulus of concrete.

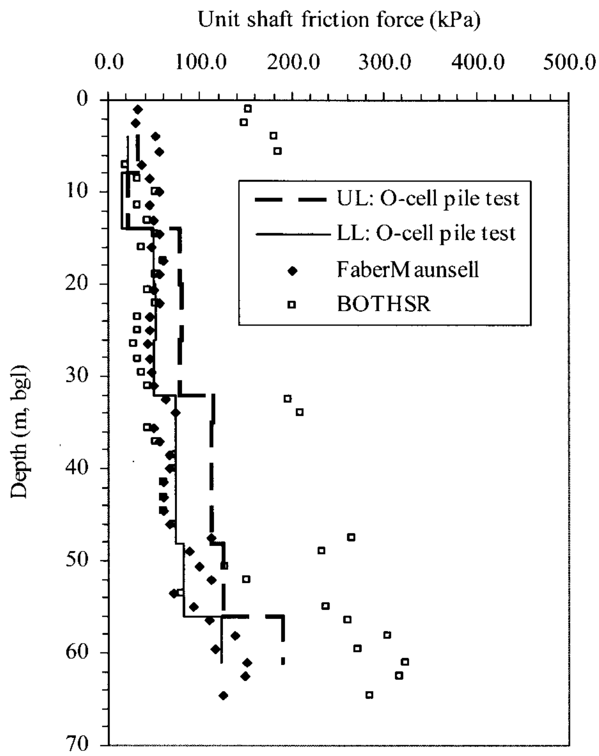

Fig. 7. Influence of elastic modulus of concrete on shaft friction force at Pier 7-570.

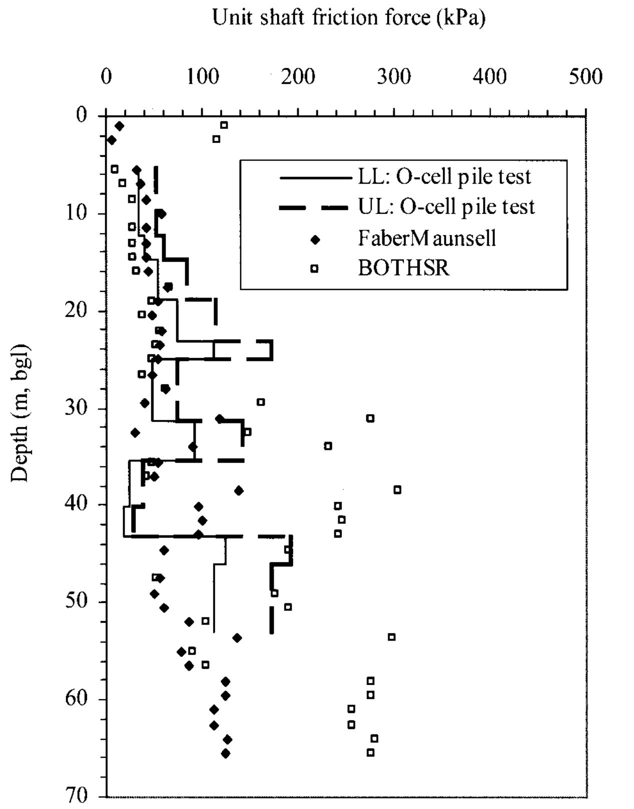

Fig. 8. Influence of elastic modulus of concrete on shaft force at Pier 7-621.

7 CONCLUSIONS

From pile load tests carried out in soft alluvium in south Taiwan to validate the design criteria to be used in the design of the foundations for the Taiwan High Speed Railway, the following conclusions have been reached:

1. Pile diameter does not affect the unit shaft friction force along the pile in the ranges considered, 1.5m to 2.0m.
2. Shaft friction along the pile plays a key role in the ultimate pile capacity for the piles installed in soft alluvial soils. The percentage of end bearing to pile ultimate capacity is approximately 22% to 24.%.
3. Base grouting does not seem to contribute significantly to end bearing. If grouting to increase the base resistance were to be evaluated further tests would be appropriate.
4. Variation of elastic modulus of concrete may result in variations of between 16 to 25% in the values predicted for the shaft friction force.
5. The in-flow of soil during the opening of O-cells may disturb test results close to the cells.

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