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Bearing mechanism and pile foundation design

Conception de mécanisme des coussinets et de fondation des pilots

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ABSTRACT

In this paper, over 40 pile load test data were reviewed and the bearing capacity of the piles was studied. Through the analysis of pile load tests, the bearing mechanism of pile is established as follows: (a) Skin friction is mobilized by pile shaft displacement and its magnitude depends on the order of shaft displacement. (b) Ultimate skin friction is observed at certain depth and this depth shifts downwards with increasing pile load. At above/below this certain depth, the magnitude of skin friction is smaller than the ultimate shear strength. (c) The magnitude of skin friction depends on pile length. When the pile length exceeds 30m, the skin friction is more than 95% of the bearing capacity of pile. From this bearing mechanism, the pile adhesion factor and neutral point of negative skin friction are evaluated.

RÉSUMÉ

Plus d'une quarantaine de données de test du pilot avec charge ont été revu et la capacité des coussinets a été étudiée dans ce document. A travers des analyses du test du pilot avec charge, le mécanisme des coussinets du pilot est établi comme suit: (a) Le frottement superficiel est engendré par le déplacement de l'arbre du pilot et l'envergure du frottement superficiel change en proportion du déplacement. (b) L'utime frottement superficiel est remarqué à un certain profodeur et cette profondeur se déplace vers le bas avec l'augmentation du charge. En dessus/dessous cette certaine profondeur, l'envergure du frottement superficiel est plus petite que l'utime puissance. (c) Le coefficient du frottement superficiel est la fonction de la longueur du pilot. Quand la longueur du pilot dépasse 30m, le coefficient du frottement superficiel dépasse 95% de la capacité des coussinets du pilot. Le sens du facteur de reduction du frottement superficiel (facteur d'adhésion) et le point neutre du frottement superficiel négatif s'expliuqe en utilisant ce mécanisme des coussinets.

1 INTRODUCTION

Variations in the design standards and codes for determing pile bearing capacity often exist in different countries. Such variations are caused by the differences in the proposed formulae for pile toe capacity and skin friction, restriction of soil parameters for design and the recommended range of safety factor. Each standard and code was established based on the engineering background of individual country, such as types of piles, soils and their properties at the main cities and surrounding areas. Owing to rapid expansion of developed areas and many construction works, it may be difficult to apply the standards and codes rationally at times. These difficult cases are often due to new types of piles/construction methods and different types/properties of soils encountered. To avoid geotechnical risk and to reduce construction cost, the pile design should be reviewed based on the bearing mechanism of pile. This will provide a better rational guide for pile design involving difficult cases. This paper aims to investigate the bearing mechanism of pile from the review of a large number of pile load tests conducted on cast-in-situ concrete bored piles.

2 MECHANISM OF SKIN FRICTION DEVELOPMENT

2.1 *Test Pile*

The data for this paper is obtained from a large number of preliminary ultimate instrumented pile load tests conducted in Singapore and Malaysia. A typical instrumented test pile is shown in Fig. 1. The parameters of a typical pile load test are as follows:

- ° Type of pile : Bored pile (diameter 800-1300mm)
- ° Length of pile : 15 to 50m
- ° Soil type : Alluvial soil, Delluvial soil (cemented soil), Weathered sedimentary rock, and Weathered granite.
- ° Total number of tests : 45
- ° Loading pattern : 2 to 3 load cycles with maximum test load 2 to 3 times pile working load.
- ° Instrumentation : Strain gauges (8 to 20 elevations with 2 to 4 gauges per elevation) Extensometer (2 to 3 elevations)

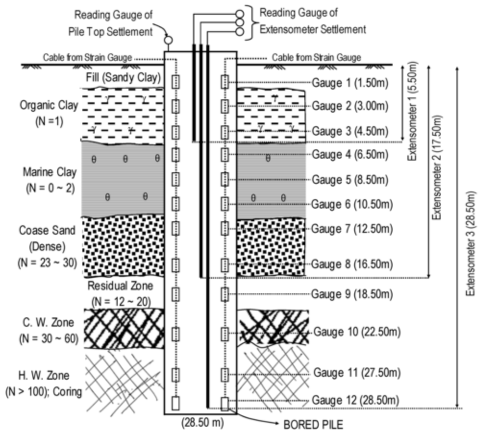


Fig. 1. Instrumentation For Pile Load Test

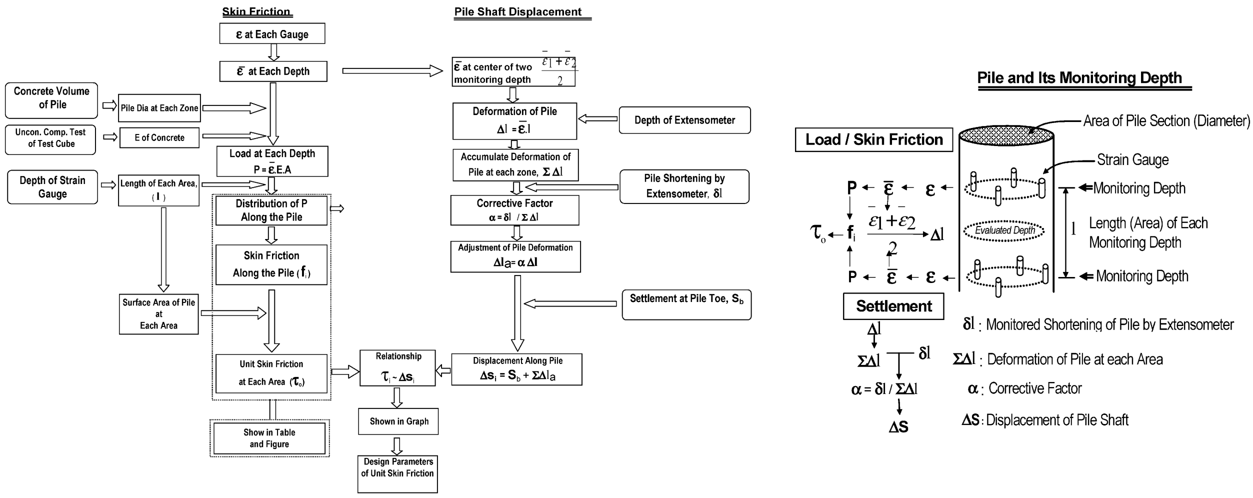


Fig. 2. Flow Chart for Evaluation of Skin Friction

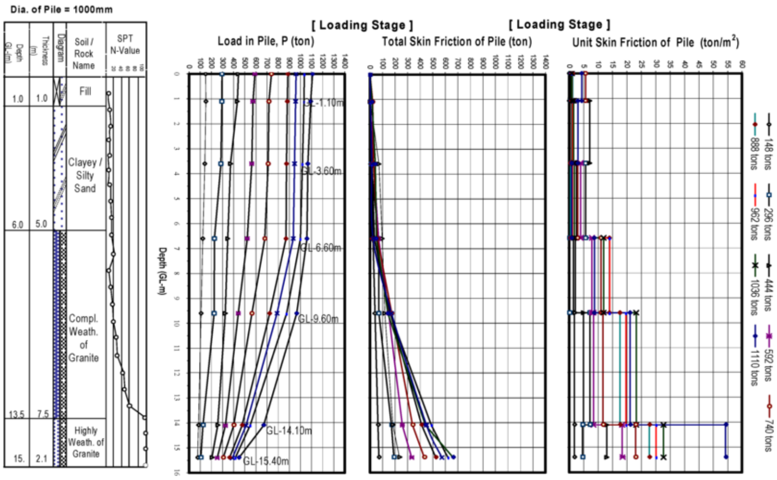


Fig. 3. Stress Distribution in Pile from Load Test

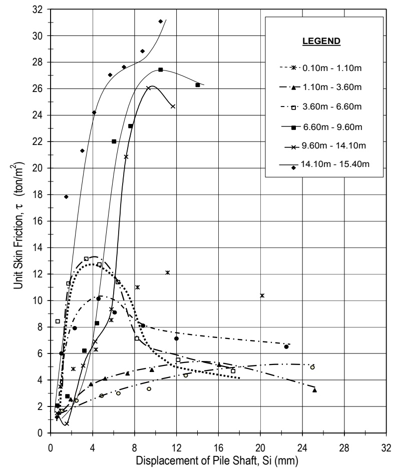
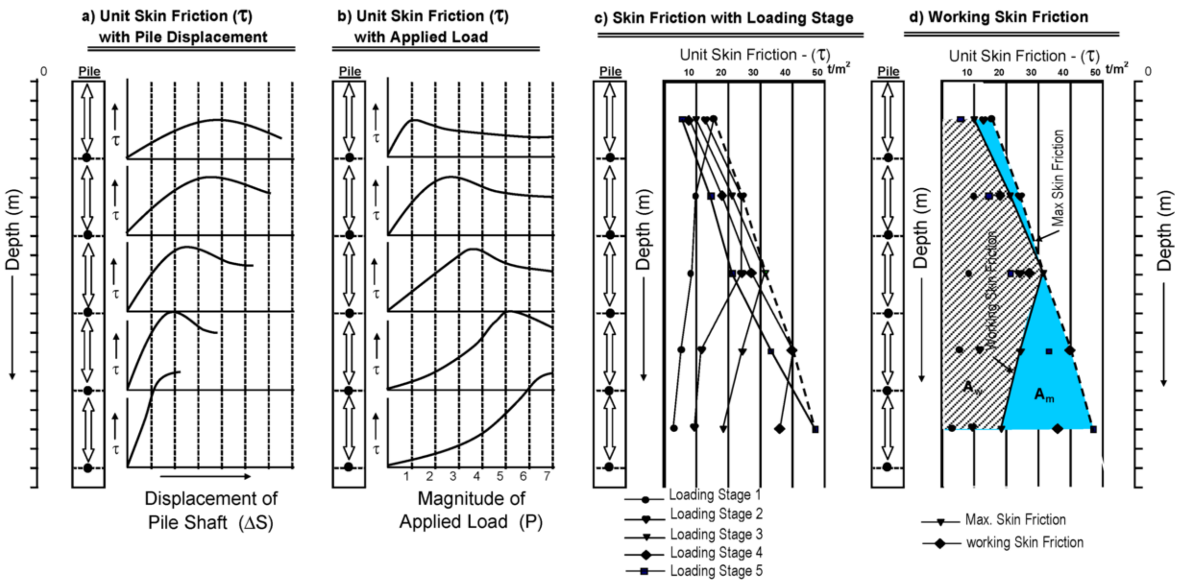


Fig. 4. Relationship between Displacement of Pile and Unit Skin Friction



g. 5. Magnitude of Skin Friction from Load Test

2.2 *Interpretation of Test Pile Data*

The procedure of interpretation of pile load test data is illustrated in Fig. 2. As the first step of interpretation, the test records summarise the load transfer and mobilized skin friction along the pile shaft (Fig. 3). To investigate the bearing mechanism, the unit skin friction at each depth is evaluated against the displacement of pile shaft. As shown in Fig. 4, the unit skin friction/pile shaft movement relations show similar trend as the stress-strain relation of soil shear strength test results. As such, the unit skin friction increases with pile shaft displacement. A maximum shear strength is mobilized at a certain displacement, after which the moblilized strength is reduced to the residual shear strength.

The load transfer along the pile depends on the displacement of pile shaft, which is generally large at the pile top and small at the pile toe. Owing to this tendency, the magnitude of unit skin friction varies with depth, as shown in Fig. 5(a) showing the variation of unit skin friction (τ) with displacement of pile shaft (ΔS), Fig. 5(b) showing the relation between unit skin friction (τ) and applied load on pile top (P), Fig. 5(c) showing the variation of unit skin friction (τ) along the pile shaft for each loading stage, and Fig. 5(d) showing the working skin friction (Aw) compared with maximum skin friction (Am). Fig. 5 shows that the elevation of maximum mobilised unit skin friction τmax shifts downward with increase in applied load. At the end of the load tests, residual shear strength of unit skin friction (τres) is generally mobilized at the upper pile shaft elevations while the full shear strength is still being developed at the lower pile shaft elevations.

A summary of pile load test data interpretations is given in Table 1. It is evident that the mobilised pile shaft displacement at τmax depends on soil type. This displacement is large for soft/loose soils and small for hard soils/weathered rocks. A relation between the maximum mobilised unit skin friciton (τmax) and standard penetration resistance N value from the pile load tests is shown in Fig. 6.

Table 1. Skin friction of piles in various soils and weathered rocks

Ground Material		Skin Friction					SPT-N value
		Max. Skin Friction		Residual Skin Friction		Ratio	
Formation	Soil / Rock Weathered Grade	Displacement (mm)	Strength τ_{max} (KN/m^2)	Displacement (mm)	Strength τ_{res} (KN/m^2)	τ_{res}/τ_{max}	
Top Soil / Fill	Sandy Clay / Sandy Silt	10.0	44	19.7	31	0.68	7
	Silty Sand / Reclaimed Sand	8.8	110	14.0	25	0.21	14
Alluvium	Marine Clay	7.5	50	16.0	40	0.80	1
	Silty Clay	4.0	64	-	-	-	10
	Organic Clay/ Organic sand / Peat	7.8	40	16.0	31	0.77	2
	Sandy Clay / Clayey Sand / Silty Sand	13.8	90	24.4	32	0.45	17
Jurong Formation	Residual Soil of Limestone (VI)	9.3	117*	-	-	-	12
	Compl. Weathered Mudstone (V)	7.5	195	-	-	-	28
	Highly Weathered Mudstone (IV)	8.0	400*	-	-	-	>100
	Moderately Weathered Limestone (III)	5.7	1520*	-	-	-	>100
Bukit Timah Granite	Residual Soil of Granite (VI)	7.1	77	16.6	59	0.69	19
	Completely Weath. Granite (V)	7.2	135	8.3	108	0.77	46
	Completely Weath. Granite (V)	8.1	287	12.8	253	0.94	72
	Highly Weathered Granite (IV)	5.0	690*	10.0	430	0.91	>100
	Moderately Weathered Granite (III)	5.0	2600*	-	-	-	>100
Boulder Clay	Residual Soil of Boulder Clay	5.1	60	9.5	52	0.79	19
	Residual Soil of Boulder Sandstone	5.9	86	-	-	-	25
	Weathered Zone of Boulder Clay	8.0	144	12.0	58	0.52	37
	Cemented Zone of Boulder Clay	7.1	398	11.0	253	0.87	>100
Old Alluvium	Weathered Zone of Old Alluvium	14.0	98	16.3	62	0.63	32
	Cemented Zone (I) of Old Alluvium	14.5	258*	-	-	-	>100
	Cemented Zone (II) of Old Alluvium	9.8	820	14.5	790	0.96	>100

Note : (*) - Under Progress stage

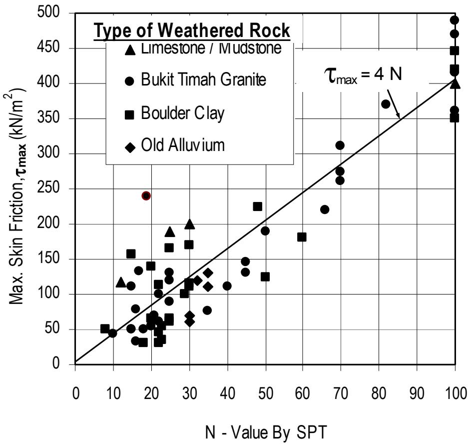


Fig. 6. Relationship between τ_{max} and N-Value

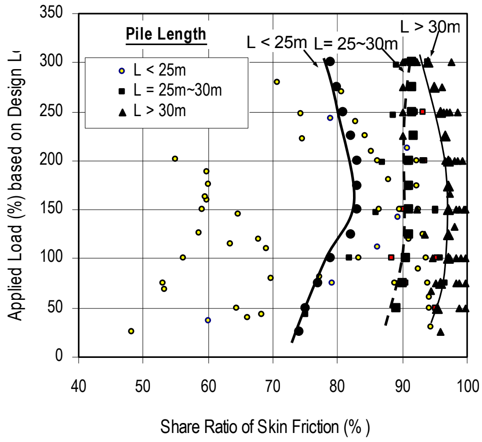


Fig. 7. Ratio of Skin Friction with Increment of Load

3 SKIN FRICTION FOR PILE DESIGN

3.1 *Maximum Moblilised Unit Skin Friction*

In pile design, the maximum mobilised unit skin friction (τmax) is considered to be the same as the soil shear strength. However, this is found to be not suitable from the present study due to (a) the zone of τmax is observed only at limited elevations along the pile shaft, and (b) τmax develops at certain displacement which is difficult to evaluate during actual construction.

3.2 *Residual Unit Skin Friction (τres)*

Most of the load test piles for this study had not failed as the range of final displacement of pile is between 15 to 30mm. At this relatively small displacement, only τmax and τres could be measured at above the bearing layer while those in the bearing stratum near the pile toe could not be measured. Further data interpretation is carried out by defining α as the ratio of τres/τmax. It is found that the α values show similar magnitudes as the pile adhesion factor commonly adopted in pile design. Thus these α values can be used for pile design. Used as design input, this τres has the same safety allowance based on Figs. 5(c) and (d). So if τres is monitored correctly and used as design input, the safety factor for skin friction can take a smaller value with regards to rational/economical design.

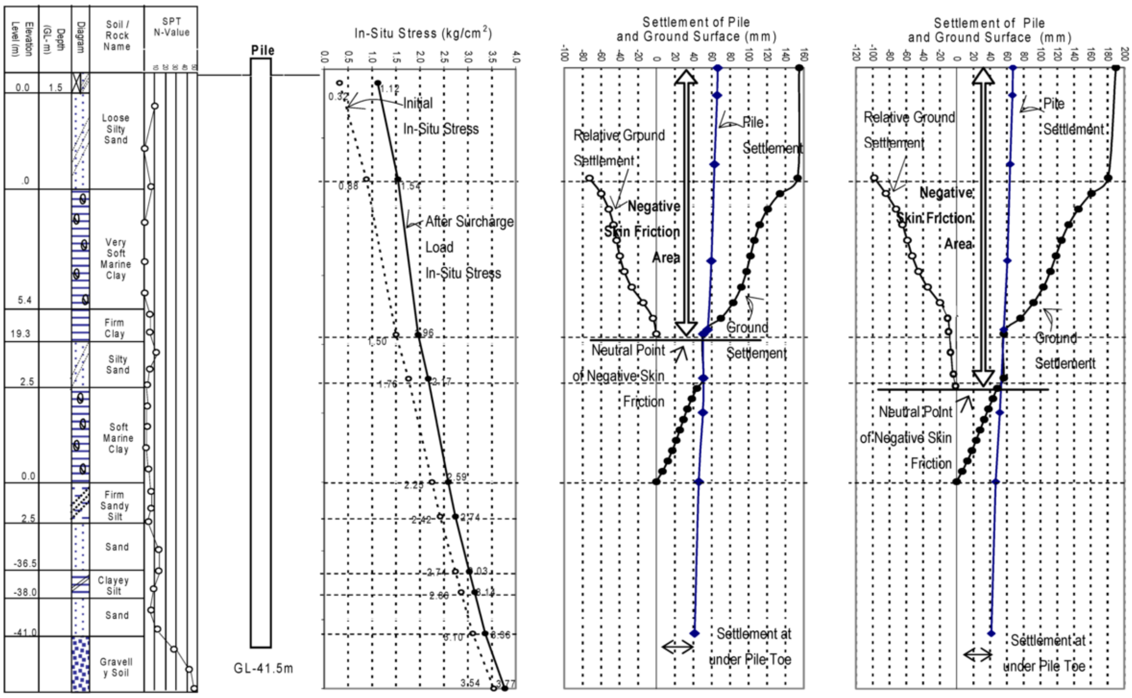


Fig. 8. Ground Settlement and Negative Friction of Pile

3.3 *Perecentage of Skin Friction in Pile Bearing Capacity*

The percentage of skin friction in pile bearing capacity is summarized in Fig. 7. It is noted that for piles over 30m long, the skin friction contributes over 90% of the pile bearing capacity. Another interest point to note is that the applied load does not appear to have significant influence on the percentage of skin friction. This means that although the transferred stress under the pile toe increases due to increase in applied load, the ground does not experience large settlement. If there is large settlement under the pile toe, all skin friction along the pile shaft is reduced to residual strength. Then the stress under the pile toe will increase and this may trigger pile failure.

3.4 *Negarive Skin Friction*

Fig. 8 shows the data of pile under loading in thick soft clay areas, where the consolidation of soft clay produces ground settlement under an embankment surcharge load. It is found that the skin friction is a function of displacement between the pile shaft and the surrounding soil. As in conventional thoeries, positive skin friction is developed when the settlement of pile shaft is larger than the settlement of soil and negative skin friction is developed when the settlement of pile shaft is smaller than the settlement of soil.

Fig. 8 also shows the pile shaft settlement under loading and the ground settlement responses. Initially the two settlement graphs show the same value at RL+20m (neutral point). With the progress of ground settlement, this neutral point is lowered to RL-24m. The ground settlement is caused by consolidation at the elevation level of RL-8.0 to 30.0m. This means that negative skin friction will not take place at the lower pile shaft and the extent of negative skin friction is related to the magnitude of ground settlement and consolidation ratio.

4 CONCLUSION

The findings of the present study are summarised as follows:

- The mechanism of developemnt of pile skin friction is better understood from the interpretation of a large number of pile load tests and is found to be useful to explain several phenomena of pile load transfer.
- Although pile load tests are performed for the purpose of design verification, the data should be stored in the database and to be used for the analysis and interpretation of design parameters as well as for the review of design procedure. The selection of pile length usually depends on the magnitude of skin friction in the bearing strata and pile toe bearing capacity whereby large shear strength can be mobilised. The problem is that such large strength is difficult to measure from laboratory and in-situ tests. Using a database of pile load test data, the geotechnical risks in pile design can be reduced.
- Recently, the reliability of test result has improved due to the availability of highly accurate and stable instruments and site quality control by experienced engineers.

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