Apr 13th - Apr 17th

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Proceedings: Fifth International Conference on Case Histories in Geotechnical Engineering
New York, NY, April 13-17, 2004

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ABSTRACT

The skin friction of pile is found as a parameter of pile shaft displacement. It will not be a simple/constant values for each type of soil/weathered rock. Pile load test data shows skin friction grows to maximum strength at certain displacement and then reduces to residual strength. Due to this property, the main active skin friction zone is shifted downwards with the increase of load.
From the shared ratio of total skin friction in pile bearing capacity, the share ratio of skin friction is found related with pile length. This means that for 30m long pile, the skin friction share is approx.95% of bearing capacity. The shared ratio shows almost constant value for each pile under 100% ~ 300% of design load if there is no failure in the pile. From this point of view, the failure of pile bearing mechanism will be due to the change of skin friction share ratio.

INTRODUCTION

Today, the pile design is proceed by taking certain safety factor into the interpretation on the evaluated ultimate skin friction and ultimate bearing capacity. This procedure is constructed on the assumption that the skin friction and toe bearing capacity generates together and achieves the ultimate value at the same time.

Based on the analysis of pile load test on bored pile, it is found that the skin friction and toe bearing capacity are the parameters of pile shaft displacement. Both values did not achieve the ultimate value at the same time. This paper presents the study result of the bearing mechanism of pile for to review the pile design.

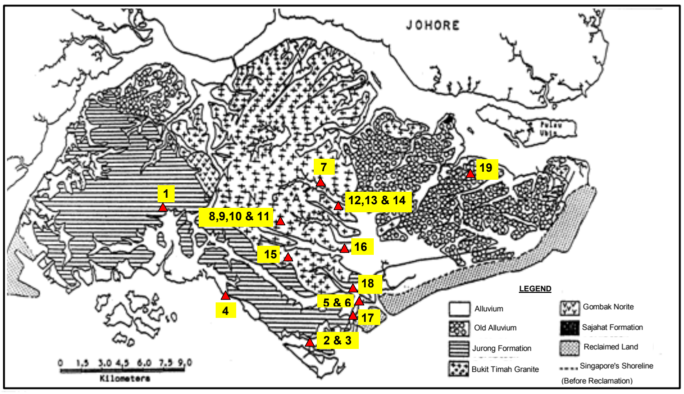


Fig. 1. Singapore geological map and location of test piles

ULTIMATE LOAD TEST ON PILE

The ultimate pile load test is for to verify the ultimate bearing capacity that is evaluated by the pile design work. So the applied load on the test pile is 250 ~ 300% of design load, which is considered based on the safety factor in the design work.

The test piles which are studied in this paper are bored piles with 800 ~ 1500mm in diameter and the length are 14m ~ 40m. The object test piles have instruments such as strain gauge and extensometer (see fig. 2). The ground materials of these test piles location consist of 3 types of bedding formation, such as granite, sedimentary rock (Jurong Formation) and Pleistocene cemented layer (Old Alluvium). All these materials are heavily weathered and top zone is classified as residual soil and completely weathered zone. The toe of test pile is socket into the following hard/strong materials:

Granite area	Pile toe is penetrated into highly weathered zone or moderately weathered zone. The penetration length in highly weathered zone is 3 ~ 8m, where N>100 and 1 ~ 3m in moderately weathered zone, when RQD>35%.
Sedimentary rock	Pile toe is penetrated into highly weathered zone more than 3m where N>100.

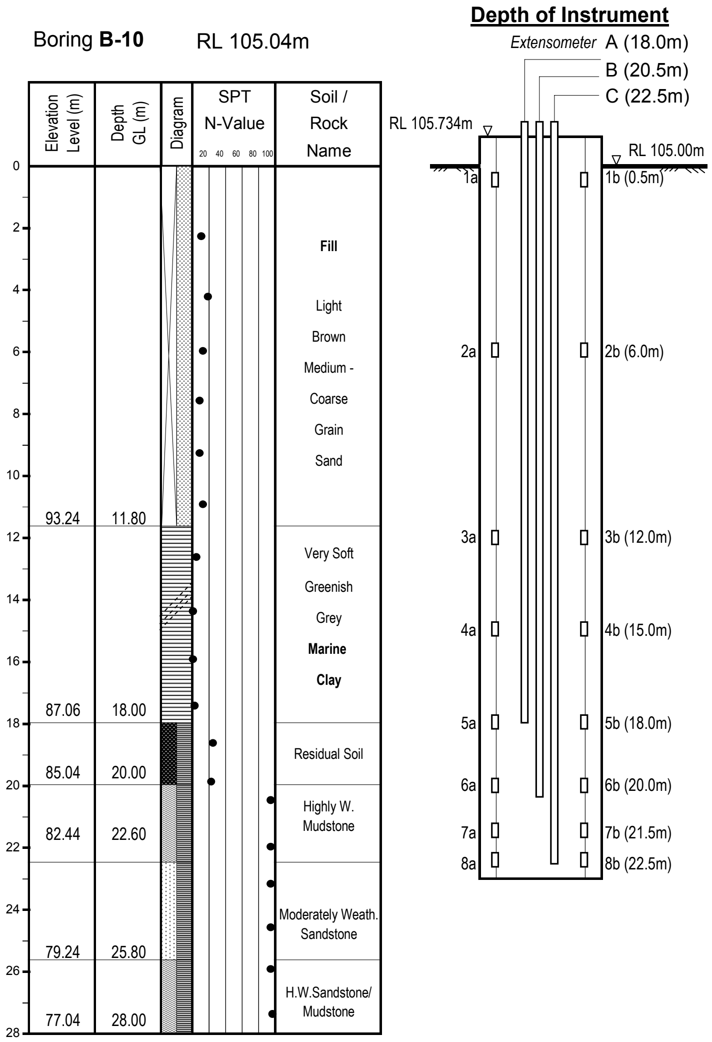


Fig. 2. Sample of instrumentation in test pile

Pleistocene Cemented Layer	Pile toe is penetrated into cemented zone more than 5m where N>100.

From the interpretation result of the monitoring data, it shows that stress distribution, friction and deformation/displacement of pile shaft can be obtained at each depth of pile. The flow chart in fig. 3 shows the process of data interpretation.
The phenomenon/behaviour of pile under surcharge load is explained as follows: (see fig. 4).
The stress develops in the pile shaft by surcharge load on top of the pile and transfer the stress downwards with damping. Each depth of pile is deformed by the stress developed at each depth. Then the stress at the pile toe is transferred into the ground material. The ground material under the pile toe is compressed due to the transfer of stress. The compression of ground material and the deformation of pile shaft will accumulate from the pile toe to the top. Then it is monitored as the displacement of pile shaft and settlement of pile top.
The skin friction is generated by the displacement of pile shaft and its magnitude is found as the parameter of displacement.

SKIN FRICTION

Properties of Skin Friction

The relationship between the skin friction and pile shaft displacement under the increase surcharge load is shown in fig. 5. The skin friction is generated with the increment of pile shaft displacement and the maximum skin friction is observed at 5 ~ 15mm displacement. Then it reduces to residual strength when the displacement continues. The maximum skin friction is confirmed as the parameter of shear strength of soil and as shown in table 1 and figs. 6 & 7.
In general, the magnitude of displacement which generates the maximum skin friction has good relationship with the shear strength and elastic modulus of soil, such as:

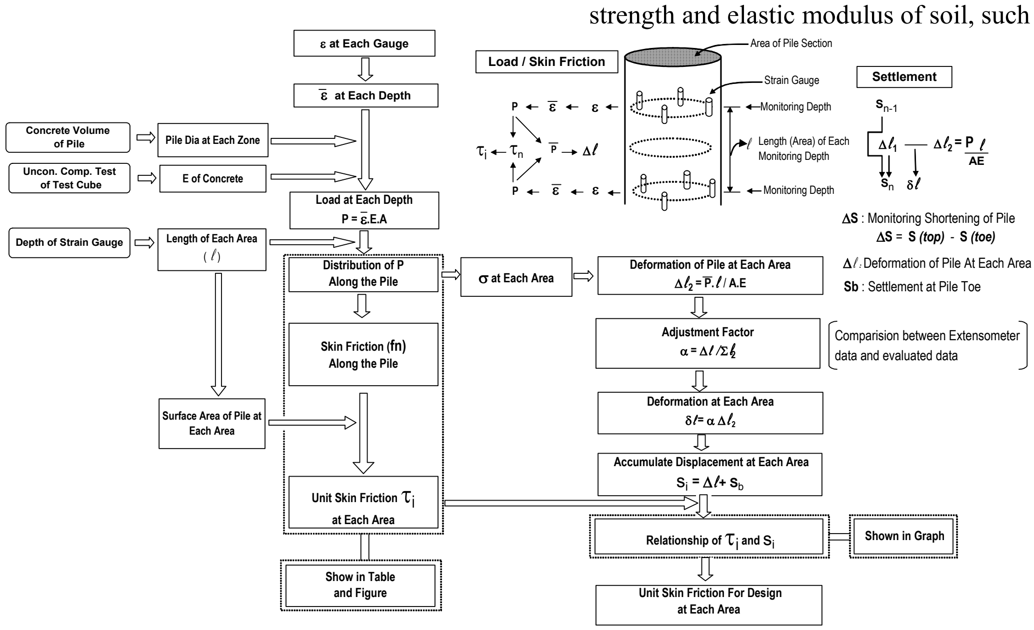
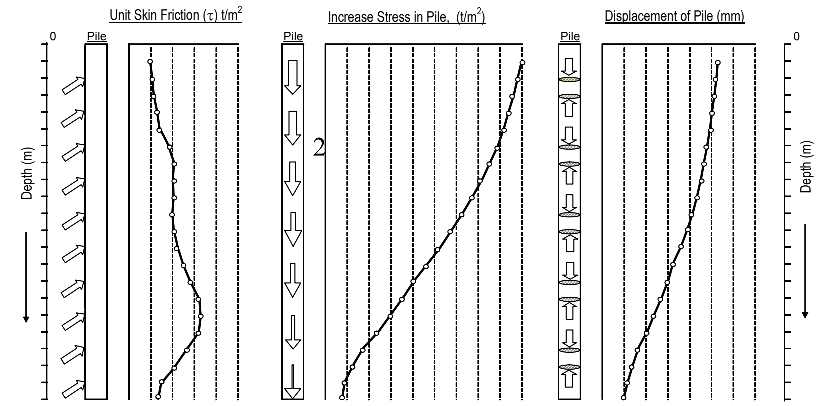
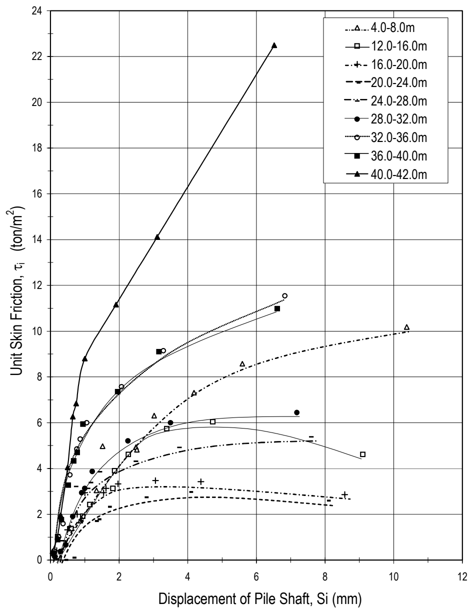


Fig. 3 Flow chart of analysis work of instrumentation





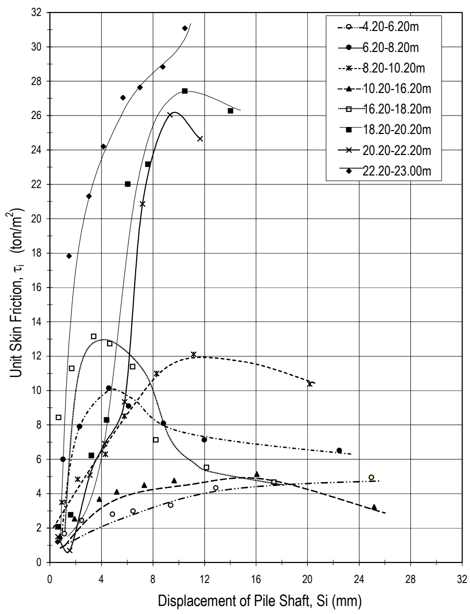


Table 1. Skin friction of pile in various soil and weathered rock

Ground Material		Skin Friction					Soil Parameters	
Formation	Soil / Rock Weathered Grade	Max. Skin Friction		Residual Skin Friction		Ratio	N	C_u
		Displacement (mm)	Strength τ_{max} (KN/m^2)	Displacement (mm)	Strength τ_{res} (KN/m^2)	$\frac{\tau_{res}}{\tau_{max}}$		(KN/m^2)
Top Soil / Fill	Sandy Clay / Sandy Silt	10.0	44	19.7	31	0.68	7	20
	Silty Sand / Reclaimed Sand	8.8	110	14.0	25	0.21	14	24
Alluvium	Marine Clay	7.5	60	16.0	52	0.85	14	24
	Silty Clay	4.0	64	-	-	-	10	29
	Organic Clay/ Organic sand / Peat	7.8	40	16.0	31	0.77	2	11
	Sandy Clay / Clayey Sand / Silty Sand	13.8	90	24.4	32	0.45	17	30
Jurong Formation	Residual Soil of Limestone (VI)	9.3	117*	-	-	-	12	99
	Compl. Weathered Mudstone (V)	7.5	195	-	-	-	28	210
	Highly Weathered Mudstone (IV)	8.0	400*	-	-	-	>100	2100
	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	50
	Completely Weath. Granite (V)	7.2	135	8.3	108	0.77	46	203
	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	2643
	Moderately Weathered Granite (III)	5.0	2600*	-	-	-	>100	-
Boulder Clay	Residual Soil of Boulder Clay	5.1	60	9.5	52	0.79	19	45
	Residual Soil of Boulder Sandstone	5.9	86	-	-	-	25	-
	Weathered Zone of Boulder Clay	8.0	144	12.0	58	0.52	37	98
	Cemented Zone of Boulder Clay	7.1	398	11.0	253	0.87	>100	175
Old Alluvium	Weathered Zone of Old Alluvium	14.0	98	16.3	62	0.63	32	60
	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

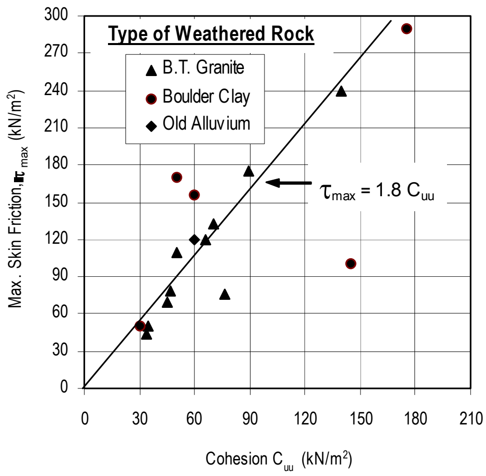


Fig. 6. Relationship between τ_{max} and C_{uu}

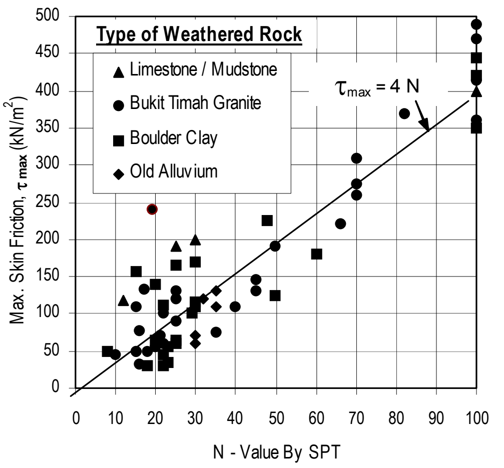


Fig. 7. Relationship between τ_{max} and N-Value

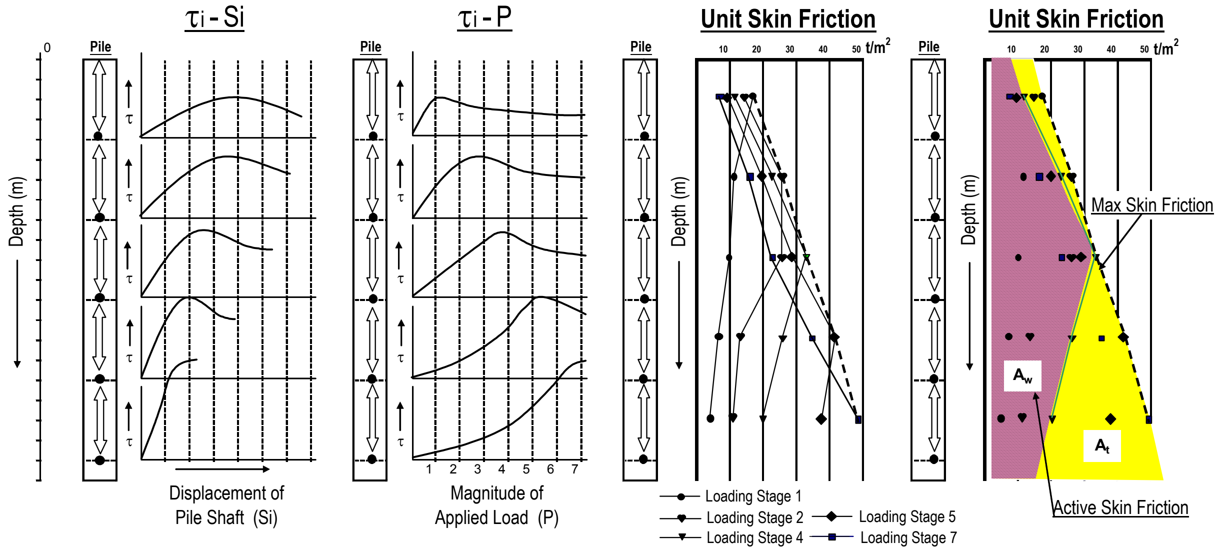
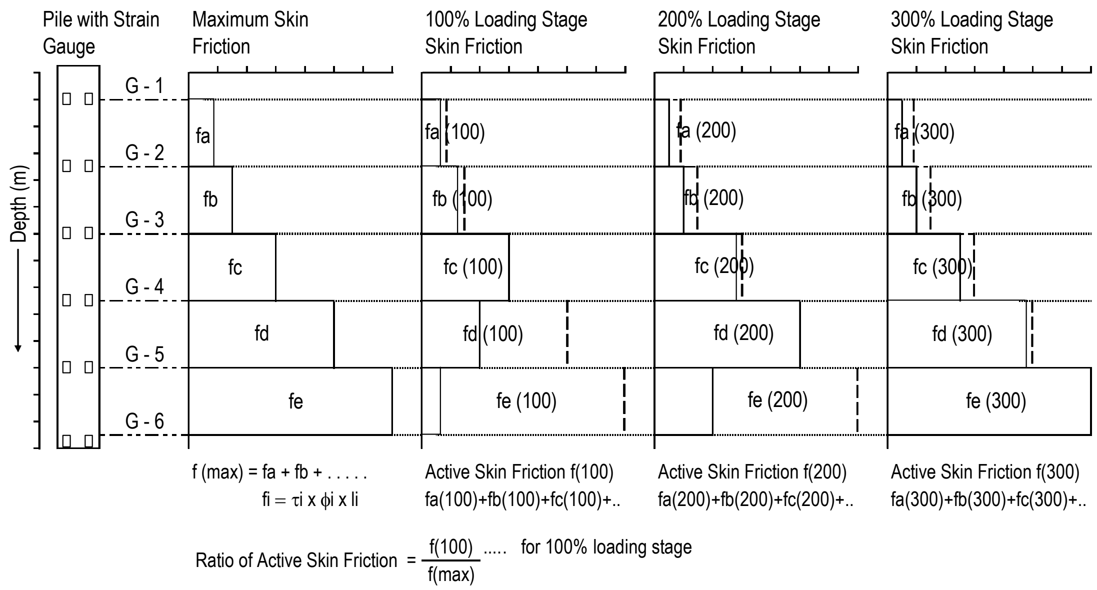


Fig. 8. Magnitude of skin friction under load test



Relatively small displacement - at the soil of big shear strength/large elastic modulus.

Relatively big displacement - at the soil of low shear strength/small elastic modulus.

This relation means the magnitude of displacement is a parameter of elastic modulus of soil.

When the skin friction is monitored during the pile load test, the active skin friction under certain loading stage does not show good relation with shear strength of soil because the skin friction being a parameter of pile shaft displacement.
The active skin friction under increase loading stage is shown in fig. 8.

- º Left figure shows the relationship between the skin friction and the pile shaft displacement at several depths.
- º The second figure shows the skin friction at each loading stage. The load increases from number 1 to 7. The maximum skin friction at each depth generates different loading stage.
- º The third figure shows active skin friction with depth. With the increment of loading, the depth of maximum skin friction shifts downwards and total skin friction increases.
- º The fourth figure shows the relations between the active skin friction at certain loading stage and the maximum skin friction along the pile shaft. As shown in this figure, the skin friction at upper zone is at residual strength stage and lower zone is at the increment stage to maximum strength.

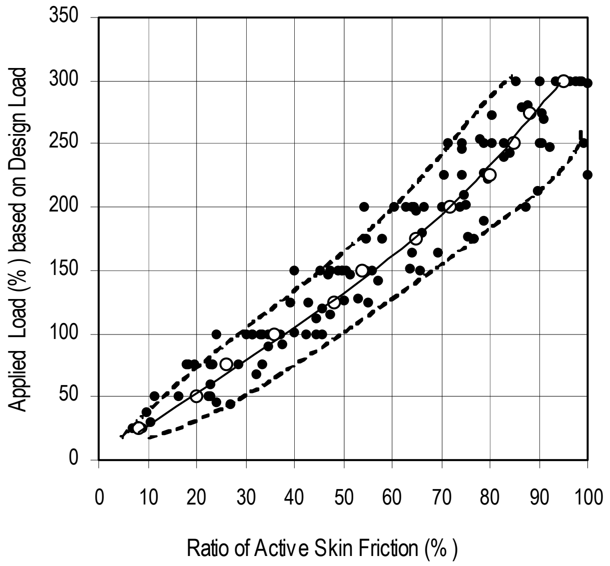
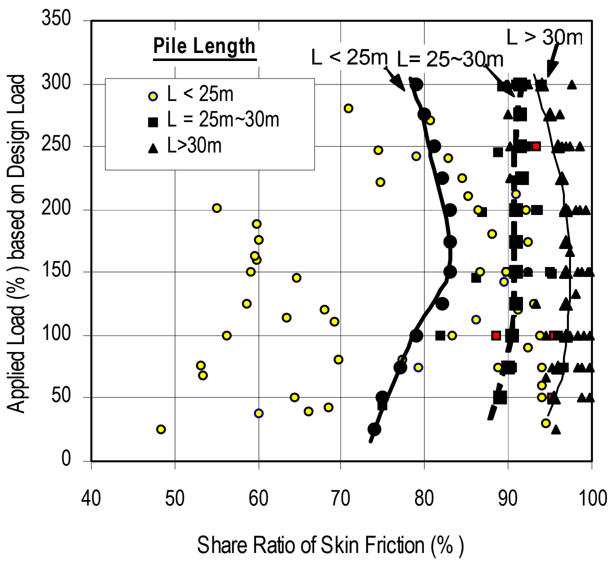


Fig. 10. Active skin friction with increment of load

Active skin friction

Fig. 9 shows the illustration of active skin friction. In fig. 9, the maximum skin friction during 300% loading is shown as f(max). Then the active skin friction at 100% loading, 200% loading and 300% loading show f(100), f(200) and f(300) respectively. The ratio of active skin friction with maximum skin friction is evaluated using each load test data and shown in fig. 10. By this evaluation, the active skin friction is found as follows:
(1) The ratio of active skin friction is not shown 100% of f(max) at any loading stage. The ratio under 300% loading stage is still 95% of f(max).
(2) The ratio of active skin friction under 100% and 200% loading stage is 38% and 73% respectively, which is slightly on the safety side of the actual design.

Table 1 summarises the ratio between maximum skin friction and residual skin friction. The ratio at loose sand of fill material and alluvium formation show less than 50% and at cohesive soil is in the range of 0.7 ~ 0.85. Also, the ratio in weathered rock is in the range of 0.7 ~ 0.95.
The displacement at the moderately strong ~ strong rock near the pile toe is generally small, such as less than 5mm and the correct residual value are not monitored. Due to this, the ratio in weathered rock will change if it can be mobilize up to 10mm.
This range of ratio is almost the same as adhesion factor.



BEARING MECHANISM OF PILE

The share ratio of skin friction in pile bearing capacity is summarised in fig. 11. As shown in this fig. 11, more than 80% of bearing capacity is obtained from skin friction. The share ratio of skin friction increase with longer pile length, such as if pile is more than 30m long, 95% of bearing capacity comes from skin friction. The large share ratio of skin friction is considered to come from the pile deformation which generates maximum skin friction. For example, the total deformation of pile under 300% of design load is approximately as follows:
15m long pile approximately 5.0 ~ 10.0mm
30m long pile approximately 10.0 ~ 20.0mm

If the total pile deformation is 15mm, the maximum skin friction and residual skin friction will take place at most of the depth of pile shaft. If the total pile deformation is 7.5mm, the skin friction at more than 50% of the pile shaft will be under the development stage and the maximum skin friction will not generate in pile shaft.
Another one remarkable point is the share ratio of skin friction will not change by magnitude of loading. It is almost constant under 100% ~ 300% loading for non failure pile. This point suggests that if the failure of bearing mechanism takes place in pile, above constant share ratio will change significantly. Most possible case is the toe bearing cannot generate due to problem of soft toe. But if there is any problem in the skin friction, it also causes the failure of bearing mechanism.

The share ratio shows in this paper is for Singapore's case study. It will change according to the stratigrahic structure of soil layer. Also, the share ratio will change for steel pile which can transfer large stress to pile toe.

In the studied pile load test data, the relationship of settlement and bearing capacity of pile toe material cannot be obtained because settlement is usually small. So the allowable settlement of pile toe and ultimate toe bearing capacity for several types of soil/rock is not found in this study.

DESIGN OF PILE

Based on this study, the following points are recommended to take into the consideration of pile design.

(1) The share ratio of skin friction in total bearing capacity of pile.
The share ratio of skin friction is found as a parameter of pile length. In the pile design, it is better to study the bearing capacity of pile base on the share ratio.
Also the share ratio is understood to depend on the stratigraphic structure of ground material and type of pile. Due to this point, the share ratio shall be further studied for a variety of soils and pile types.

(2) Today, it is difficult to obtain the accurate skin friction from laboratory/in-situ shear test result on hard soil and weathered rock due to the following reasons:
- º There are limits in the accuracy in the laboratory test result which use undisturbed sample from stiff, hard soil and weathered rock, where large skin friction is generated.
  This is according to the disturbance of specimen during sampling, handling and treatment in laboratory.
- º The relations between the skin friction and shear strength of ground material is not clearly analysed. Generally, this relationship is shown as certain index factor and sometimes keeps in the black box.
- º The presence of disturbance and its shear strength of ground material during piling work is not well studied. The shear failure takes place at the weak zone such as the disturbed zone. So the magnitude of skin friction depends on the shear strength of the disturbed zone.

Due to this reason, the skin friction and toe bearing are designed using N value for usual pile design.

(3) For pile design, the monitored skin friction from pile load test is kept in a database for each type of soil, and uses this as guide value. In future, this database can be worked for analysis the bearing mechanism of pile.

CONCLUSION

Through the study of pile load test, the following properties are evaluated.
(1) Skin friction value is not simple/constant and it is generated by pile shaft displacement.
(2) Skin friction has maximum strength at certain displacement. It reduces to residual strength if displacement increases.
(3) The depth of main active skin friction zone is shifted downwards by increase of load.
(4) The active skin friction will not achieve 100% of theoretical skin friction because skin friction is the parameter of pile shaft displacement.
(5) The share ratio of skin friction shows almost constant value however load increase from 100% to 300% of design load. The constant value is related with pile length.

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