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Soil/Pile Set-up Effects on Driven Pile in Malaysian Soil

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ABSTRACT

Bearing capacity of a driven pile often increases with time after its installation. This phenomenon is well known as soil/pile set-up. Although the phenomenon is common and has been reported by many researchers, the increase capacity of pile with time is not always considered in pile design. This is mainly due to lack of understanding about the mechanism behind how principal factors such as soil type, pile material and its installation method affect soil/pile set-up. Pile testing such as maintained load test (mlt) or dynamic pile testing (dpt) is only conducted only after some time after installation. This raises some questions on the rate of pile capacity increase and the length of time after which soil/pile set-up effect becomes insignificant. Although in reality, the capacity increase of pile depends on various factors, the duration of full set-up is assumed to be dependent solely on soil type and rule-of-thumb judgment of the engineer at site is normally practiced. Consideration of the above factors has lead to this study, which has been carried out to investigate the soil/pile set-up as happened in Malaysian soil. Six case studies on soil/pile set-up in Malaysian soil conditions are presented. Pile capacities obtained from tests carried out at different elapsed time after installation are compared in order to further understand the effects of soil/pile set-up on driven pile capacities. Soil/pile set-up factor is back-calculated to understand its effects on Malaysian soil. Time effects on ratio of pile capacity at time, t over initial pile capacity (qt/q-initial) is also discussed at the end of this paper

KEYWORDS: driven pile, elapsed time, soil group, soil/pile set-up factor

INTRODUCTION

History of soil/pile set-up

Soil/pile set-up, a phenomenon of time-dependent bearing capacity increase of driven pile, has gained the attention of researchers, practitioners and even governmental authorities 1, 2, 3, 4, 5, 6. Although there are many advantages to be gained by considering its effects in pile design, soil/pile set-up is however not incorporated in pile design due to lack of full understanding about its mechanisms and how principal factors such as soil type, pile material and its installation method affect soil/pile set-up. If the increment of pile capacity with time is taken into consideration, benefits such as smaller pile section (diameter), shorter pile length, lower capacity of driving equipment required, and subsequently shorter piling duration all of which will definitely lead to overall cost reduction of piling work.

History of soil/pile set-up can be traced back to 100 years ago where it was first mentioned by Wendel[7]. The first well-documented case of pile set-up in non-cohesive soils, not attributable to porewater pressure changes, was presented by Tavenas & Audy 8. Chow et al.[9] performed tension test on open-ended-324mm diameter, steel pipe piles at sand site in France. The result shows that the long-term set-up was normally in the region of 50 to 150 percent of initial pile capacity and that the scatter was very large. Long *et al.*[10] compiled a database of set-up cases, and divided them into three main groups: clayey soil, mixed soil, and sand.

Research by Axelsson[2] showed that similar gains were observed in smaller rods driven into sand. Bowman[11] studied the microscopic and macroscopic response of dense sands under high stress ratios in order to understand the mechanisms of pile set-up. Recently, University of Florida further investigated soil/pile set-up in coastal plain soils up to 4.7 years. The horizontal effective stress against the piles, the effect of soil type, the effect of excess pore water pressure dissipation, were evaluated in the test program 4.

This particular study is conducted to investigate soil/pile set-up factor experienced by Malaysian soil. A total six (6) Malaysian case studies on driven pile are compiled from previous published papers 1, 12, 13. Tested capacities at different time for a particular pile are compared to understand the effects of soil/pile set-up on pile capacity. Soil/pile set-up factor is back-calculated and time effects on ratio of capacity at time t over initial pile capacity ($Q_t/Q_{initial}$) also discussed at the end of this paper.

PHENOMENON OF PILE/SOIL SET-UP EFFECTS

Time-dependent pile capacity increase depends on many factors such as soil grain characteristics, in-situ stress level, pile geometry, chemical processes and pile installation procedure 9, 14, 15. Soil/pile set-up is predominately associated with an increase in shaft resistance. Axelsson[14] and Skov and Denver[16] reported that end bearing capacity changes little in time compared to shaft. As pile is driven, the installation induces major displacement or shear strains on shaft. Such displacement causes the pore water pressure in soil surrounding the pile to increase. In cohesionless soil, the excess pore water pressure dissipated quickly. Excess pore water pressures induced by pile driving seldom exceed 20% of the effective overburden stress 17. Soil/pile set-up taking place in pile in cohesionless soil is thought to be due to the following reasons 15:

(a) chemical effects which may cause the sand particles to bond to the pile surface,

(b) soil ageing effects resulting in increase in shear strength and stiffness with time,

(c) Gain in radial effective stress due to creep effects or relaxation on the established circumferential arching around the pile shaft during installation.

Pile installation in clay is different from pile driving in sand. In cohesive soil, the soil at pile toe is pushed laterally to location at or beyond the pile radius which will lead to shear failure of the soil. The soil in the immediate vicinity of the pile is significantly remolded by the driving process. This generates excess pore water pressure and subsequently causes re-consolidation as the excess pore water pressure dissipates. Pile penetration into clay induced an excess pore water pressure that can be much larger than the initial effective overburden stress 18. After the completion of pile driving and the dissipation of excess pore water pressure, the soil reconsolidates resulting in the increase of effective stress.

Komurka *et al.* (Ref. 3) divided the soil/pile set-up mechanisms into the following three phases:

a) logarithmically nonlinear rate of excess pore water pressure dissipation (phase I),

b) logarithmically linear rate of excess porewater pressure dissipation (phase II) and

c) Independent of effective stress (phase III).

During the initial phase (nonlinear), the rate of porewater pressure dissipation is not constant with respect to the log of time for some periods. The duration of nonlinear dissipation is a function of soil and pile. For example: the less permeable of soil, or the greater volume of soil displaced by pile, will cause the longer duration of nonlinear dissipation. Similar situation happened on the less permeable pile. In phase II, the rate of dissipation becomes constant with respect to log time. The displaced soil will experience an increase in effective vertical and horizontal stresses leading to consolidation and increase in shear strength. In clean sands, dissipation of excess pore water pressure may take place immediately or continue for several hours. On the other hand, longer time is required for full dissipation in the case of cohesive soil. Logarithmically linear dissipation in clay may continue for several weeks, months or even years 16.

The third phase of set-up is known as independent stage of effective stress or ageing. The dissipation of excess porewater pressure becomes very low and infinite time maybe required for the completion of set-up mechanisms. In this phase, set-up rate is independent of effective stress and related to the phenomenon of ageing. Axelsson[19] and Schmertmann[20] mentioned that aging effect increases the shear modulus, stiffness, dilatancy of soil but reduces its compressibility. These three phases of set-up might overlap and more than 1 phase may simultaneously contribute to the development of set-up. However, ageing may not always occur 20. Mechanisms of set-up is shown in Figure 1.

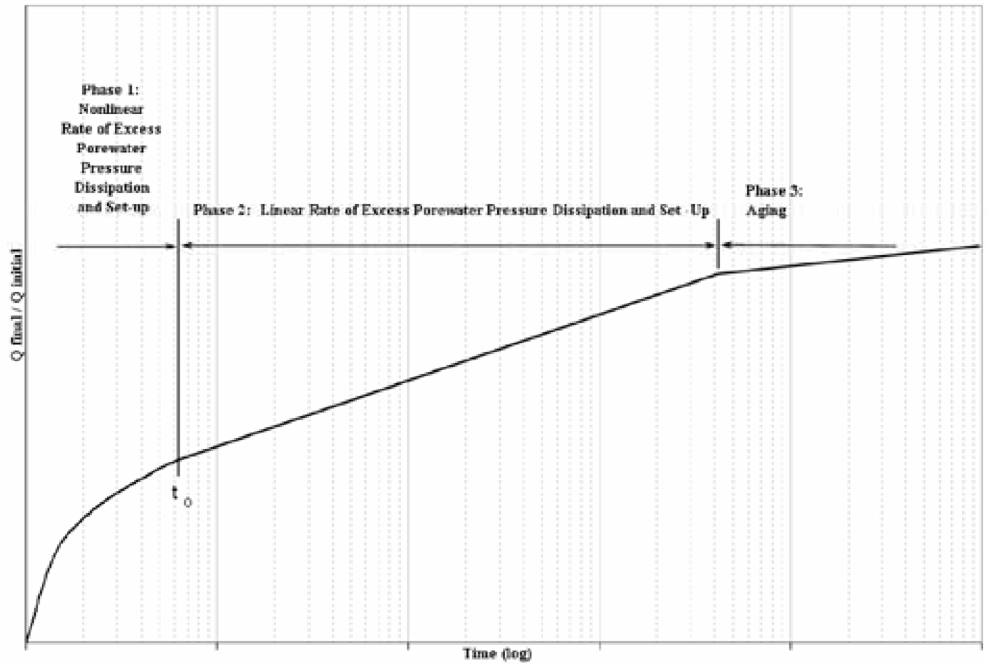

Figure 1: Mechanisms of soil/pile set-up (Komurka *et. al.*, 2003)

Soil/pile set-*up factor, A*

A number of empirical equations have been proposed to quantify the magnitude of soil/pile set-up. Skov and Denver 16 have proposed a dimensionless set-up factor, A, to explain the effect of soil/pile set-up.

$$Q_t = Q_{initial}\,[A\log(\frac{t}{t_{initial}}) + 1] \quad (1)$$

where Q_t= pile capacity at time t; $Q_{initial}$= pile capacity at initial reference time $t_{initial}$; $t_{initial}$ = time at which the rate of excess porewater pressure dissipation becomes uniform; t = time elapsed after initial driving. Factor A represents the relative increase in pile capacity per log cycle of elapsed time.

In the proposed equation as shown in Eq. 1, set-up effect is assumed to be linear with respect to log time. Some researchers suggested that setting of $t_{initial}$ as 1 day seems reasonable 19, 21, 22. Equation (1) was developed based on total capacity of pile (lump shaft and base capacity) and both variables $t_{initial}$ and A are soil type-dependent functions. Determination of set-up distribution along the shaft is required if the correlation between $t_{initial}$ and A to soil type in non-uniform soil is desired. In this paper, it should be noted that A factor is an empirical value which is back-calculated from the total capacity of pile in order to provide technical data about early prediction of set-up effect in Malaysian soil condition.

Equation 23 explained the relationship of set-up for driven pile in soft soils according to its sensitivity. Similarly, 24 presented a formula to predict set-up rate in soft soil in Shanghai while 25 proposed an empirical relationship of set-up in sand using load test data. These formulas (23, 24, 25) were developed based on total pile capacity which includes the instantaneous capacity at end-of-drive, Q_{EOD} , which can be determined by dynamic monitoring. Formulas on soil/pile set-up by the above 3 researchers are summarised in Table 1.

Table 1: Soil/pile set-up empirical formulae

Author	Empirical Formula	Soil Type	Eqn
Guang-Yu (1988)	$Q_{14} = (0.375S_t + 1)Q_{EOD}$ Where St = sensitivity of soil; Q14 = pile capacity at 14 days	Fine grained soil	(2)
Huang (1988)	$Q_t = Q_{EOD} + 0.236[1 + \log(t)(Q_{\max} - Q_{EOD})]$ Where Qt = capacity at time t; QEOD = capacity at EOD; Qmax = maximum capacity	Soft soil	(3)
Svinkin (1996)	$Q_t = 1.4Q_{EOD}t^{0.1}$ upper bound $Q_t = 1.025Q_{EOD}t^{0.1}$ lower bound	Sand	(4) (5)

CASE STUDY

Background of case study

A total 6 Malaysian case studies (CS) were abstracted from the published papers 1, 12, 13. Analysis was carried out to investigate the soil/pile set-up. All six cases were from projects were located in peninsular Malaysia; three (3) cases from Selangor State (CS1, CS3, CS6) which neighbouring with Kuala Lumpur, and one (1) case from each state like Kuala Terengganu in Terengganu State (CS2), Ipoh in Perak State (CS4) and Kota Bahru in Kelantan State (CS5) respectively.

The geological formation of each project varies according to their geographically location. In Kelantan and Selangor, period of these regions is known as Quaternary where the major soil types are marine and continental deposits, such as silt, sand and peat with minor gravel. The bedrock level is usually very deep and it is commonly known as Kenny Hill formation especially in Selangor area. The major geological formation of Terengganu is intrusive acidic igneous bedrock. The deposits are mainly composed of phyllite, slate, shale and sandstone. Bedrock type in this region is commonly known as carbonaceous. Period in part of Perak is known as Cretaceous. The continental deposits consist of thick, cross-bedded sandstone with subordinate conglomerate and shale or mudstone. Geological map of Peninsular Malaysia is shown on Figure 2.

Figure 2: Geological map of Peninsular Malaysia

Subsurface investigation

Standard Penetration Test (SPT) was used to obtain the relevant soil properties and parameters in the above case studies. Information likes soil profile, relative density or consistency as well as SPT N values are compiled and presented in Figure 3 and Figure 4.

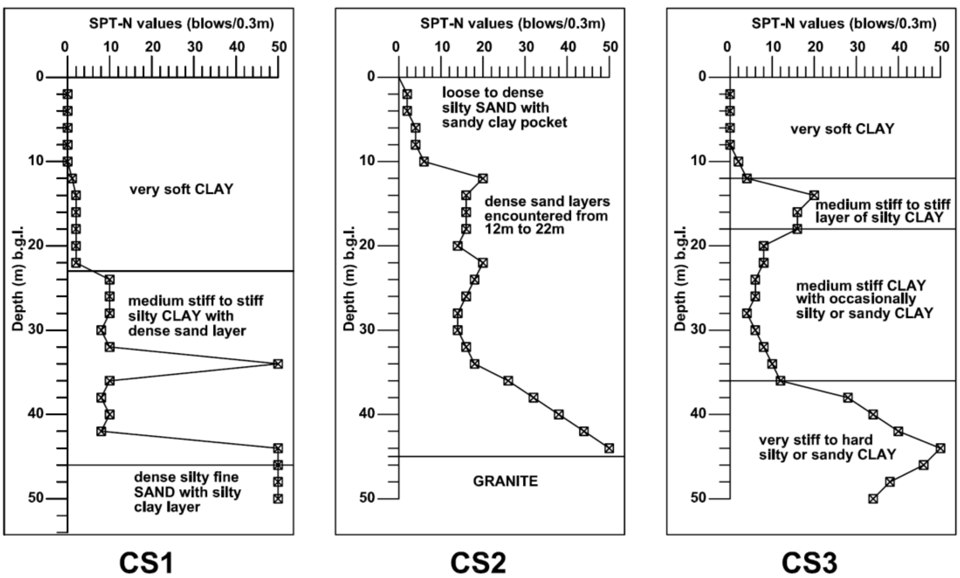

Figure 3: Typical subsoil profile of CS1, CS2 and CS3

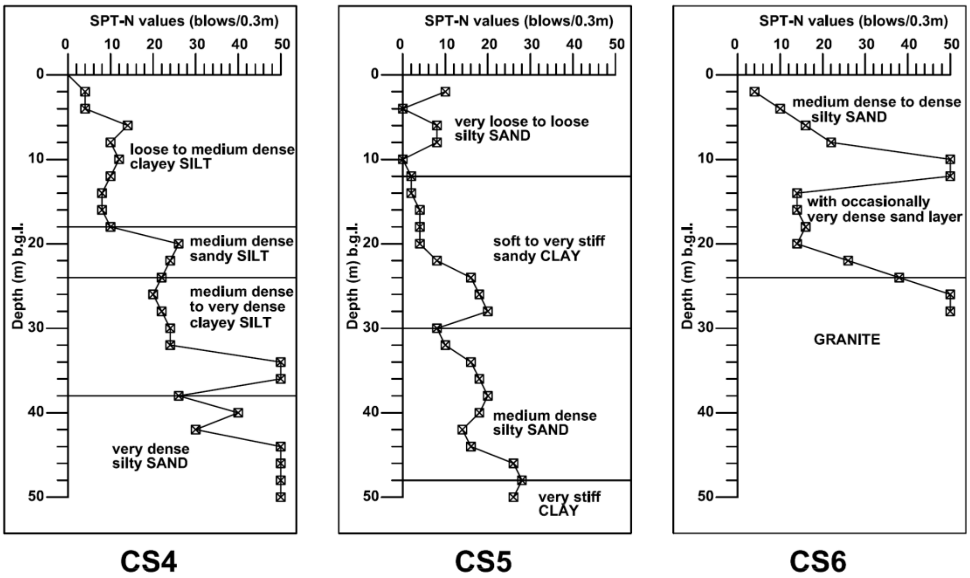

Figure 4: Typical subsoil profile of CS4, CS5 and CS6

RESULTS AND DISCUSSION

Piling Information

Data for a total 11 numbers of test piles which namely as P1 to P11 from the case studies are abstracted for further analysis. P1 and P2 abstracted from CS1, P3 from CS2, while P4 to P7 from CS3. Pile P8 from CS5, P9 and P10 from CS 5 and the last P11 from CS6. Two types of pile are found to have been used : reinforced concrete square pile (RC) and spun pile. RC square pile is in the size of 200 – 400mm while that of spun pile is in the range of 250 – 500mm in diameters. Method of pile installation used is hydraulic hammer drive. Information such as hammer type, hammer lifting height, and pile set measurement are summarized in Table 2.

Table 2: Test pile information

Case Study	Pile Ref	Pile type/ size (mm)/ length (m)	hammer (ton) / drop height	Pile set (mm/blow)
CS1	P1	RC/400/57.5	7 ton / 1m	8mm/blow
	P2	RC/400/47.5	7 ton / 1m	13mm/blow
CS2	P3	RC/200/36	3 ton	n.a.
CS3	P4	Spun/250/33	n.a.*	n.a.
	P5	Spun/250/35.5	n.a.	n.a.
	P6	Spun/250/14.5	n.a.	n.a.
	P7	Spun/250/23.5	n.a.	n.a.
CS4	P8	Spun/400/28.5	7 ton / 0.9m	1.8mm/blow
CS5	P9	RC/400/48.5	n.a.	0.8mm/blow
	P10	Spun/450/56.4	n.a.	1.1mm/blow
CS6	P11	RC/500/24.6	7 ton / 0.8m	1.0mm/blow
* n.a.: not available				

The shortest pile length is 14.5m in CS3. Such short length might be due to the existence of stiff layer found at depth 12 – 18m b.g.l. as shown in Figure 3. Pile in CS1 has the longest length of 57.5m and the corresponding pile set is 8mm per blow. Details of other piles can be found from the same table except P3 to P7, where the hammer drop height and pile set criteria were not mentioned from the original paper. Pile P9 and P10 also lacked of hammer drop height. However, the information is less important in this particular study.

Pile testing result

Generally, two types of pile tests were carried out in order to verify the pile capacity. They are dynamic pile test, (DPT) and Maintained Load Test (MLT). In general, MLT is performed until pile failure or 2 times of the working load of pile whichever comes first; While for DPT, CAPWAP, a signal matching analysis is used to assess the pile capacity after testing. Elapsed time of pile test, pile capacity, type of pile test as well as the test criteria are shown in Table 3. A minimum of two tests were performed on each pile. Some piles were tested at the end of driving such as P4, P5 and P11 while others were tested at different days after installation as can be seen in Table 3. The longest elapsed time of 148 days was observed in the case of pile P3 of CS2. The results of pile test are also shown in Table 3.

Table 3: Pile testing results

Pile Ref	Elapsed time (days)	Test Load (kN)	Type of test / test criteria
P1	3	3963	DPT / n.a.
	19	5121	DPT / n.a.
P2	7	411	DPT / n.a.
	33	475	DPT / n.a.
P3	41	330	MLT / 12mm displacement
	148	400	MLT / 12mm displacement
P4	EOD	137	DPT / n.a.
	8	910	DPT / 14.2mm
P5	EOD	138	DPT / 5.7mm displacement
	26	600	MLT / 15mm displacement
	29	956	DPT / 15mm displacement
P6	23	250	MLT / 2.5mm displacement
	26	340	DPT / 4.5mm displacement
P7	19	400	MLT / 5mm displacement
	22	593	DPT / 8mm displacement
P8	9	1600	MLT / 15mm displacement
	19	2080	DPT / 15mm displacement
P9	12	2600	MLT / 15mm displacement
	24	3150	DPT / 15mm displacement
P10	15	2150	MLT / 15mm displacement
	50	2500	DPT / 15mm displacement
P11	EOD	2250	DPT / 15mm displacement
	9	3400	MLT / 15mm displacement
* n.a.: not available			

The changes of pile capacity with time

Plot of pile capacities versus elapsed time in logarithmic scale is shown in Figure 5. A trend of capacity increased with time is observed. In this study, each test pile has only two tested results. Such restricted number of data poses difficulty in the determination of relation between the trend of increase, linear or non-linear, of set-up rate with respect to logarithmic time. This point is further explained in section '**Time effect on Qt/Qinitial ratio, A**'. For the purpose of graph plotting in log scale, results for piles tested at EOD are assumed as data at one day after installation.

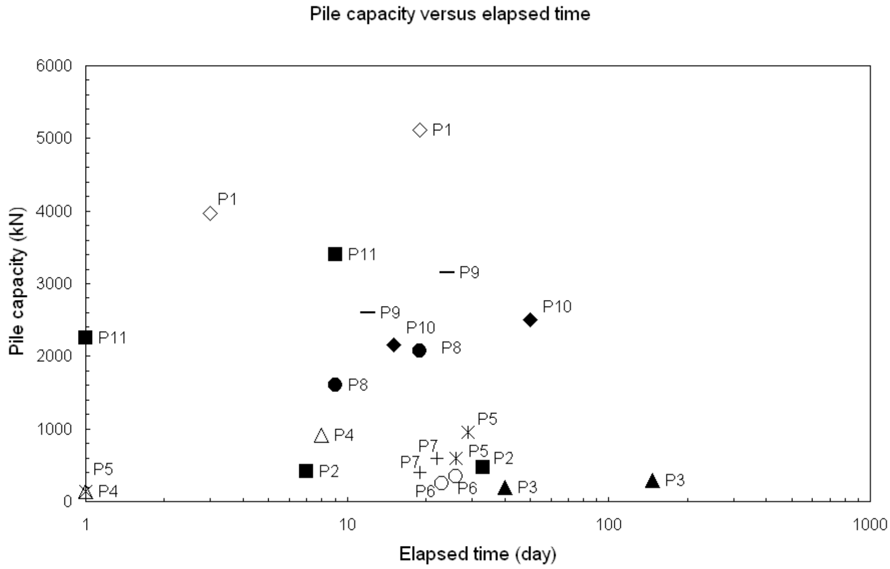

Figure 5: Pile capacity versus logarithm elapsed time

The capacity obtained from pile tests includes contribution from both end bearing and shaft friction. Research studies have shown that soil/pile effect occurs more on pile shaft. Study by 4 showed that the base capacity of pile remained unchanged and not affected by time. Hence, it is generally believed that the increase in capacity with time is mainly due to the effects of soil/pile set-up on shaft friction. It should also be pointed out that besides soil/pile setup, other factors might also contribute to the increase in pile capacity. Factors such as overestimation of pile capacity, chemical effects, ageing effect, creep effects have been highlighted in past research works.

Dimensionless Set-up Factor, A

Set-up factor, A for each test pile is back-calculated based on the equation (1). Some assumptions have been made during the calculation is done. (a) no segregation of shaft capacity from lump capacity in the above calculation, (b) the set-up state for all the test pile is assumed in linear state of logarithm time. (c) pile tested at EOD is assumed happened at 1 day for the purpose of calculation. Besides, Q initial is estimated based on the same equation which later to be referred as $Q_{initial}$ to check the relationship of $Q_t/Q_{initial}$ in log time.

In Table 4, calculation results show that A factor ranged between 0.09 to 6.25. The minimum A factor happened at P8 which is a 400mm diameter spun pile with length 28.5. While maximum A factor 6.25 happened at P4 which is spun pile, 250mm in diameter and embedded length of 33m. P8 should have recorded the highest A factor based on equation 1, but authors encounter that the calculated $Q_{initial}$ is unreasonable low. In this case, the A and $Q_{initial}$ is recalculated based on static formula and the result is more reasonable. Similar problem happened on P6, P7 and P9. No A factor suggested for P7 since the calculated pile capacity is higher than the test result. This is maybe due the soil profile happened at P7 is slightly different from the soil profile presented at Figure 3.

One of the reasons of the capacity increase with time is due to the set-up phenomena. Soil type is believed also playing its role in the magnitude of set-up. The lowest set-up A factor happened on pile (P8) installed in silt deposits while highest value is P4 installed in clay deposit. Other than set-up effects, other factors should not also be neglected in the variation of A values. Reasons like capacity lump in one (no segregation of shaft capacity from the total pile capacity), uncertainty on soil/pile set-up state, different method to assess pile capacity, etc. would alter the A factor. Anyhow, finding of this paper is useful to reveal an early prediction on soil/pile set-up happened in Malaysian soil

Table 4: Calculated set-up factor and Q initial based on Equation 1

Pile Ref	Set-up factor A	Calculated Q initial, $Q_{initial}$ (kN)
P1	0.44	3274.1
P2	0.28	330.8
P3	0.99	125.7
P4	6.25	137 (from EOD result)
P5	2.37(based on Q_{26})	138 (from EOD result)
	4.05(based on Q_{29})	
P6	(0.31**)	(235.3*)
P7	-	(661.8*)
P8	7.84; (0.09**)	188.7 (1863.9*)
P9	2.91; (0.18**)	628.5 (2520.7*)
P10	0.49	1363
P11	0.54	2250

(*) Pile capacity is calculated based on the following static empirical formula:
a) Pile at cohesionless soil : shaft friction resistance = 2.N.A_s; toe resistance = 400.N.A_p; where N = standard penetration test, blow number per foot, A_s = shaft area of pile; A_p = toe cross section area. (Meyerhoof, 1976)
b) Pile at cohesive soil : shaft friction resistance = c_u.A_s; toe resistance = 9.c_u.A_p; where, = adhesion factor ; c_u = undrained cohesive shear strength, and interpreted by c_u = 4N – 6N (Stroud & Butler, 1975) if N > 5 or cu = 5+7.5N when N <5 (Japanese Road Association, 1980)
(**) Soil/pile set-up factor is calculated based on the capacity predicted by static formula*

Time effect on $Q_t/Q_{initial}$ ratio, A

Effect of elapsed time towards $Q_t/Q_{initial}$ ratio is investigated in this section. In figure 6, relationship between $Q_t/Q_{initial}$ ratio and elapsed time in logarithm scale is shown. Generally, the result shows the $Q_t/Q_{initial}$ ratio increase in logarithm time. From the figure, a best line is drawn based on the available results and found that the $Q_t/Q_{initial}$ ratio is low at the beginning and increased rapidly after that. This phenomenon is against the assumption that relationship of set-up over time is logarithmically linear. Few reasons might affected the above $Q_t/Q_{initial}$ relationship such as dissipation of excess porewater pressure at cohesive soil take longer time to become logarithm linear compared to cohesionless soil, the non-uniform soil profile might affect the setup states overlapped in time or the tested pile capacities might not accurate enough.

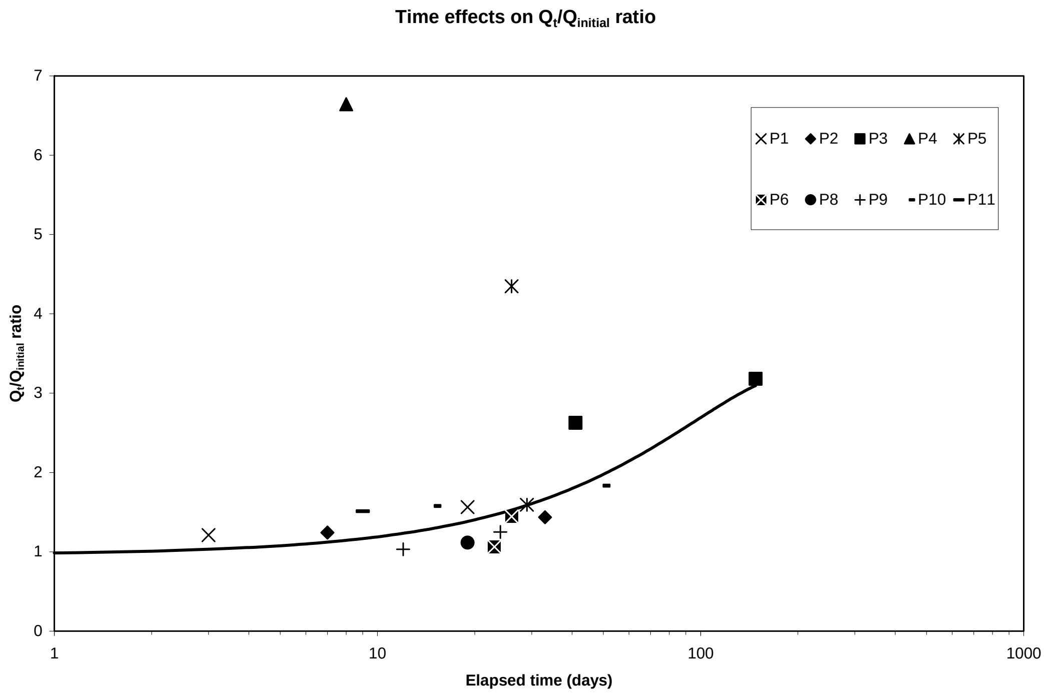

Figure 6: $Q_t/Q_{initial}$ versus logarithm elapsed time

SUMMARY AND CONCLUSION

A total 6 case studies (CS) and 11 numbers of test piles (P1 – P11) are presented in this paper to investigate from the aspect of soil/pile set-up. All the projects located in peninsular Malaysia. Two types of pile used in the cases such as RC square pile (with size 200 – 400mm) and spun pile (with diameter 250 – 500mm). Method of pile installations are hydraulic hammer drive.

The results shown that the back-calculated A factor from lump capacities are ranged from 0.09 – 6.25. Set-up effect is believed one of the factors which increase the pile capacity with time. Other factors might also alter the pile capacity like overestimation of pile capacity, chemical effect, soil ageing or creep effect. The A value is calculated from lump resistance and which may not able reveal the actual situation of soil/pile set-up which happened on the pile. A factor could be refined if segregation of shaft capacity, from lump capacity is done. Anyway, authors believed that the back-calculated A factor could give some early prediction and feeling about set-up effects happen on Malaysian soil.

About the $Q_t/Q_{initial}$ ratio, increment trend with time is observed. This phenomenon is slightly against the assumption where the set-up is assumed in linear or $Q_t/Q_{initial}$ is increased linearly if in log time. Factors like pile not mobilized fully during test, overestimation of pile capacity, overlapped of set-up states are believed have contributed to the non-linear set-up states in log time. As a conclusion, set-up effect is playing a role on time-dependent capacity of driven pile in Malaysian soil. Quantifying of set-up magnitude on pile design is possible if proper investigation on set-up factor is done and subsequently it brings more merit to the relevant industry.

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