JACK-IN PILE IN MALAYSIA: A MALAYSIAN CONSULTANT'S PERSPECTIVE

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Abstract: *Jack-in pile foundation has been successfully adopted in Malaysia since late 1990s and currently, large diameter spun piles up to 600mm in diameter with working load up to 3000kN have been successfully adopted for high-rise buildings of up to 45-storeys. This paper summarises some Malaysian experience in design and construction of high capacity jack-in pile systems based on results of maintained load tests and settlement monitoring carried out on completed structures. Recommendations on empirical correlations between ultimate shaft resistance (f_{su}) and ultimate base resistance (f_{bu}) with SPT'N' are also presented. Comparison is made with existing correlations which are based on conventional driven pile systems.*

1. INTRODUCTION

Jack-in pile foundation has been successfully adopted in Malaysia since late 1990s and currently, large diameter spun piles of up to 600mm diameter with working loads of up to 3000kN have been successfully adopted for high-rise buildings of up to 45-storeys. The popularity of jack-in pile foundation systems especially for construction works in urban areas is due to their relatively lower noise and lower vibration compared to conventional piling systems such as driven piles. Jack-in pile foundation also offer advantages in terms of faster installation rates, better quality control, less pile damage and cleaner site conditions as it does not require the use of stabilizing liquid/drilling fluid typically associated with bored piles and micropiles. In practice, piles installed using the jack-in method are expected to be shorter than driven piles. This is because driven piles are often driven to greater length than is truly necessary due to the uncertainties associated with their geotechnical capacity during driving. However, jack-in piles are jacked to the specified capacity and therefore, result in savings without compromising the safety, serviceability requirements and integrity of the pile foundation. However, like all available pile systems, jack-in pile system also have its drawbacks, such as the need for a relatively stronger platform to support large and heavy machinery and a generally larger working area to install the piles. However, the drawbacks can be managed if the designer is aware of these limitations. Jack-in pile foundation systems have been successfully adopted in congested condominium developments, piling works at different platform levels with limited working space and works carried out at lower ground level associated with basement construction.

Figures 1 and 2 show a typical high capacity jack-in pile machine for 600mm diameter spun pile in Malaysia and a schematic of the machine respectively. Table 1 summarises some key technical data for the machines.

In this paper, a review of current design and construction practice adopted in Malaysia for jack-in pile foundation based on about 20 years of experience together with extensive load test results are presented.

Figure 1: Typical high capacity jack-in pile machine in Malaysia.

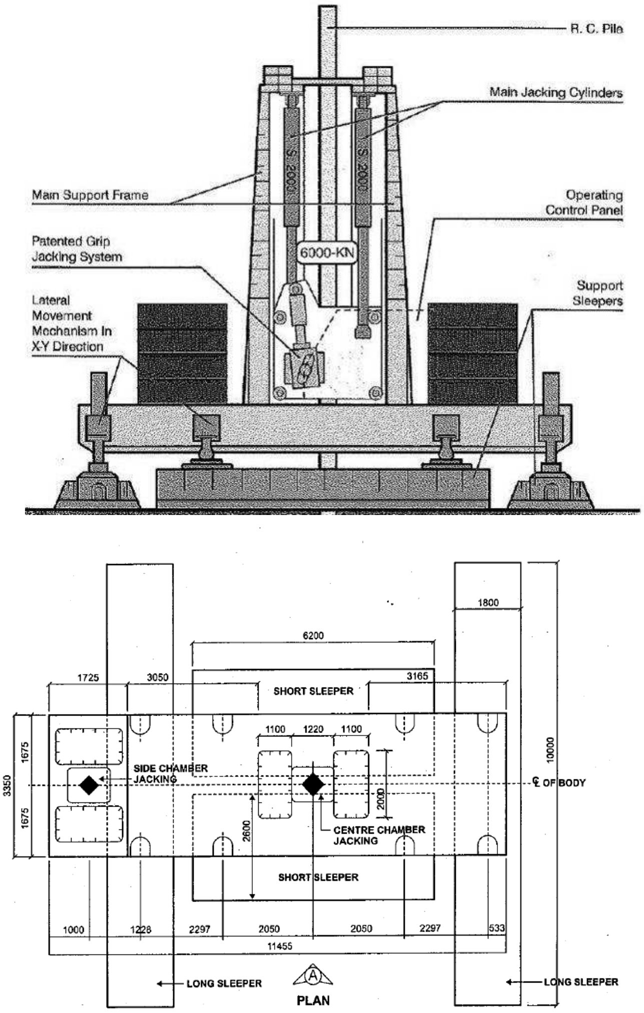

Figure 2: Typical schematic of high capacity jack-in pile machine.

Table 1: Key technical data of high capacity jack-in pile machines.

ITEM	TECHNICAL DATA
Maximum Jacking Force	6000kN (Practical limit)
Applicable Spun Pile Diameter	250mm to 600mm
Applicable RC Square Pile Size	250mm to 400mm
Self Weight (Excluding counterweight)	178t to 200t
Overall dimension (Length x Width x Height)	11.1 x 10.0 x 9.1 13.55 x 12.0 x 7.44
Minimum clearance required for piling works (Centre jacking)	5.5m to 6.9m
Bearing pressure on sleeper	Up to 175kN/m^2

2. REVIEW OF GEOTECHNICAL CAPACITY FOR JACK-IN PILES

Professor Mark Randolph in 2003 presented the 43rd Rankine Lecture titled "Science and empiricism in pile foundation design" (Randolph, 2003) in which he highlighted the importance of residual pressures locked in at the pile base during installation in mobilization of end-bearing resistance. For bored piles, with initially zero base pressure at zero displacement, end-bearing pressure can only be mobilised at relatively large base displacement. However, for driven and jacked piles, significant residual pressures are locked in at the pile base during installation (equilibrated by negative shear stresses along the pile shaft, as if the piles were loaded in tension) (Randolph, 2003). As such, jack-in pile is expected to mobilise higher end-bearing resistance at working load compared to driven piles. This is because the magnitude of residual pressures for jack-in pile is expected to be even greater compared to driven piles.

Beside higher end-bearing resistance at working load, the mobilised shaft friction for jack-in piles is also expected to be higher based on White & Lehane (2004). White & Lehane (2004) investigated the phenomenon of decrease in shaft friction in a given soil horizon as the pile tip penetrates to deeper levels or commonly known as friction fatigue. Some of the key findings from their research include:

a) A greater number of cycles imposed during pile installation leads to a larger reduction in shaft friction at a given soil horizon. Figure 3, which compares the normalised horizontal stress along the pile shaft with different installation cycles using jack-in and pseudo-dynamic methods clearly shows the reduction in horizontal stress (and hence, shaft friction) along the pile shaft with the increase in installation cycles.
b) Amplitude of the installation cycles also affects friction fatigue.
c) Two-way cycling (e.g. vibro-hammer) leads to a greater degradation than one-way cycling.

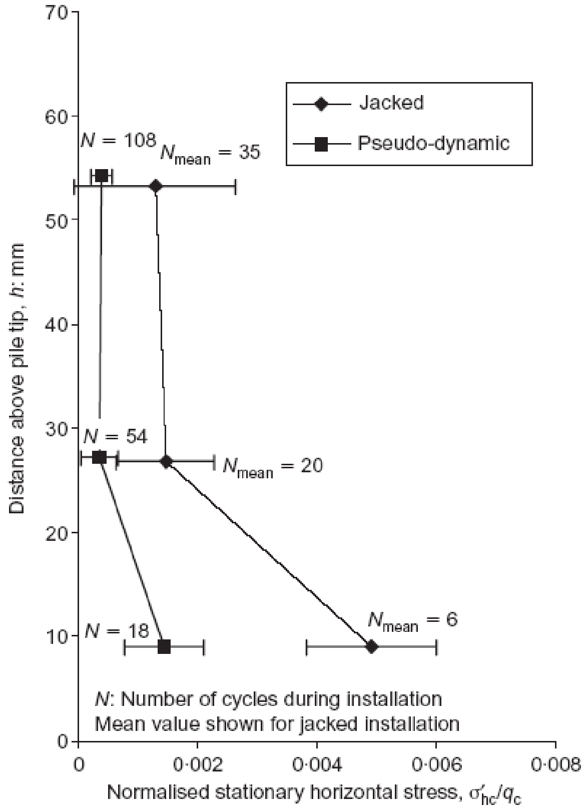

Figure 3: Influence of loading cycles during installation on stationary horizontal stress (White & Lehane, 2004).

In conclusion, White & Lehane (2004) state that "Modern installation techniques of pile jacking involve reduced cycling, and may therefore yield higher shaft friction than conventional dynamic installation methods".

Deeks, White & Bolton (2005) also presented the response of jack-in displacement piles in sand using the press-in method which is similar to the jack-in method described in this paper. The conclusions from Deeks, White & Bolton, 2005 are:

a) The measured jacking force during installation indicates the plunging capacity of the pile.
b) Jacked piles have a high base stiffness, due to the preloading of the soil below the base during installation, and the presence of residual base load.
c) The stiffness of jacked piles exceeds typical recommended design stiffnesses for driven and bored piles by factors of more than 2 and 10 respectively.

3. CASE HISTORIES

3.1 The first project

The Authors' first experience in the use of jack-in piles in 1999 is in a very challenging site. The site is located on a former municipal dumping site with mine tailings overlying limestone formation!

Figure 4 shows typical borelog profiles across one of the tower blocks of the proposed apartment (16-18 storeys). Prestressed spun piles of up to 450mm diameter with working load of 1500kN were successfully adopted for this project.

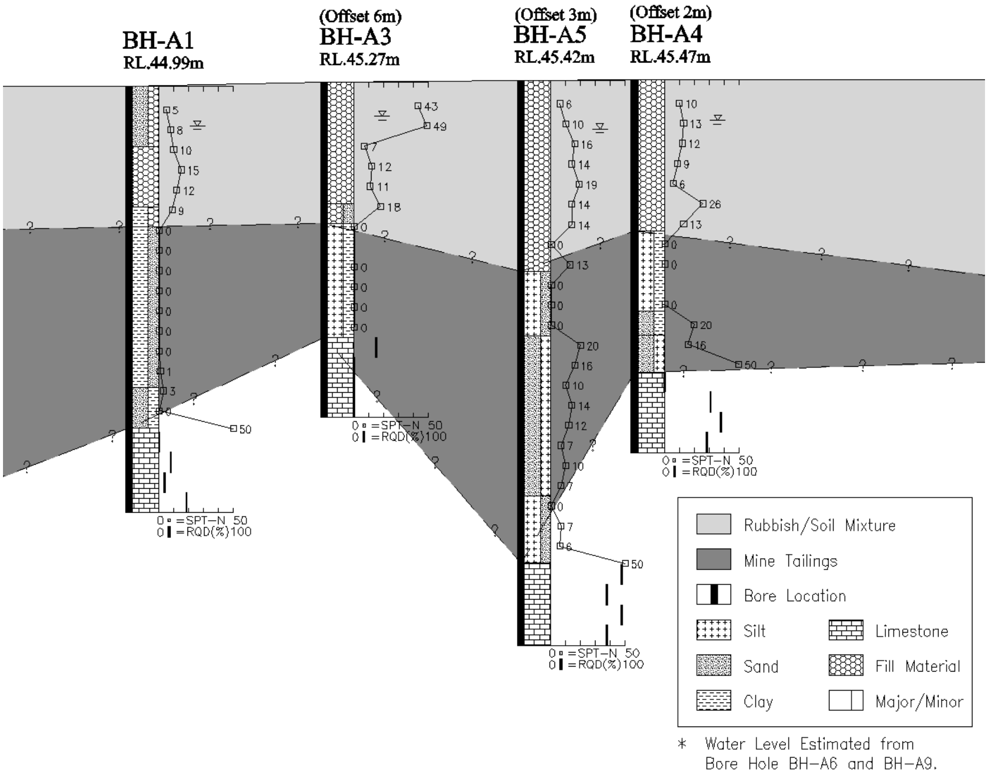

Figure 4: Typical borelog profiles showing rubbish/soil mixture with mine tailings overlying karstic limestone bedrock.

Static maintained load tests carried out at the site show satisfactory performance of the jack-in piles and some load test results are summarized in Table 2.

Table 2: Load test results for jack-in pile in former municipal dumping site with mine tailings overlying limestone bedrock.

Pile Diameter (mm)	Settlement (mm)		Remarks
	Working Load	2*Working Load	
450	9.9	25.7	Residual settlement after unloading from working load = 1.6mm
450	5.2	28.8	Residual settlement after unloading from working load = 0.2mm

From the sample load test results, it can be observed that the pile performance is satisfactory even for such difficult site conditions. It can be seen that the pile settlement at working load is acceptable. The larger settlement at two times working load is expected as the pile is designed for a factor of safety of 2.0 in the first place, i.e. pile ultimate capacity is reached at two times working load.

From that first challenging project in 1999, high capacity jack-in pile has been adopted in various projects in the urban area of Kuala Lumpur and Selangor. Some of the recent projects carried out in Granite formation are discussed in the following sections.

3.2 Case histories in Granite formation

Maintained load test results for four different sites in Mont Kiara, Kuala Lumpur and Subang, Selangor are available to assess the performance of the jack-in pile foundation system. The four different sites are as follows:

a) Site A – 31-storey condominium (high-rise apartment) development
b) Site B – 45-storey condominium (high-rise apartment) development
c) Site C – 40 to 43-storey condominium (high-rise apartment) development
d) Site D – 15-storey condominium (high-rise apartment) development

Figure 5 shows actual view of the condominium tower of Site B which was recently completed and handed over to purchasers.

Figure 5: Competed condominium towers of Site B.

In general, all the four sites are underlain by Granite formation with overburden materials mainly consisting of silty SAND/sandy SILT with variable thicknesses. Typical borehole profiles for the sites are shown in Figures 6, 7, 8 and 9.

Subsoil conditions of all the four sites typically consist of weathered granite formation with SPT-N increases with depth. Boulders were also encountered during subsurface investigation and actual piling works. The presence of the boulders was expected in such weathered granite formation. Due to the presence of boulders and intermediate hard layers, some preborings were also carried out to facilitate pile installation works (Figure 10).

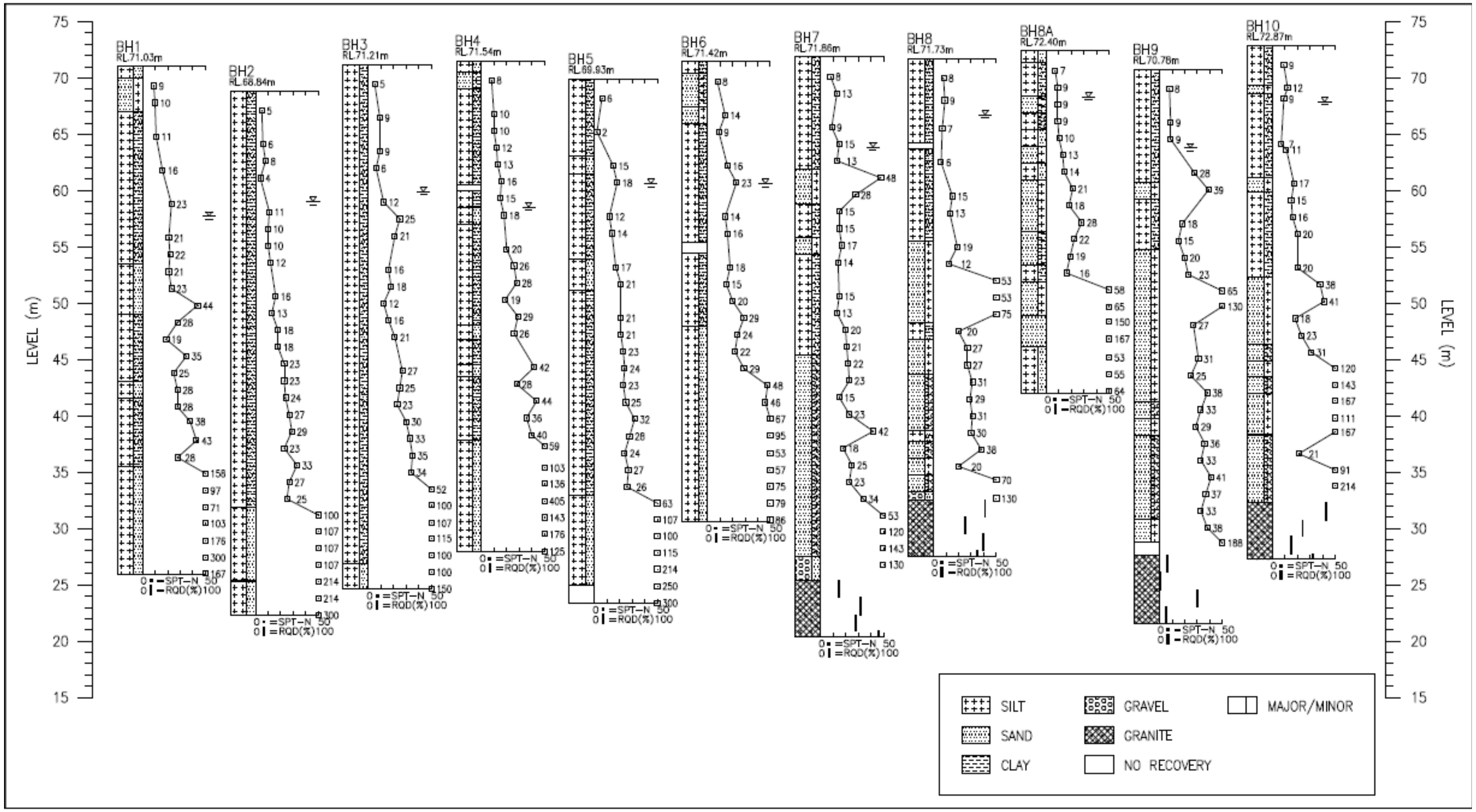

Figure 6: Borehole profiles at Site A.

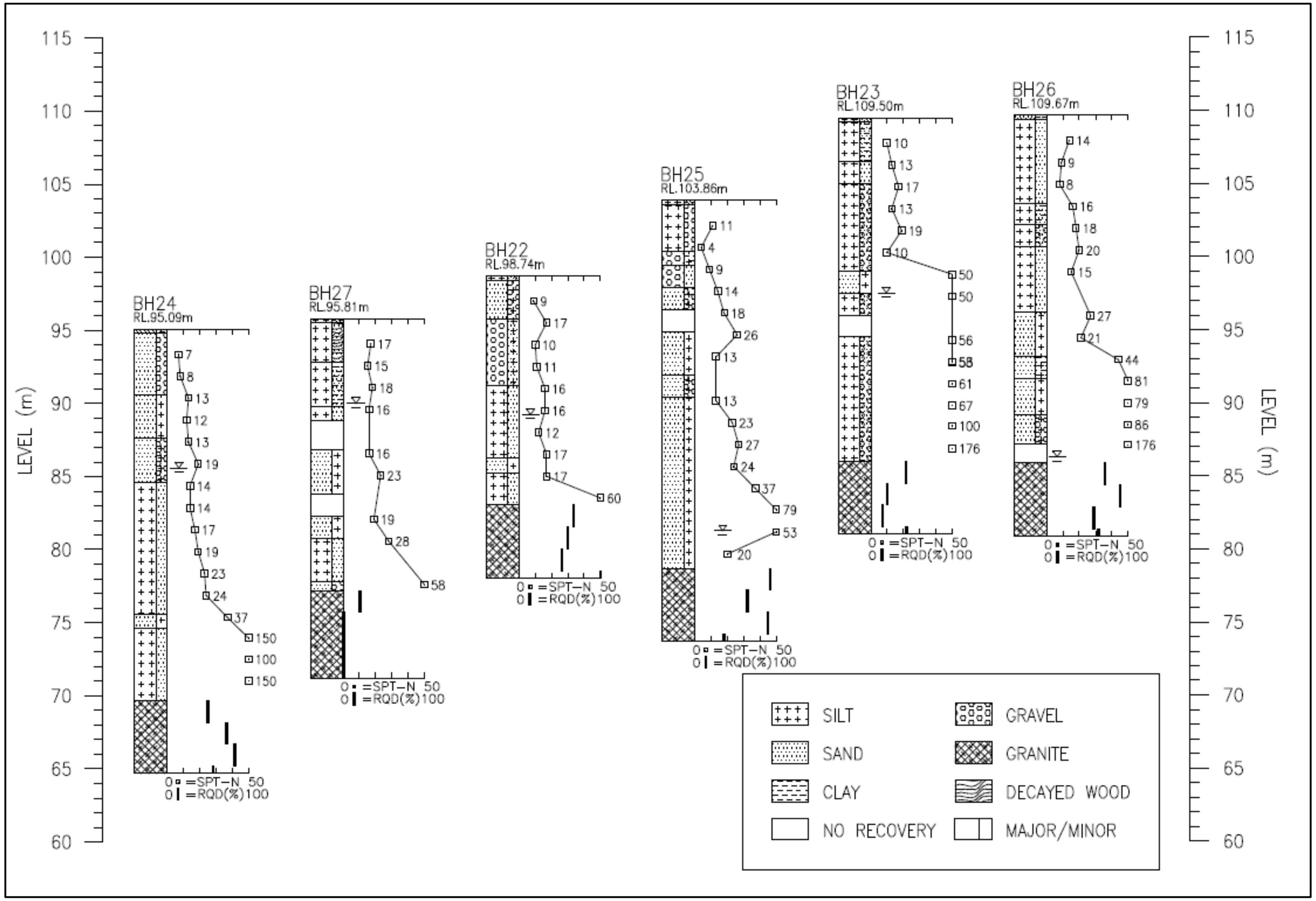

Figure 7: Borehole profiles at Site B.

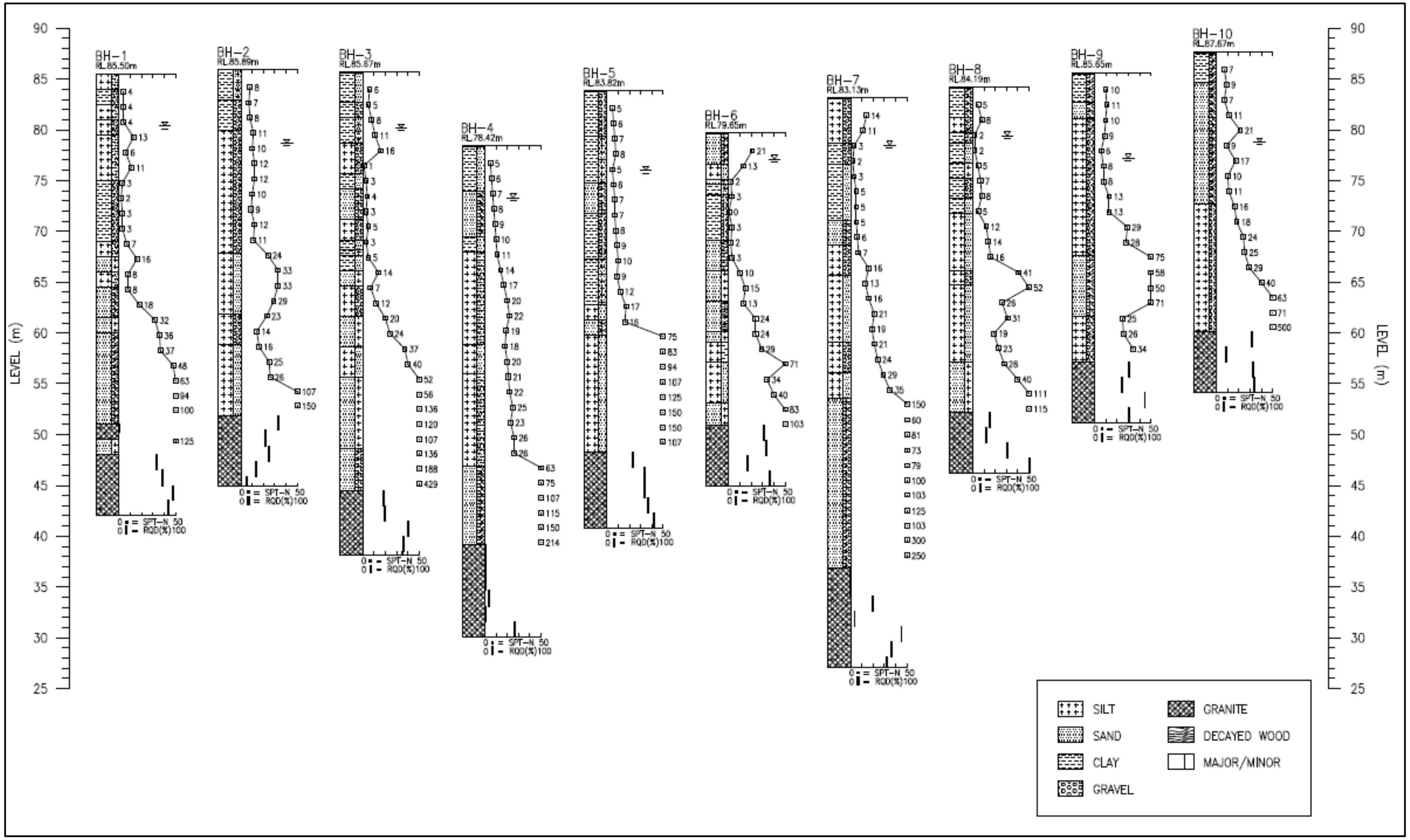

Figure 8: Borehole profiles at Site C.

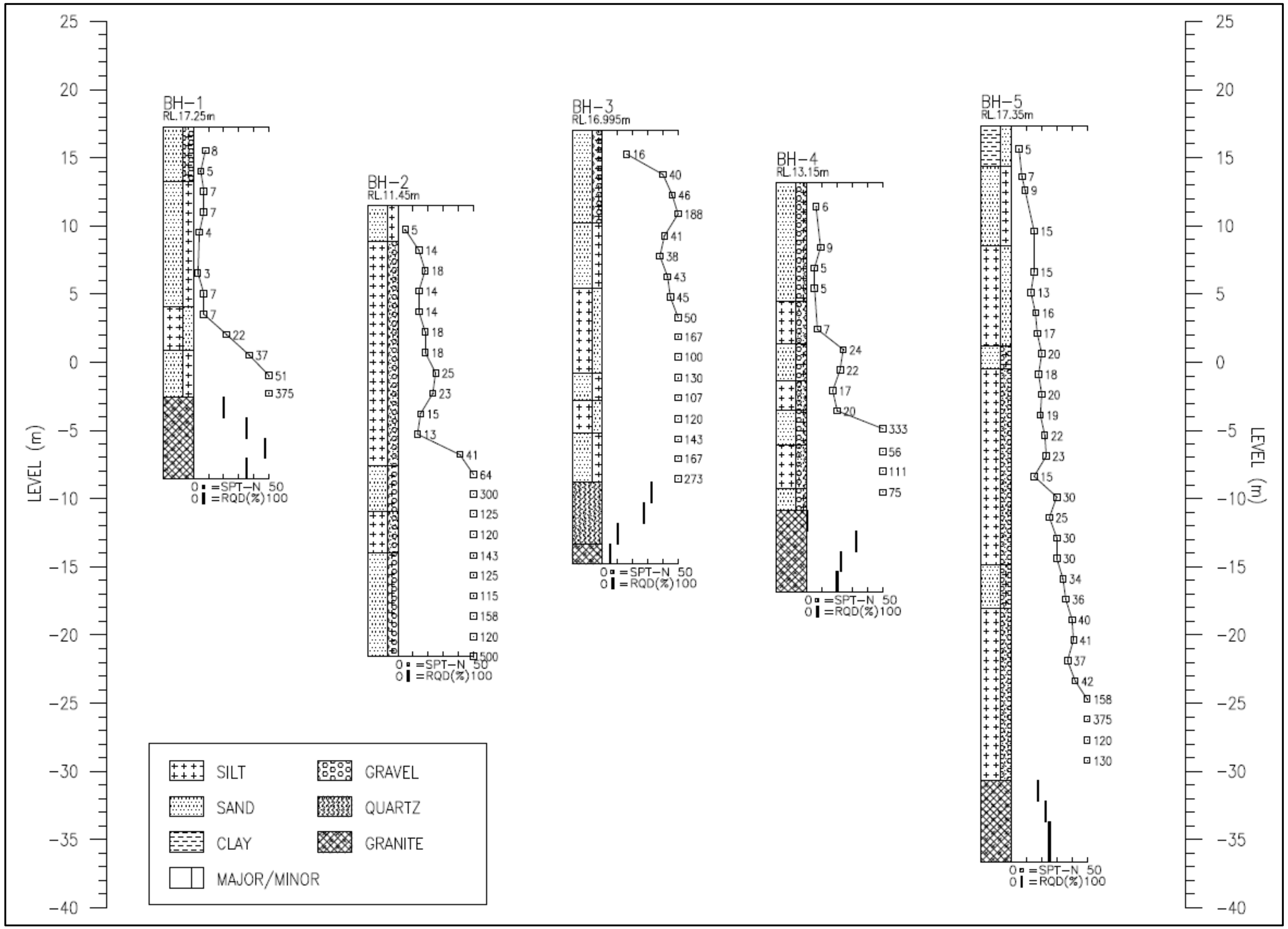

Figure 9: Borehole profiles at Site D.

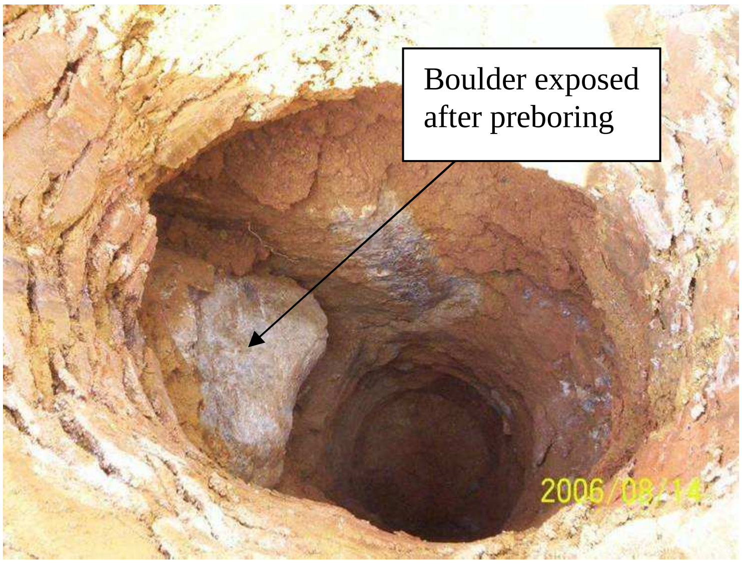

Figure 10: Boulders detected at Site B.

Details of the jack-in pile adopted and tested for the four sites are summarised below:

a) Site A

PILE TYPE	WORKING LOAD	TERMINATION CRITERIA*
ϕ450mm spun pile (thickness – 100mm)	1520kN	Jacked to 2.5 times working load with holding time of 30 seconds
ϕ500mm spun pile (thickness – 110mm)	2300kN	Jacked to 2.0 times working load with holding time of 30 seconds

b) Site B

<table>
<tr><th>PILE TYPE</th><th>WORKING LOAD</th><th>TERMINATION CRITERIA*</th></tr>
<tr><td>ϕ450mm spun pile (thickness – 80mm)</td><td>1600kN</td><td rowspan="3">Jacked to 2.1 times working load with holding time of 60 seconds</td></tr>
<tr><td>ϕ500mm spun pile (thickness – 90mm)</td><td>2100kN</td></tr>
<tr><td>ϕ600mm spun pile (thickness – 100mm)</td><td>2800kN</td></tr>
</table>

c) Site C

PILE TYPE	WORKING LOAD	TERMINATION CRITERIA*
ϕ450mm spun pile (thickness – 100mm)	1900kN	Jacked to 2.0 times working load with holding time of 30 seconds
ϕ500mm spun pile (thickness – 110mm)	2300kN	
ϕ600mm spun pile (thickness – 110mm)	3000kN	

d) Site D

PILE TYPE	WORKING LOAD	TERMINATION CRITERIA*
ϕ400mm spun pile (thickness – 100mm)	1700kN	Jacked to 2.0 times working load with holding time of 30 seconds
ϕ500mm spun pile (thickness – 110mm)	2300kN	
ϕ600mm spun pile (thickness – 110mm)	3000kN	

*The maximum jack-in pressure with holding time of 30 seconds is carried out for a minimum of two (2) cycles.

It can be observed that different termination criteria were adopted for the four different sites with maximum jack-in pressure ranging from 2.0 to 2.5 and holding time varying from 30-seconds to 60-seconds. The reasons behind this is due partly to technical research carried out by the Authors during that time in early 2000s to find the most optimum maximum jack-in pressure and partly to satisfy other parties (e.g. Clients, Structural Engineers, etc.) who are not familiar with the relatively new jack-in pile foundation system. As such, sometimes more conservative maximum jack-in pressure and holding time is adopted for certain projects. Generally, maximum jack-in pressure to 2.0 times working load with a holding time of 30 seconds is sufficient (2 cycles). The implication of the difference in maximum jack-in pressure and holding time is not expected to affect the findings in this paper.

A total of twenty-two (22) numbers of static load tests were carried out for the above four sites and results of the pile load tests are summarised in Table 3. All the piles selected for testing at the above four sites passed the load test criteria with settlement within allowable limits.

Table 3: Summary of pile load test results.

Pile Diameter (mm)	Pile Length (m)	Settlement (mm)		Remarks
		Working Load	2*Working Load	
Site A				
450*	10.5	6.4	12.9	-
500	37.0	4.5	11.9	-
500*	20.6	9.2	20.5	20m preboring
Site B				
450	12.0	3.0	7.0	-
500	17.7	7.8	17.8	-
500	22.6	5.4	12.8	-
500	9.5	5.4	15.0	-
500*	6.5	8.3	19.7	-
600	17.7	4.8	12.2	-
600*	20.7	5.6	13.1	-
600	14.5	9.9	21.3	-
Site C				
450	27.6	8.9	18.2	-
450*	32.5	6.7	15.9	-
500	24.7	8.9	22.2	Instrumented (PTP-1)
600	27.0	8.6	17.7	-
600	17.5	7.4	16.4	-
600	23.0	8.0	20.8	Instrumented (PTP-2)
600*	21.4	7.4	17.3	Instrumented (PTP-3)
Site D				
400	7.5	9.2	20.0	-
500*	16.5	6.4	21.8	-
600*	34.8	8.5	16.8	Instrumented (PTP-1) Pile tested up till 2.5*WL. Settlement at 2.5*WL: 23.8mm. Residual settlement after unloading from 2.5*WL: 5.5mm.
600	25.5	7.5	15.4	Instrumented (PTP-2) Pile tested up till

				2.5*WL. Settlement at 2.5*WL: 21.9mm. Residual settlement after unloading from 2.5*WL: 6.3mm.

*Plots of load-settlement results shown in Figures 11 to 14.

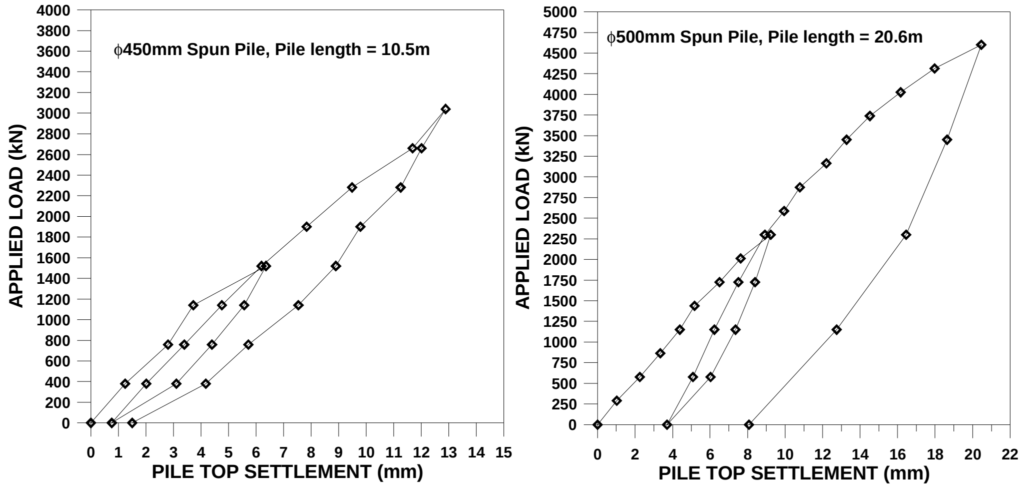

Figure 11: Load-settlement results of pile load test at Site A.

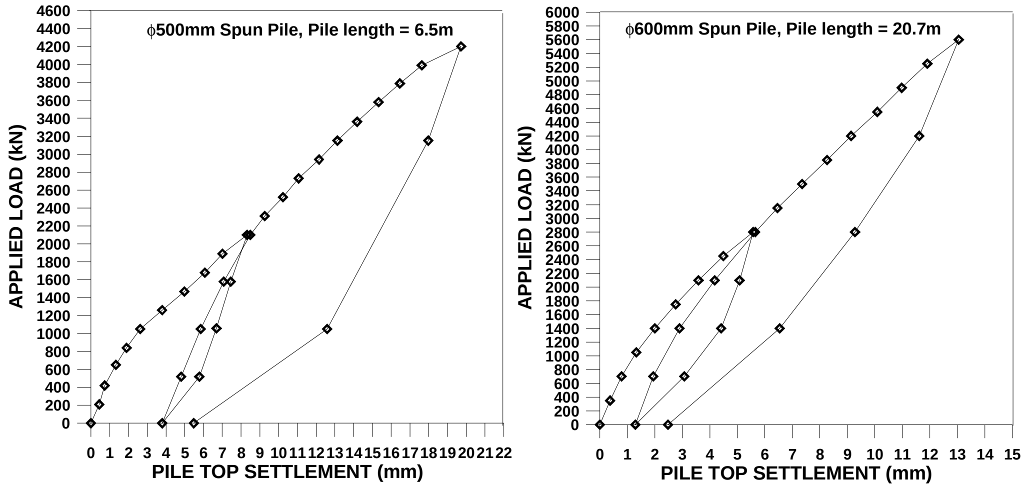

Figure 12: Load-settlement results of pile load test at Site B.

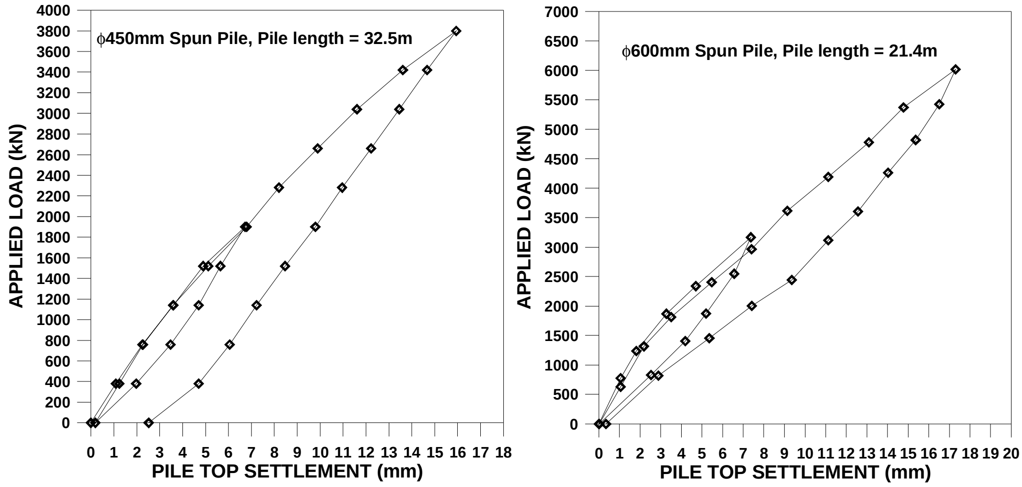

Figure 13: Load-settlement results of pile load test at Site C.

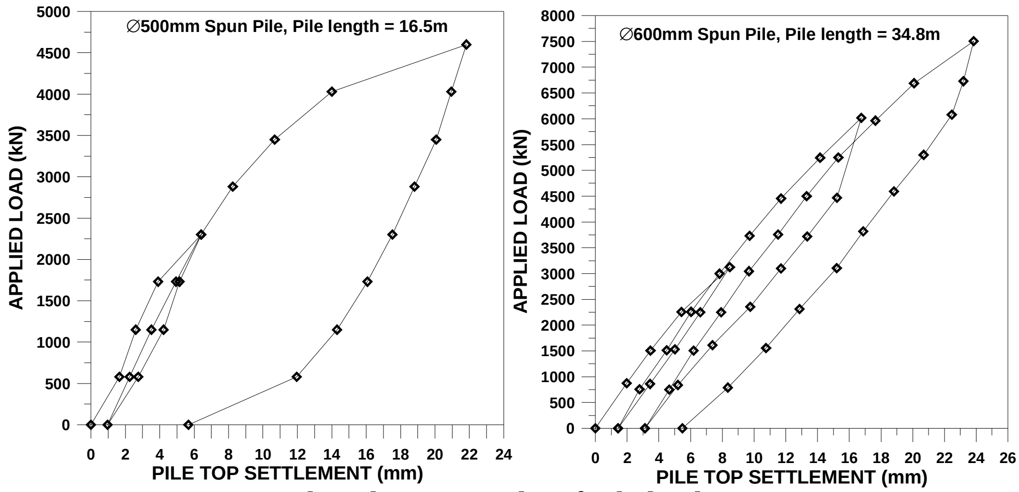

Figure 14: Load-settlement results of pile load test at Site D.

From the above pile load test results, the following conclusions are observed:

a) Pile performance is satisfactory for pile lengths as short as 6.5m with settlement at working load and two times working load of 8.3mm and 19.7mm respectively.
b) Pile performance is satisfactory for piles where preboring has been carried out. This demonstrates the validity of the assumption that the geotechnical capacity of the pile is a function of the jack-in force during pile installation.
c) The termination criterion adopted of jacking to two times of working load (WL) with holding time of 30 seconds is adequate. In fact, the load test results (Figures 11 to 14) indicate there is room for possible optimization, as the piles can support up to two times working load

without showing signs of failure. Two of the piles tested up to 2.5*WL in Site D also demonstrated that the geotechnical capacity of the pile was more than 2.5*WL as the residual settlement after unloading from the maximum test load is relatively small (5.5mm and 6.3mm respectively).

For Site C, rock socketed bored piles were also constructed and tested and the test results are summarised below:

a) ϕ750mm bored pile – Pile length: 23.8m with 0.9m rock socket
   Working Load (WL): 3880kN
   Settlement at WL: 6.9mm
   Settlement at 2*WL: 44.1mm
b) ϕ1200mm bored pile – Pile length: 28.7m with 0.5m rock socket
   Working Load (WL): 9800kN
   Settlement at WL: 11.5mm
   Settlement at 2*WL: 17.0mm

Based on the above results, it is interesting to note that the settlement performances of the rock socketed bored piles and spun piles are comparable. Therefore, combination of two different types of foundations is acceptable provided that the foundations are designed and constructed properly.

4. RECOMMENDED TERMINATION CRITERION FOR JACK-IN PILES INSTALLATION IN WEATHERED GRANITE

Based on the above case histories where the performance of the jack-in pile foundation is satisfactory with all the piles tested achieving a minimum of two times the pile working load, the recommended termination criterion for jack-in piles in weathered granite formation are as follows:

"The termination criterion is to jack the pile to 2.0 times of the design load for a minimum of two cycles. The corresponding pressure has to be held for minimum 30 seconds with settlement not exceeding 2mm or unless otherwise specified by the Engineer."

Questions often arise with regards to the adequacy of maintaining the jack-in pressure for the relatively short duration of 30 seconds only where long-term settlement of the pile cannot be verified. However, it should be noted that the termination criterion has the objective of installing the pile in order to achieve the required geotechnical capacity and is not for settlement verification. This is similar to installation of driven piles where the termination (or "set") criterion of piles is determined to ensure adequate geotechnical capacity and long-term settlement of the piles definitely cannot be assessed during pile driving. For bored piles, verification of pile capacity and settlement characteristics depends solely on load tests.

The designer is still responsible for assessing the adequacy of the installed pile length based on available subsurface investigation (SI) information. For example, achieving the required termination criterion on a thin layer of intermediate hard layer/boulder and followed by soft soil below it is not adequate for piles where end-bearing contributes a significant proportion of its capacity. The pile should terminate in a competent stratum to ensure the load-carrying capacity of the pile is adequate for long-term within acceptable serviceability limits. This is similar to conventional driven pile design practice.

Therefore, similar to conventional pile design, the termination criterion for jack-in piles should be subjected to verification via a maintained load test to ensure adequate geotechnical capacity within acceptable serviceability limits. However, the jack-in pile offers considerable advantage over conventional driven and bored piles system as summarised in Table 4.

Jack-in pile foundation system offers many advantages compared to other piling systems as every pile installed is somewhat being verified that it can sustain at least two times the pile working load without excessive settlement. This is supported by research findings of Deeks, White & Bolton (2005) and case histories discussed earlier. Driven piles can only offer indirect verification which depends on a lot of external factors such as hammer performance, drop height, etc. while no such benefits are offered by bored piles.

Table 4: Comparison of different types of piling systems.

	JACK-IN PILE	**DRIVEN PILE**	**BORED PILE**
Cyclic load during pile installation	Less cycles compared to driven pile	Number of cycles more especially for long piles	N.A.
Termination criteria	Static (pseudo) load imposed onto pile head	Dynamic load imposed onto pile head	Based on SI information
Variables affecting efficiency of load	1. Hydraulic system of jacks	1. Efficiency of hammer, helmet, etc.	N.A.

transfer during pile installation	2. Calibration of pressure gauge	2. Hammer drop height 3. Cushion properties 4. Eccentricity of pile/hammer	
Verification of geotechnical capacity during installation	Relatively straightforward as loading rate is slow	Indirect verification based on dynamic analysis. Often unreliable.	N.A.
Probability of pile damage during installation	Low	High	Depends on workmanship

Due to the relatively lower risk associated with jack-in piles as every pile is somewhat tested to verify its geotechnical capacity during installation, Chow & Tan (2009) have also proposed less conservative partial factors of safety for jack-in pile design to Eurocode 7. Such approach is consistent with the principles of Eurocode 7 where lower partial factors are allowed in conjunction with increased site verification via pile testing.

5. MOBILISED SHAFT FRICTION AND END-BEARING RESISTANCE OF JACK-IN PILES

Preliminary instrumented test piles were carried out at Site C (3 Nos.) and Site D (2 Nos.) in order to measure the mobilized shaft friction and end-bearing resistance of the jack-in piles. The piles were instrumented using the Global Strain Extensometer (GLOSTREXT) system (Krishnan & Lee, 2006). The results of the instrumented test piles have been presented by Chow & Tan (2010). Figures 15 to 17 show the load transfer curve for shaft friction and end-bearing for PTP-1, PTP-3 (Site C) and PTP-1 (Site D) respectively.

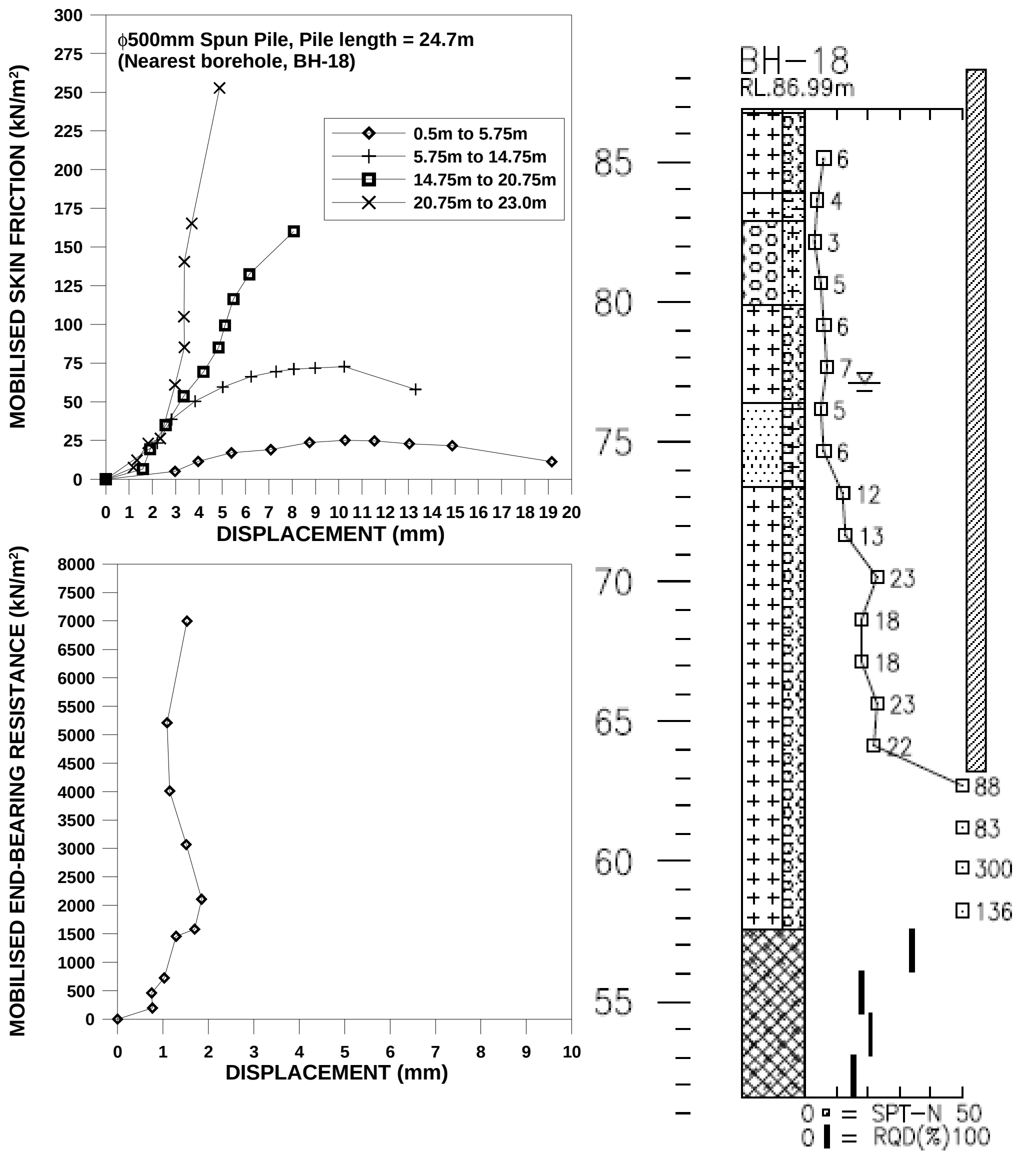

Figure 15: Mobilised shaft friction and end-bearing resistance for PTP-1 (Site C) – Borehole profile relevant to test pile also shown.

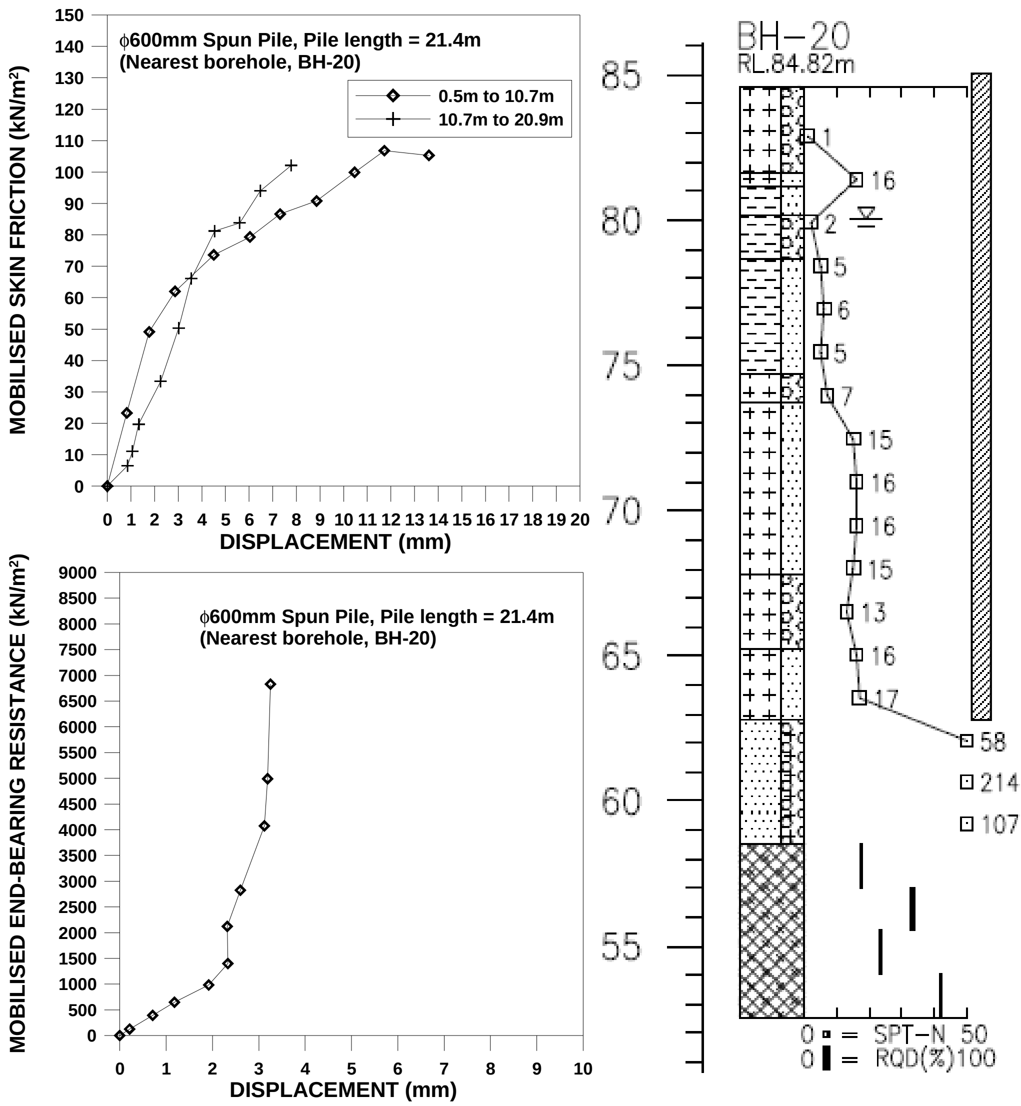

Figure 16: Mobilised shaft friction and end-bearing resistance for PTP-3 (Site C) – Borehole profile nearest to test pile shown.

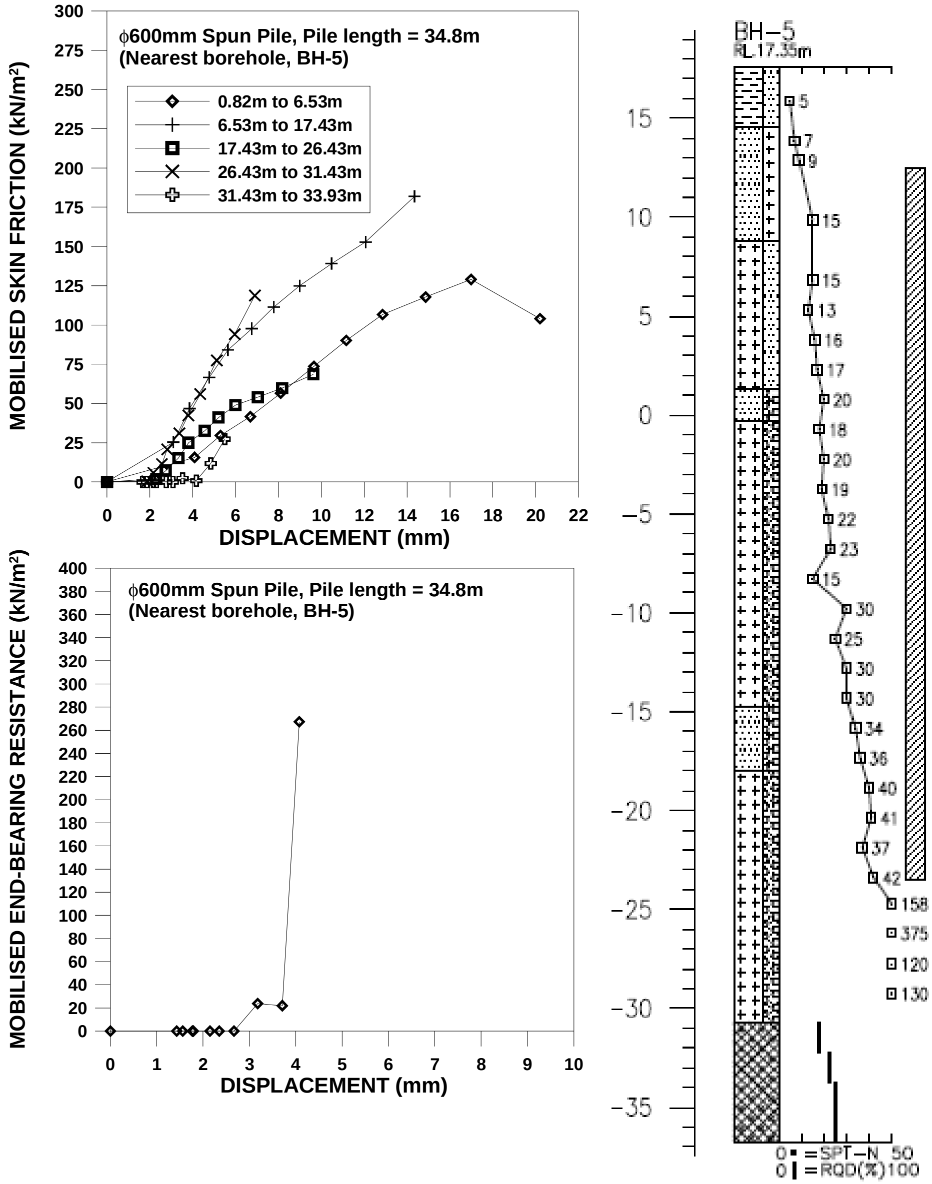

Figure 17: Mobilised shaft friction and end-bearing resistance for PTP-1 (Site D) – Borehole profile nearest to test pile shown.

The following observations can be made from the test results:

a) The pile base exhibits stiff response where significant end-bearing was mobilised at relatively small settlement. This is expected due to the precompression of the soil at the base during pile installation and also due to the effect of residual load.
b) Most of the shaft friction and end-bearing resistance have not reached the ultimate value even at two times working load. This indicates that the ultimate capacity of the pile is higher than two times working load.
c) Based on the nearest boreholes to the test piles, the shaft friction generally exceeds 5*SPT-N (in kPa) and in one extreme result, the value is approximately 20*SPT-N. No meaningful correlations for end-bearing resistance can be derived as the base movement is relatively small to mobilise the ultimate end-bearing resistance.

Based on the instrumented load test results and other load test results, Chow & Tan (2010) recommends conservative estimate of shaft friction for jack-in piles in weathered granite to be 5*SPT-N (in kPa). This correlation is expected to be conservative based on the instrumented load test results and possibility of upward revision is high. However, further instrumented load test results need to be collected and studied before such conclusion can be made.

6. SUMMARY

The use of jack-in piles in Malaysia is increasingly common for high-rise buildings with maximum pile working load of up to 3000kN. From the Authors' first project in former municipal dumping site with mine tailings overlying limestone bedrock to more recent projects in weathered granite formation, the performance of jack-in piles have been very satisfactory. Based on the Authors' experience, the following conclusions are summarised:

a) With proper planning, jack-in pile can be adopted even in difficult ground conditions such as limestone or weathered granite formation with boulders.
b) Termination criteria recommended for weathered granite formation is:
"Jack the pile to 2.0 times of the design load for a minimum of two cycles. The corresponding pressure has to be held for minimum 30 seconds with settlement not exceeding 2mm".

c) The maximum jack-in force sustained by the pile according to the termination criteria above will provide a conservative indication of the ultimate geotechnical capacity of the pile.
d) Current correlations for estimation of geotechnical capacity of pile developed based on driven piles database are conservative and not accurate for jack-in pile.
e) Preliminary conservative correlations for skin friction of jack-in piles in weathered granite formation is 5*SPT-N.

Future research in the behaviour of jack-in pile especially load transfer behaviour for end-bearing will be beneficial to the industry. In this respect, instrumented test pile with more strain gauges at closer intervals and loaded to failure will be very useful.

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