Jack-in Pile Design and Construction for High-rise Buildings - A Malaysian Consulting Engineer's Perspective

C. M. Chow[1] and Y.C. Tan[1]
[1]*G&P Geotechnics Sdn Bhd, Kuala Lumpur, Malaysia*
E-mail: cmchow@gnpgroup.com.my

ABSTRACT: Large diameter jack-in pile foundation for high-rise buildings has been successfully adopted in Malaysia since the 1990s and currently, large diameter spun piles of up to 600 mm in diameter with working load up to 3200 kN 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 system which has been successfully adopted for high-rise buildings in weathered granite and weathered sedimentary formation. Experiences gained throughout the years will be summarized including advantages and limitations of the system. Some results of static maintained load tests will also be presented illustrating clear differences in performance in different ground conditions. Recommendations on empirical correlations between ultimate shaft resistance (f_{su}) with SPT'N' and preliminary guidance on ultimate end-bearing resistance (f_{bu}) will also be discussed.

KEYWORDS: Jack-in pile, Weathered granite, Weathered sedimentary, Shaft resistance, End-bearing resistance.

1. INTRODUCTION

Large diameter jack-in pile foundation has been successfully adopted in Malaysia since the 1990s for high-rise buildings and currently, large diameter spun piles of up to 600 mm diameter with working loads of up to 3200 kN have been successfully adopted for high-rise buildings of up to 45-storeys. The popularity of jack-in pile foundation system especially for construction works in urban areas is due to its relatively lower noise and lower vibration compared to conventional piling systems such as driven piles. Jack-in pile foundation also offers advantages in terms of faster construction speed, better quality control, less pile damage and cleaner site conditions as it does not require the use of stabilizing liquid/drilling fluid and disposal of soil from bored/drilled holes 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 cost savings without compromising the safety, serviceability requirements and integrity of the pile foundation. However, like all available systems, jack-in piles also have their 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 in Malaysia and a schematic of the machine respectively. Table 1 summarises some key technical data for the machines.

1.1 Advantages and Limitations of Jack-in Pile Foundation

Some of the advantages of jack-in pile foundation system includes:

a) Low noise and vibration (vs driven piles)
b) Faster construction rates (vs bored piles)
c) Cleaner sites (vs bored piles)

Jack-in pile foundation system can be considered as a form of Industrialised Building System (IBS) as the piles are manufactured off-site compared to conventional foundation system for high-rise such as bored piles where the piles are cast in-situ. As such, construction site where jack-in piles are adopted are usually cleaner compared to bored piles site because it generates less spoils (e.g. drilling fluids, boring and disposal of soil for bored piles) and concreting works are not required. Figure 3 shows a construction site where jack-in piles are adopted.

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

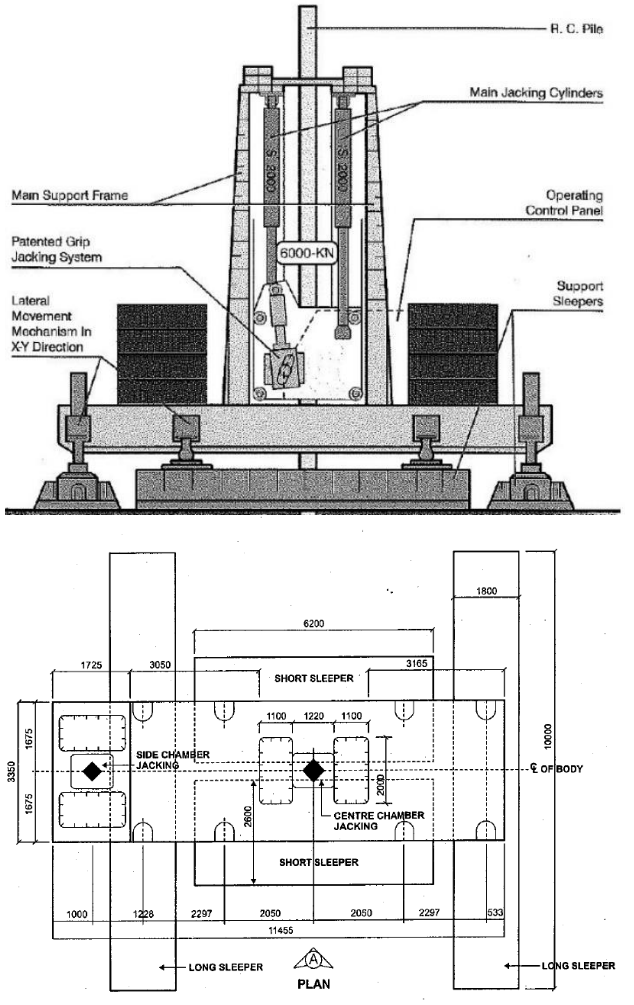


Figure 2 Typical schematic of high capacity jack-in pile machine

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

Item	Technical Data
Maximum Jacking Force	7000 kN
Applicable Spun Pile Diameter	250 mm to 600 mm
Applicable RC Square Pile Size	250 mm to 400 mm
Self Weight (Excluding counterweight)	178 t to 200 t
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)	5.5 m to 6.9 m
Bearing pressure on sleeper	Up to 175 kN/m^2

Figure 3 Example of jack-in pile construction site

However, like any foundation systems, there are also limitations of jack-in pile foundation system as follows:

a) Strong and flat piling platform required. Therefore, the use of jack-in pile foundation in soft ground requires careful assessment.
b) Slightly larger worker area required (vs driven/bored piles).
c) Limited pile size can be installed and therefore, limited pile capacities (vs bored piles). As such, for very high concentrated loadings, there may be restrictions on the use of jack-in piles due to space constraints. However, the Authors have successfully adopted combination of bored piles and jack-in piles for high-rise buildings to overcome such limitations.
d) Unable to go through intermittent hard layers/boulders/limestone floaters (vs bored piles) and therefore, in some cases, preboring is required. The economic feasibility of preboring would depends on the depth of preboring required and the Authors have also successfully adopted preboring for all the jack-in piles for a number of high-rise buildings where it is still more economical compared to bored piles.

1.2 QA/QC for Jack-in Piles

It is the Authors' opinion that one of the main advantages of jack-in piles compared to conventional foundation system is the verification of pile capacity for each and every pile during installation. Even though the duration of load application during installation is relatively short, it nevertheless is a form of pile capacity verification and when compared to conventional foundation system, it can be seen that jack-in pile does offer some form of advantage as summarised in Table 2.

Table 2 Comparison of different types of piling systems

	Jack-in Pile	Driven Pile	Bored Pile
Loading rate during pile installation	Slow	Very fast	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 transfer during pile installation	1. Hydraulic system of jacks 2. Calibration of pressure gauge	1. Efficiency of hammer, helmet, etc. 2. Hammer drop height 3. Cushion properties 4. Eccentricity of pile/hammer	1. Exposure time before concreting 2. Drilling fluid conditions and quality
Verification of geotechnical capacity during installation	Relatively straightforward as loading rate is slow	Indirect verification based on dynamic analysis. Often unreliable	Cannot be verified
Probability of pile damage during installation	Low	High	Depends on workmanship

On the subject of pile capacity verification during jack-in pile installation, reference is made to the findings by the Research Committee on Rapid Load Test Methods (1998) which summarises the following categories of pile testing:

a) $N_w < 10$ is regarded as dynamic load test (e.g. PDA)
b) N_w 10 to 1000 is regarded as rapid load test (e.g. Statnamic)
c) $N_w > 1000$ is regarded as static load test

where,

$N_w = T.c/L$
T = duration of applied load (in seconds)
L = length of the tested pile (in metres)
c = velocity of stress wave propagation in the pile (in m/s)

For example, a 50 m long concrete jack-in pile (c = 3800 m/s) which is considered quite long for onshore foundation works in Malaysia with termination holding period of 20 seconds, the N_w value would be 1520 which is more than 1000. Therefore, according to the classification of Research Committee on Rapid Load Test Methods in Japan, each jack-in pile can be considered as subjected to static load test during installation. The Authors acknowledge that there are limitations to the verification of pile performance solely based on performance during pile installation where factors such as excess pore-water pressures, long-term creep, etc. cannot be assessed but it must be pointed out that pile installation using jack-in method nevertheless provided the designer with some form of testing with load duration longer than dynamic load test or statnamic and this is a major advantage in terms of QA/QC compared to other foundation system.

1.3 Calibration of Pressure Gage of Jack-in Machine

As the maximum force on the piles during installation is an important termination criterion which will also influence the pile performance, it is important that the pressure gage which records the pressure (which translated to the jack-in force) on the piles during installation are properly calibrated. The Authors recommend site calibration to be carried out for each jack-in machine to be used at the site so that the target pressure for pile termination can be adjusted based on the site calibration carried out.

Figure 4 shows a simple site set-up where pressure is exerted from the jack-in machine on a pre-installed pile and a load cell is provided to record the actual force loading the pile. Figure 5 shows the read-out from the load cell where comparisons can be made between the force obtained from the load cell against the pressure gage readings so that adjustments can be made to the required pressure during pile termination to achieve the targeted maximum force during pile installation.

Figure 4 Site calibration of jack-in machine pressure gage with the use of load cell

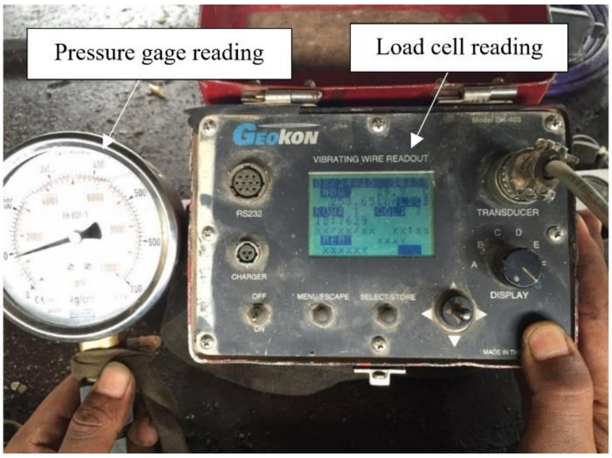


Figure 5 Comparison of pressure gage readings against force obtained from load cell

2. GEOTECHNICAL CHARACTERISTICS OF JACK-IN PILE - A LITERATURE REVIEW

Randolph (2003) in his 43rd Rankine Lecture titled “Science and empiricism in pile foundation design” 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.

White & Lehane (2004) found that besides higher end-bearing resistance at working load, the mobilised shaft friction for jack-in piles is also expected to be higher. The phenomenon is commonly known as friction fatigue where decrease in shaft friction is observed in a given soil horizon as the pile tip penetrates to deeper levels. 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 6, 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.

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”. The phenomena of lower shaft friction for piles installed using conventional dynamic installation is also known as friction fatigue and is well-established in pile design for offshore structures. This principle is incorporated in design methodology such as Imperial College Pile (ICP) Design Methods for Driven Piles in Sands and Clays [Jardine et al. (2005)].

Deeks et al. (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 et al. (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.

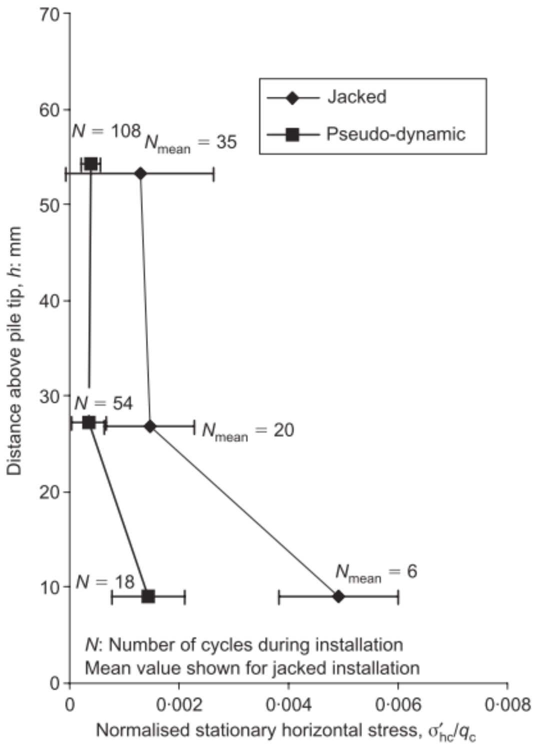


Figure 6 Influence of loading cycles during installation on stationary horizontal stress [White & Lehane (2004)]

2.1 A Review of Different Jack-in Pile Termination Criteria

One of the important factors which influences the performance of jack-in pile is the termination criteria. Some of the different termination criteria adopted are summarised below:

a) Singapore – GeoSS (2015)
   a. Piles jacked to 2.0 to 2.5 times Working Load
   b. Movement not exceeding 10 mm with holding time of minimum 30 seconds
b) Hong Kong – Li & Lam (2011)
   a. Piles jacked to 2.1 to 2.5 times Working Load
   b. Movement not exceeding 5 mm in 15 minutes
c) Australia - AS 2159-2009: Piling – design and installation
   a. R_{ug} = K x Pmax
      where K is determined from static load tests but is not more than 0.97. In the absence of static load tests, K is taken as follows:
      K = 0.90 for piles > 15 m length
      K = 0.77 for piles > 8 m, < 15 m length
      K = 0.61 for piles < 8 m length
   b. Repeated jacking at the maximum jacking force (Pmax)
      Number of cycles > 5
      Pmax maintained for not less than 15 seconds
      A time interval of not less than 2 minutes shall elapse between cycles.

It can be seen that the termination criteria adopted varies especially on the holding time. The differences are mainly attributed to different technical concerns of the foundation performance due to authority acceptance criteria, geology or subsoil conditions. For example, Hong Kong's engineers are concerned over residual settlement criterion and long-term creep of the foundation and that is why Hong Kong recommends preloading of piles (i.e. piles jacked to more than two times working load) and also significantly longer holding time (i.e. 15 minutes). Meanwhile, Australia's engineers are concerned over pile relaxation even in sand and that is why Australia recommends pile capacity as a function of maximum jack-in force and pile length and also larger number of cycles during maximum jack-in force with 2 minutes of relaxation period between cycles.

Meanwhile, in Malaysia, the Authors had proposed termination criteria for jack-in piles at the time (1990s) where information on large diameter jack-in pile performance is scarce and limited. The evolution of the termination criteria adopted by the Authors are summarised below:

a) Maximum jack-in force – 2.5*WL, Holding time 60 seconds (2 cycles)
b) Maximum jack-in force – 2.0*WL, Holding time 60 seconds (2 cycles)
c) Maximum jack-in force – 2.0*WL, Holding time 30 seconds (2 cycles)
   Note: WL = Working load of pile

The above termination criteria are mainly adopted in granite formation and it can be seen that the Authors initially adopted higher maximum jack-in force and also longer holding time. As more and more experiences are gained together with favourable static load test results and verified performance of various high-rise building foundations in granite formation, the termination criteria is refined and it was found that the criteria of maximum jack-in force of two times pile working load with holding time of 30 seconds (2 cycles) are adequate for large diameter jack-in piles in granite formation. However, with jack-in piles gaining popularity and with wider applications in different ground conditions such as metasedimentary (e.g. schist, phyllite, etc.), limestone, alluvial, etc., the Authors have further refined the termination criteria taking into considerations pile performances in different ground conditions and also experiences of other countries into a generalised termination criteria which is applicable for different types of ground conditions as follows:

"Jack the pile to 2.0 times of the design load for a minimum of three cycles with an interval of not less than 3 minutes between each reading. The corresponding pressure has to be held for minimum 20 seconds with settlement not exceeding 2 mm"

The above criteria provide a convenient reference for termination criteria of jack-in pile which is still subjected to adjustment based on geotechnical conditions of the site, load test results, contractor's workmanship, etc. The Authors have adopted termination criteria of settlement of not exceeding 2 mm with the objective of ensuring that the pile has "stopped" settling during application of maximum jack-in force and 2 mm is a practical limit as opposed to 0 mm or 1 mm which is too stringent. The settlement criterion is more stringent compared to Singapore in which the Authors believe is derived from experiences in soft ground and hence the larger allowable settlement of 10 mm and also Hong Kong where the pile is subjected to far longer maximum jack-in force of 15 minutes. The generalised criteria also aim to cover all ground conditions and as such recommends three loading cycles with relaxation period of three (3) minutes between each cycle to minimise impact of pile relaxation or false early termination due to excess pore water pressure during installation based on experience in Australia. Finally, the holding time is reduced to 20-seconds due to the overall increase in time during application of maximum jack-in force with the introduction of three loading cycles and from the Authors' experiences where the pile performance is not noticeably affected with reduction of holding time from 60-seconds to 30-seconds. The relaxation of holding time to 20-seconds will also reduce risk of machine breakdown as the high pressure during maximum jack-in force imposes high stress onto the hydraulic system of jack-in machine commonly used in Malaysia.

3. CASE HISTORIES

3.1 Granite Formation

Chow & Tan (2009) presented results of static maintained load tests where jack-in spun piles were adopted for four different developments in Mont Kiara, Kuala Lumpur and Subang, Selangor. The four different sites are as follows:

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

Recently, the Authors have also completed another high-rise project (38-storey) where pile working load of up to 3200 kN is adopted for 600 mm diameter spun piles (Site E). Figure 7 shows actual view of the condominium tower of Site A and Site B that were completed in 2009.

In general, all the five sites are underlain by Granite formation with overburden materials mainly consisting of silty SAND/sandy SILT with variable thicknesses. Presence of a gravel layer is also detected in Site D. Typical borehole profiles for the sites are shown in Figures 8, 9, 10, 11 and 12 and details of the jack-in piles adopted for the five sites are summarised in Table 3.

Figure 7 Completed condominium towers of Site A and Site B

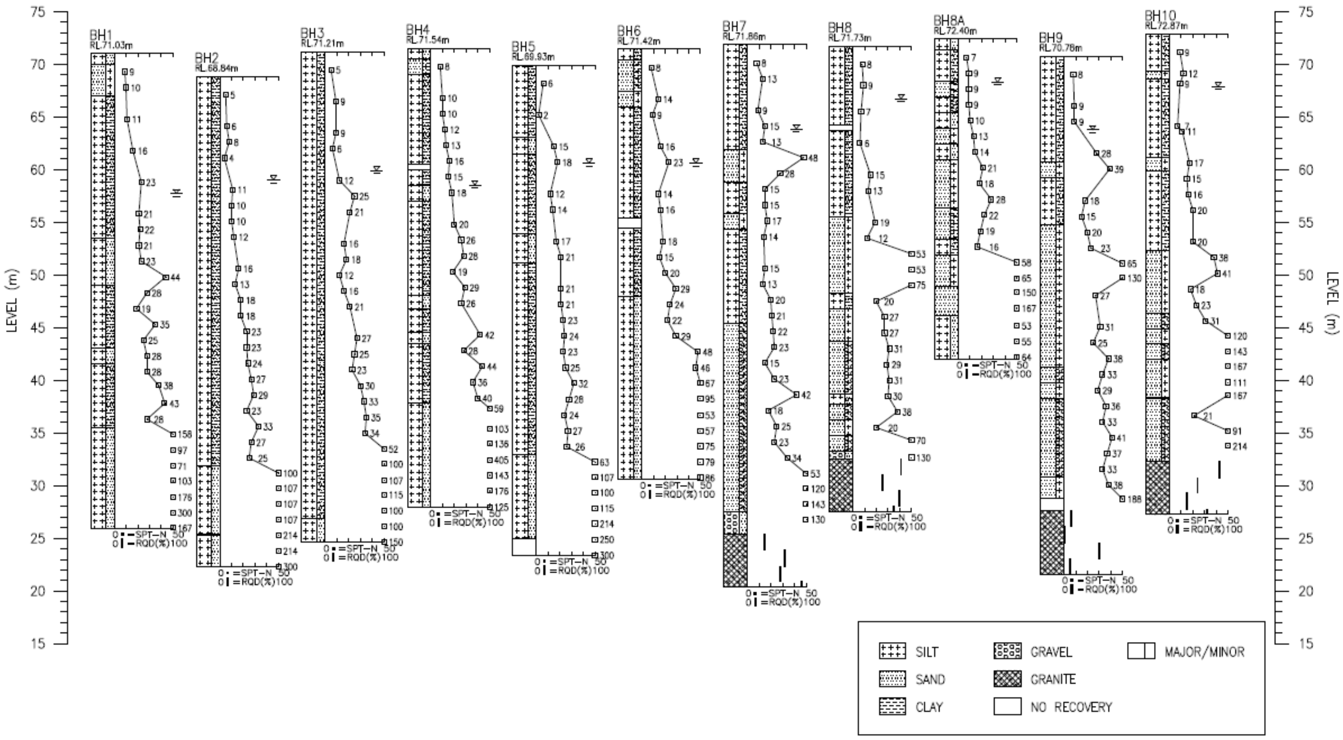


Figure 8 Borehole profiles at Site A

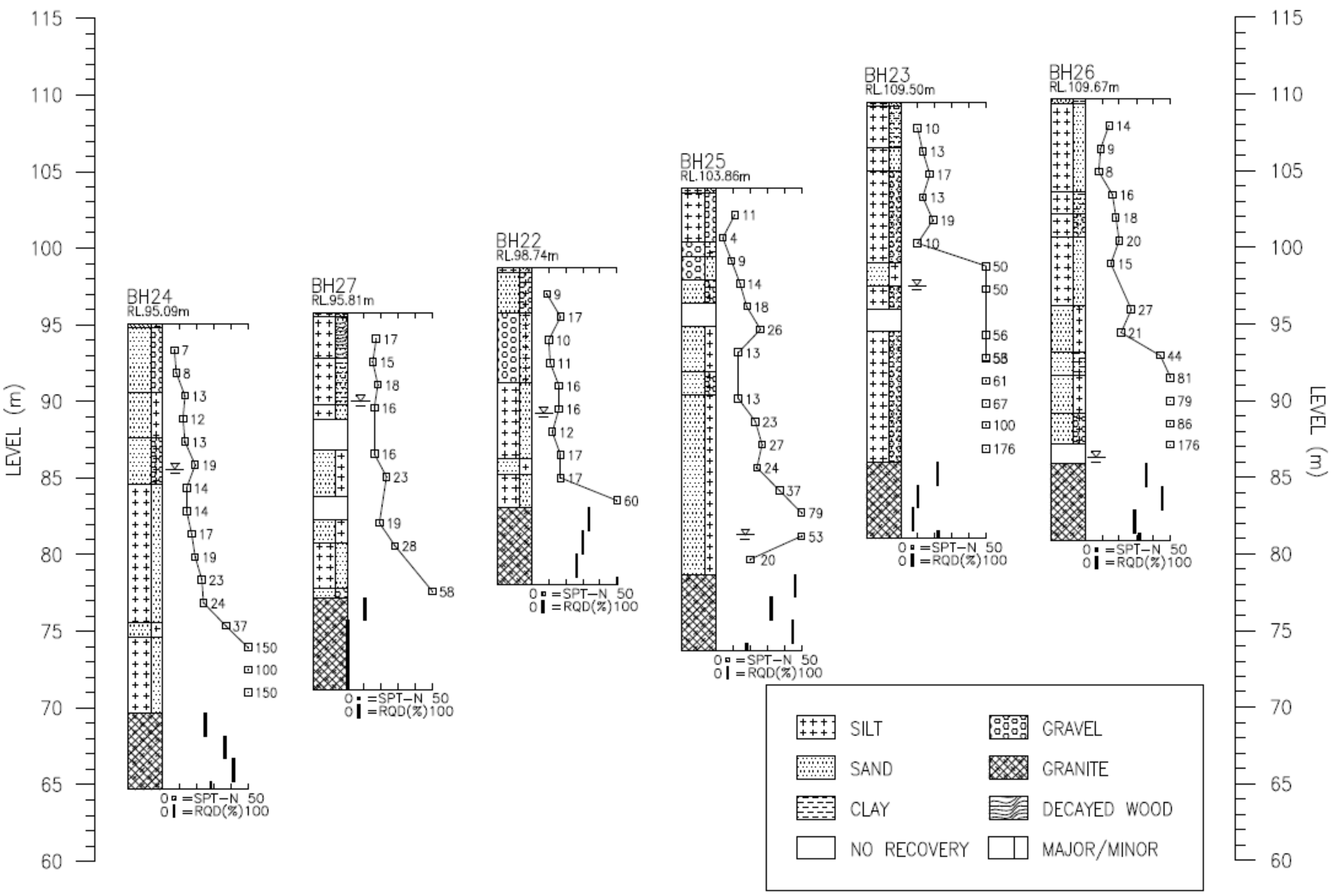


Figure 9 Borehole profiles at Site B

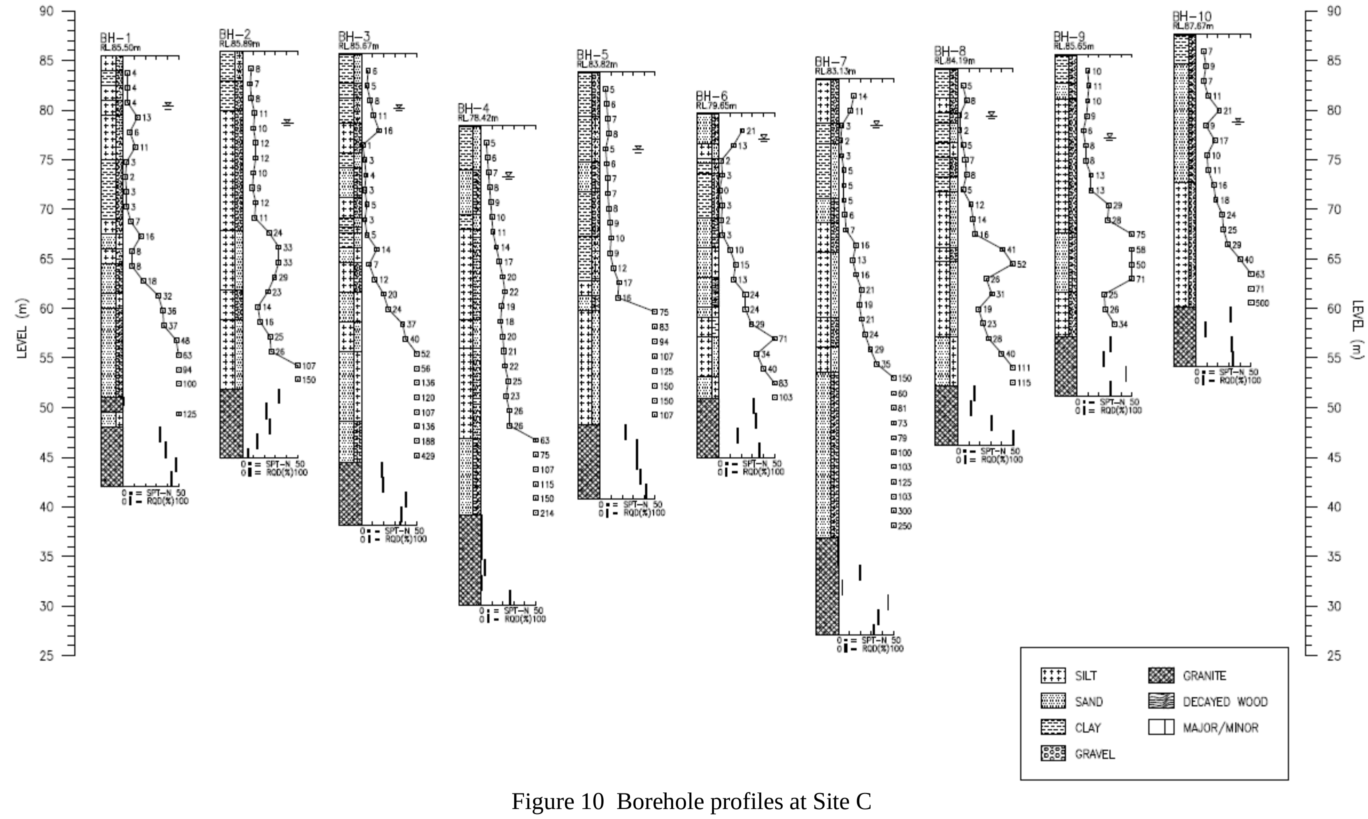


Figure 10 Borehole profiles at Site C

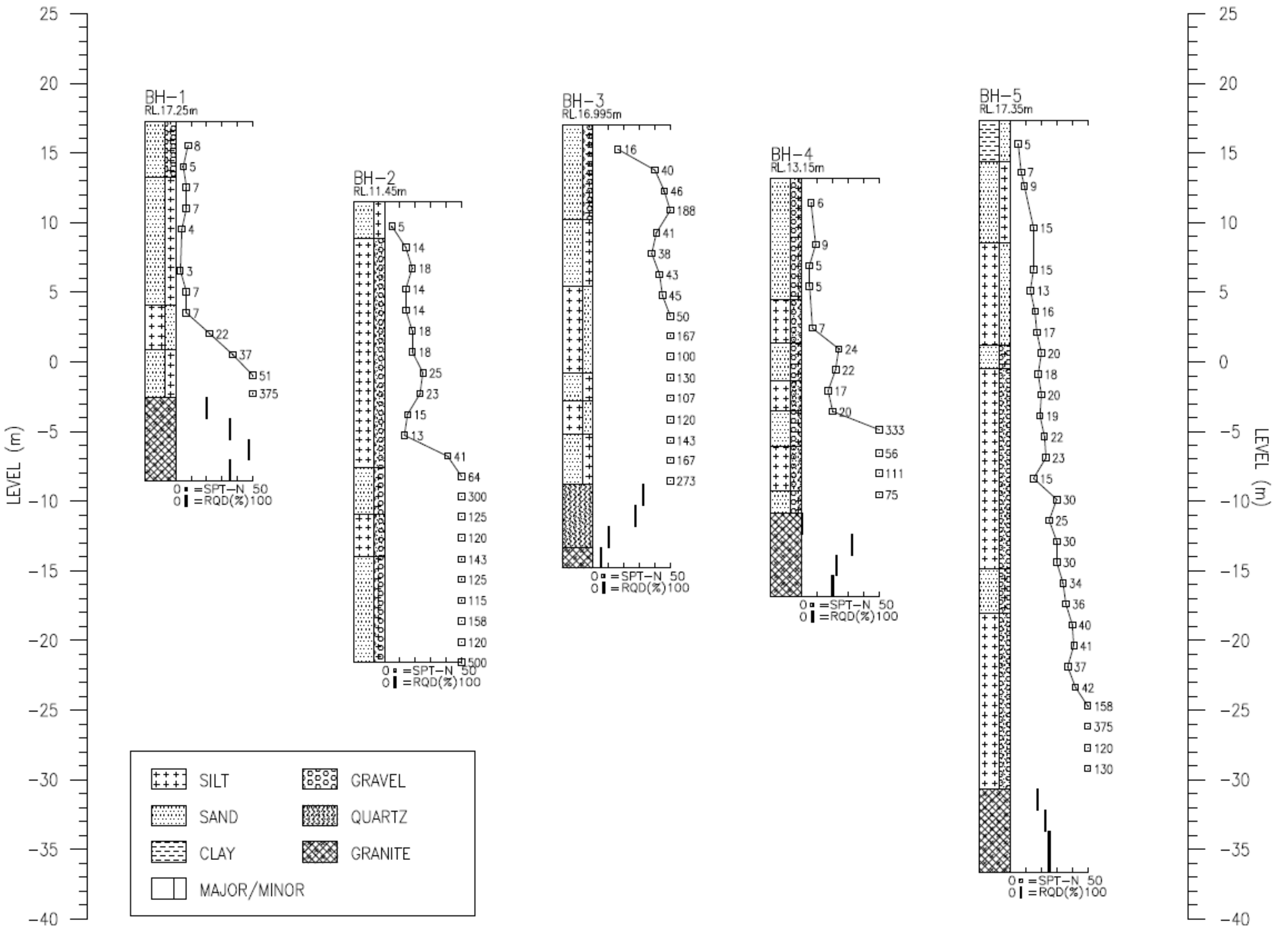


Figure 11 Borehole profiles at Site D

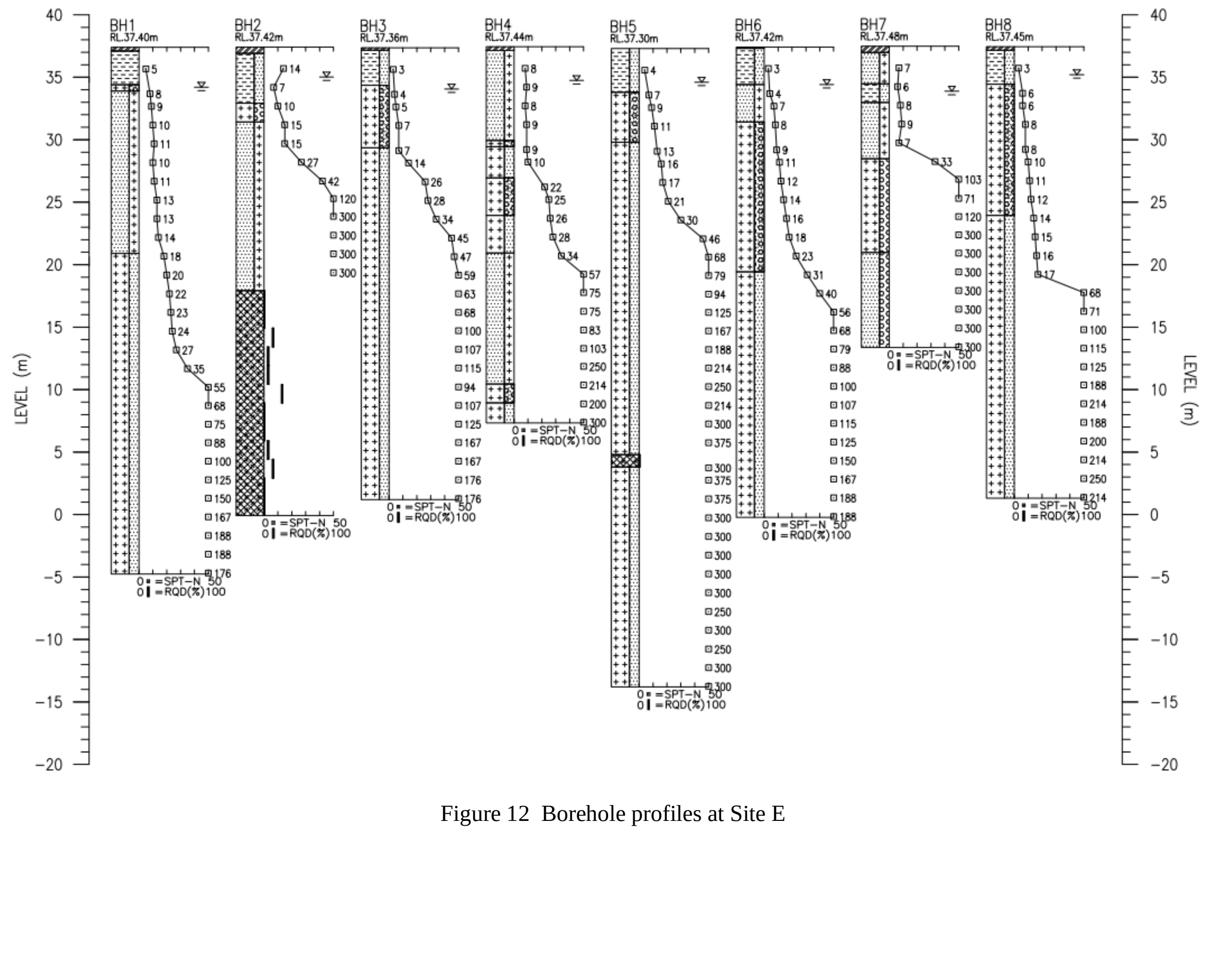


Figure 12 Borehole profiles at Site E

Table 3 Details of jack-in piles adopted for five different sites

Pile Type	Working Load	Termination Criteria*
SITE A		
ϕ450 mm spun pile (thickness – 100 mm)	1520 kN	Jacked to 2.5 times working load with holding time of 30 seconds
ϕ500 mm spun pile (thickness – 110 mm)	2300 kN	Jacked to 2.0 times working load with holding time of 30 seconds
SITE B		
ϕ450 mm spun pile (thickness – 80 mm)	1600 kN	Jacked to 2.1 times working load with holding time of 60 seconds
ϕ500 mm spun pile (thickness – 90 mm)	2100 kN	
ϕ600 mm spun pile (thickness – 100 mm)	2800 kN	
SITE C		
ϕ450 mm spun pile (thickness – 100 mm)	1900 kN	Jacked to 2.0 times working load with holding time of 30 seconds
ϕ500 mm spun pile (thickness – 110 mm)	2300 kN	
ϕ600 mm spun pile (thickness – 110 mm)	3000 kN	
SITE D		
ϕ400 mm spun pile (thickness – 100 mm)	1700 kN	Jacked to 2.0 times working load with holding time of 30 seconds
ϕ500 mm spun pile (thickness – 110 mm)	2300 kN	
ϕ600 mm spun pile (thickness – 110 mm)	3000 kN	
SITE E		
300 mm x 300 mm RC square pile	1500 kN	Jacked to 2.2 times working load with holding time of 60 seconds
ϕ500 mm spun pile (thickness – 110 mm)	2600 kN	
ϕ600 mm spun pile (thickness – 110 mm)	3200 kN	

*The maximum jack-in pressure with holding time of 30 or 60 seconds is carried out for a minimum of two (2) to three (3) cycles.

Plots of load-settlement results shown in Figures 13 to 17.

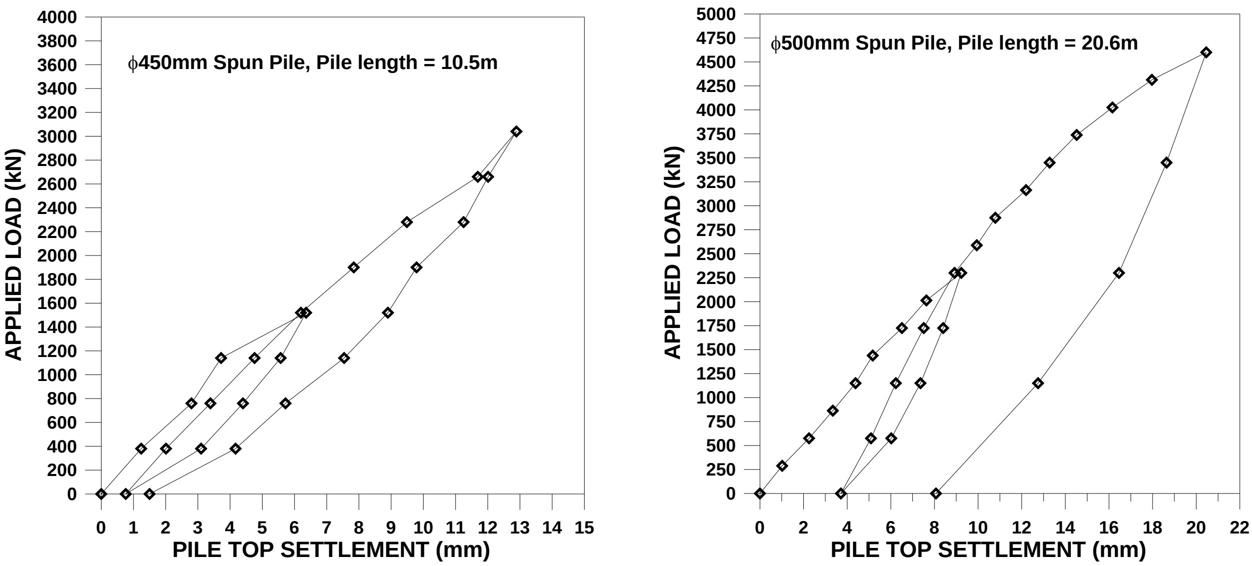


Figure 13 Load-settlement results of static load test at Site A

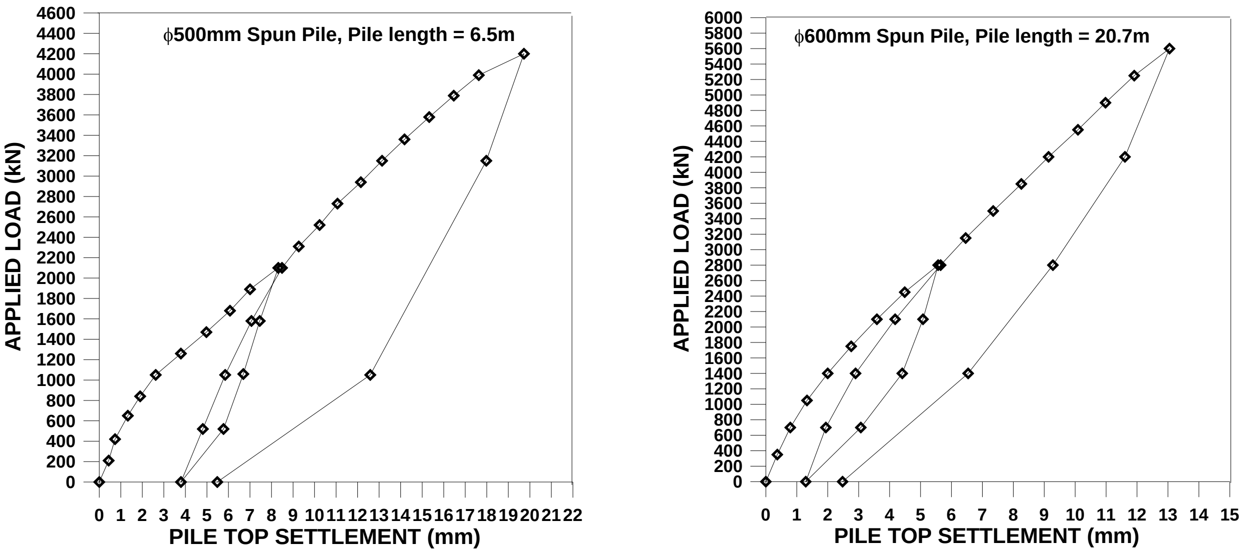


Figure 14 Load-settlement results of static load test at Site B

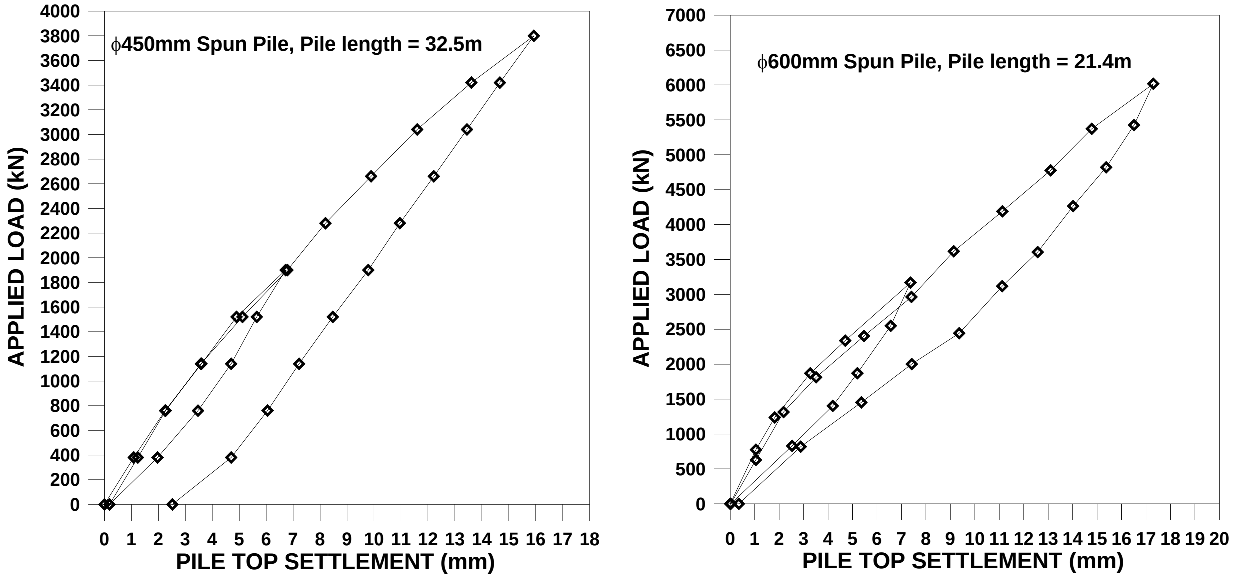


Figure 15 Load-settlement results of static load test at Site C

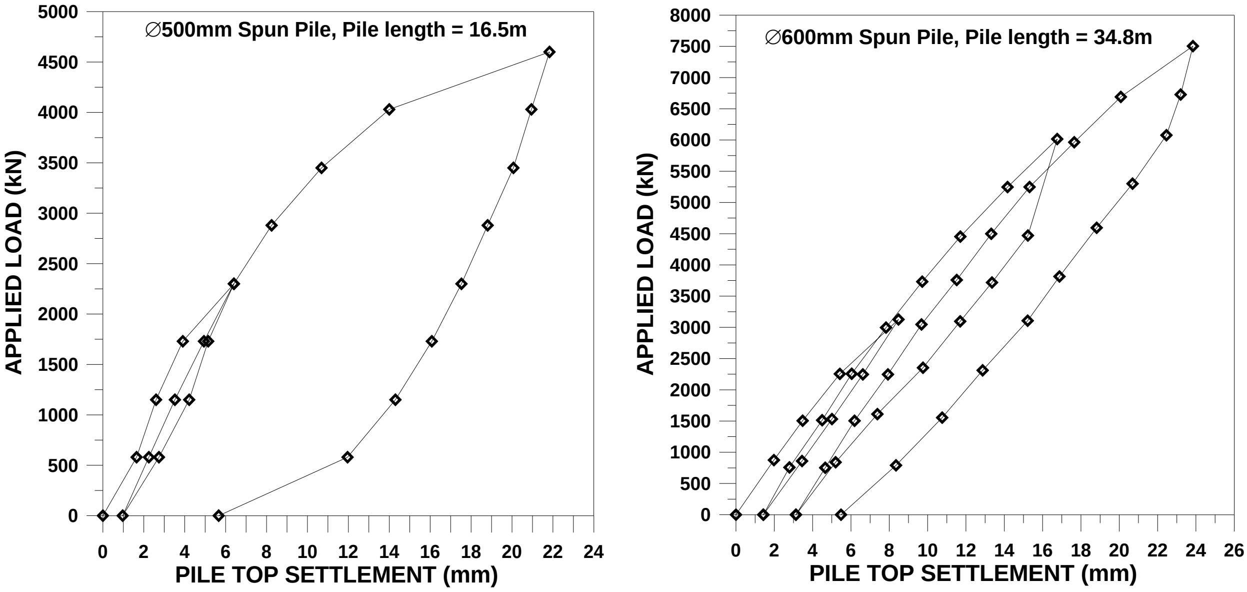


Figure 16 Load-settlement results of static load test at Site D

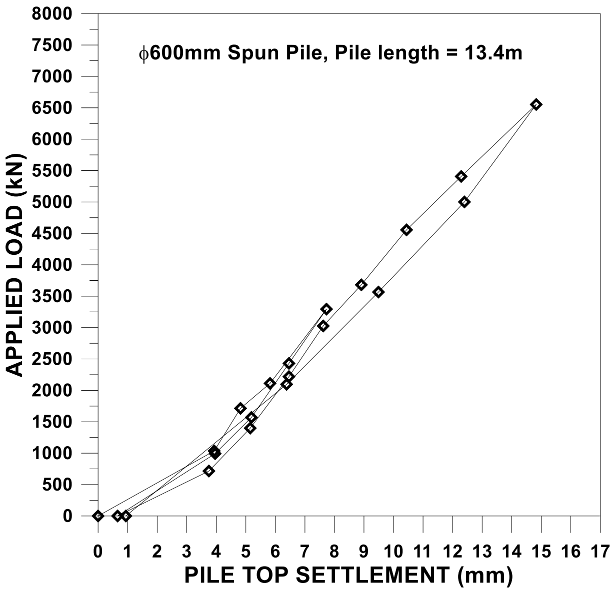


Figure 17 Load-settlement results of static load test at Site E

It can be observed that different termination criteria were adopted for the five different sites with maximum jack-in pressure ranging from 2.0 to 2.5 times working load and holding time varying from 30-seconds to 60-seconds. The reasons behind this are due to technical research carried out by the Authors to find the most optimum maximum jack-in pressure and to satisfy different stakeholders (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) as explained in Section 2.1. The implication of the difference in maximum jack-in pressure and holding time is not expected to affect the findings in this paper.

Results of the static load tests are summarised in Table 4. All the piles selected for testing at the above five sites passed with settlement within allowable limits. From the above static load test results, the following is observed:

a) Pile performance is satisfactory for pile lengths as short as 6.5 m with settlement at working load and two times working load of 8.32 mm and 19.73 mm 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, from the static load test results (Figures 13 to 17), there is room for possible optimization, as the piles can support up to two times working load without showing signs of plunging failure. Two of the piles tested up to 2.5*WL in Site D also demonstrate that the geotechnical capacity of the pile is more than 2.5*WL as the residual settlement after unloading from the maximum test load is relatively small (5.48 mm and 6.33 mm respectively).

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

a) ϕ750 mm bored pile – Pile length: 23.8 m with 0.9 m rock socket
   Working Load (WL): 3880 kN
   Settlement at WL: 6.86 mm
   Settlement at 2*WL: 44.14 mm
b) ϕ 1200 mm bored pile – Pile length: 28.7 m with 0.5 m rock socket
   Working Load (WL): 9800 kN
   Settlement at WL: 11.45 mm
   Settlement at 2*WL: 17.02 mm

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

Instrumented test piles were also carried out at Site C (3 Nos.), Site D (2 Nos.) and Site E (1 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 18 to 21 show the load transfer curve for shaft friction and end-bearing for PTP-1, PTP-3 (Site C), PTP-1 (Site D) and TP-1 (Site E) respectively.

Table 4 Summary of static load test results

Pile Diameter (mm)	**Pile Length (m)**	**Settlement (mm)**		**Remarks**
		Working Load	**2*Working Load**	
		Site A		
450*	10.5	6.36	12.89	-
500	37.0	4.53	11.89	-
500*	20.6	9.23	20.46	20 m preboring
		Site B		
450	12.0	3.04	6.96	-
500	17.7	7.82	17.81	-
500	22.6	5.39	12.77	-
500	9.5	5.41	15.03	-
500*	6.5	8.32	19.73	-
600	17.7	4.82	12.16	-
600*	20.7	5.57	13.05	-
600	14.5	9.88	21.28	-
		Site C		
450	27.6	8.88	18.21	-
450*	32.5	6.72	15.93	-
500	24.7	8.85	22.22	Instrumented (PTP-1)
600	27.0	8.62	17.67	-
600	17.5	7.35	16.37	-
600	23.0	7.99	20.75	Instrumented (PTP-2)
600*	21.4	7.37	17.30	Instrumented (PTP-3)
		Site D		
400	7.5	9.23	19.99	-
500*	16.5	6.41	21.83	-
600*	34.8	8.48	16.76	Instrumented (PTP-1) Pile tested up till 2.5xWL. Settlement at 2.5xWL: 23.84 mm. Residual settlement after unloading from 2.5xWL: 5.48 mm.
600	25.5	7.46	15.38	Instrumented (PTP-2) Pile tested up till 2.5xWL. Settlement at 2.5xWL: 21.90 mm. Residual settlement after unloading from 2.5xWL: 6.33 mm.
		Site E		
600*	13.4	7.73	14.83	Instrumented (TP-1)
600	11.0	3.68	8.07	
600	10.0	4.63	8.28	
600	17.0	4.30	7.90	
600	27.0	4.53	7.86	
600	24.0	2.75	5.14	
600	32.5	3.63	8.15	
500	10.5	4.99	5.13	
500	24.0	4.04	10.74	
300x300 RC Square Pile	15.0	2.27	6.04	

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/non-instrumented static load test results, Chow & Tan (2010) recommended conservative estimate of shaft friction for jack-in piles in weathered granite to be 5xSPT-N (in kPa). This correlation is expected to be conservative based on the instrumented static load test results and possibility of upward revision is high (Figure 22). However, further instrumented static load test results need to be collected and studied before such conclusion can be made.

3.2 Sedimentary Formation

Chow et al. (2015) presented results of high capacity jack-in pile for high-rise building (24-storey residential apartment) with preboring in weathered sedimentary rock formation where distinct differences in performance can be observed compared to jack-in pile in weathered granite. Recently, the Authors have also completed another high-rise projects in similar ground conditions using high capacity jack-in piles.

The project sites are located in East Ledang and Puteri Harbour in Nusajaya, Johor, Malaysia where high capacity jack-in piles with working load of up to 3000 kN were successfully designed and constructed.

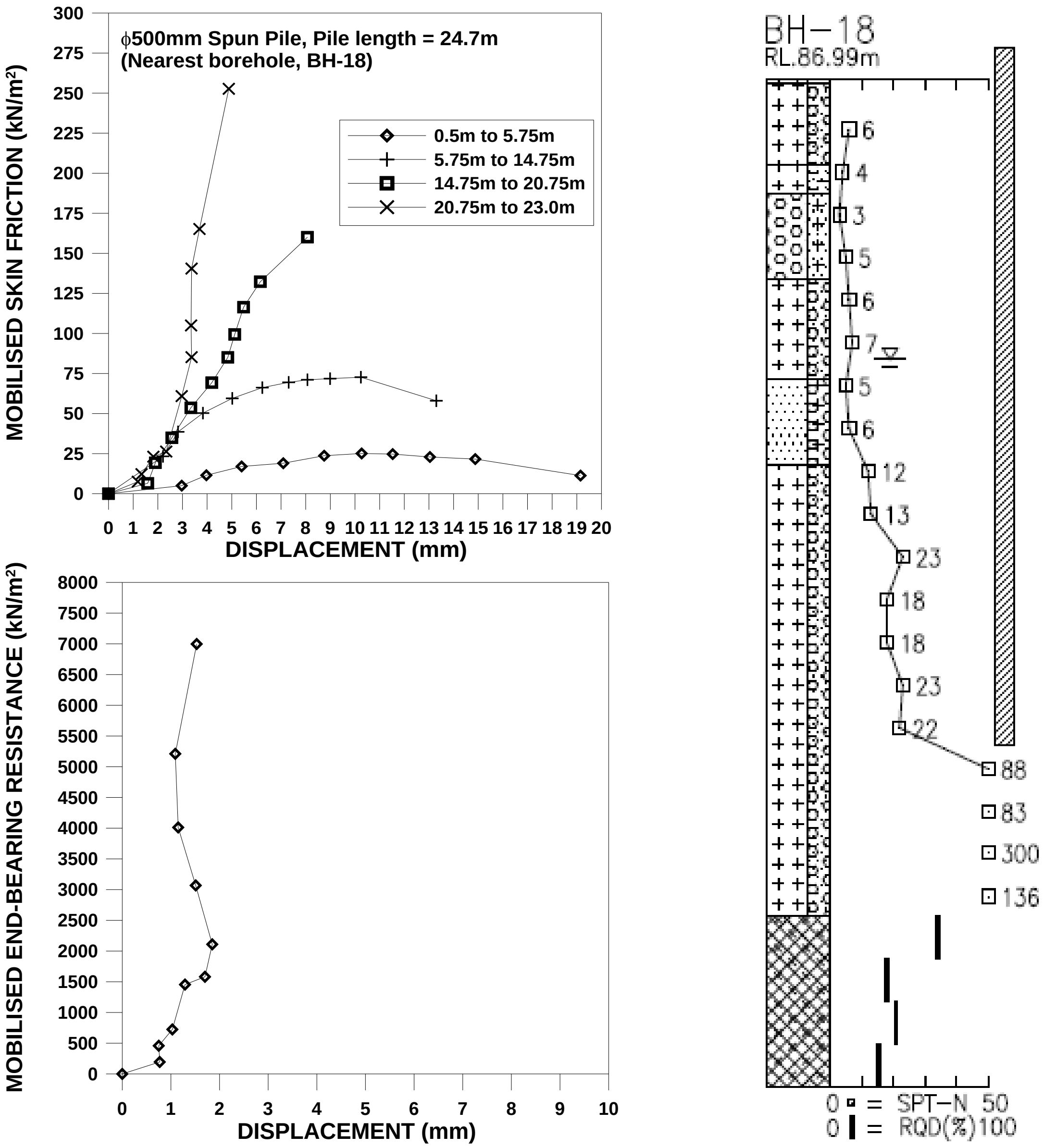


Figure 18 Mobilised shaft friction and end-bearing resistance for PTP-1 (Site C) – Borehole profile relevant to test pile also shown

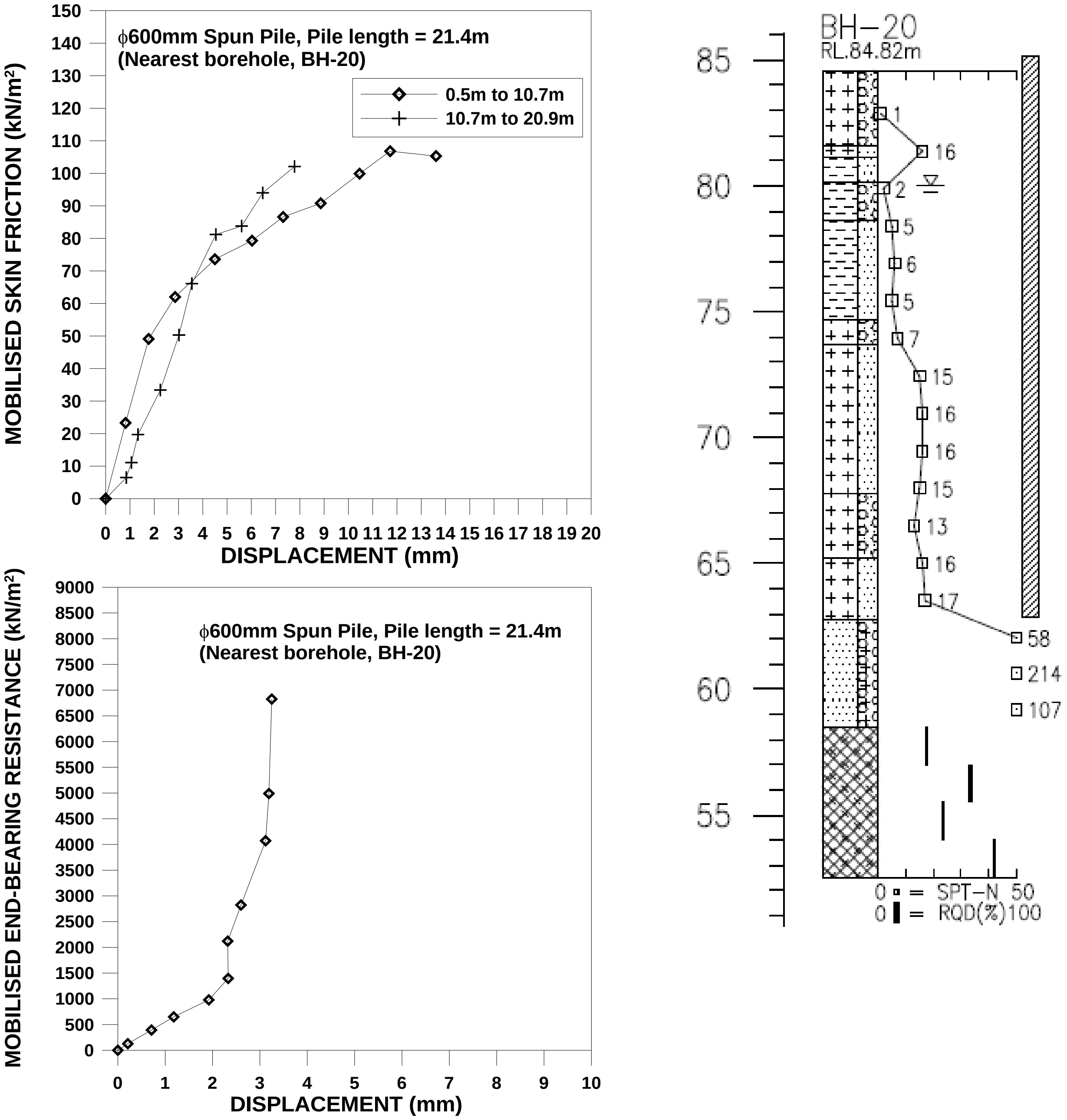


Figure 19 Mobilised shaft friction and end-bearing resistance for PTP-3 (Site C) – Borehole profile nearest to test pile shown

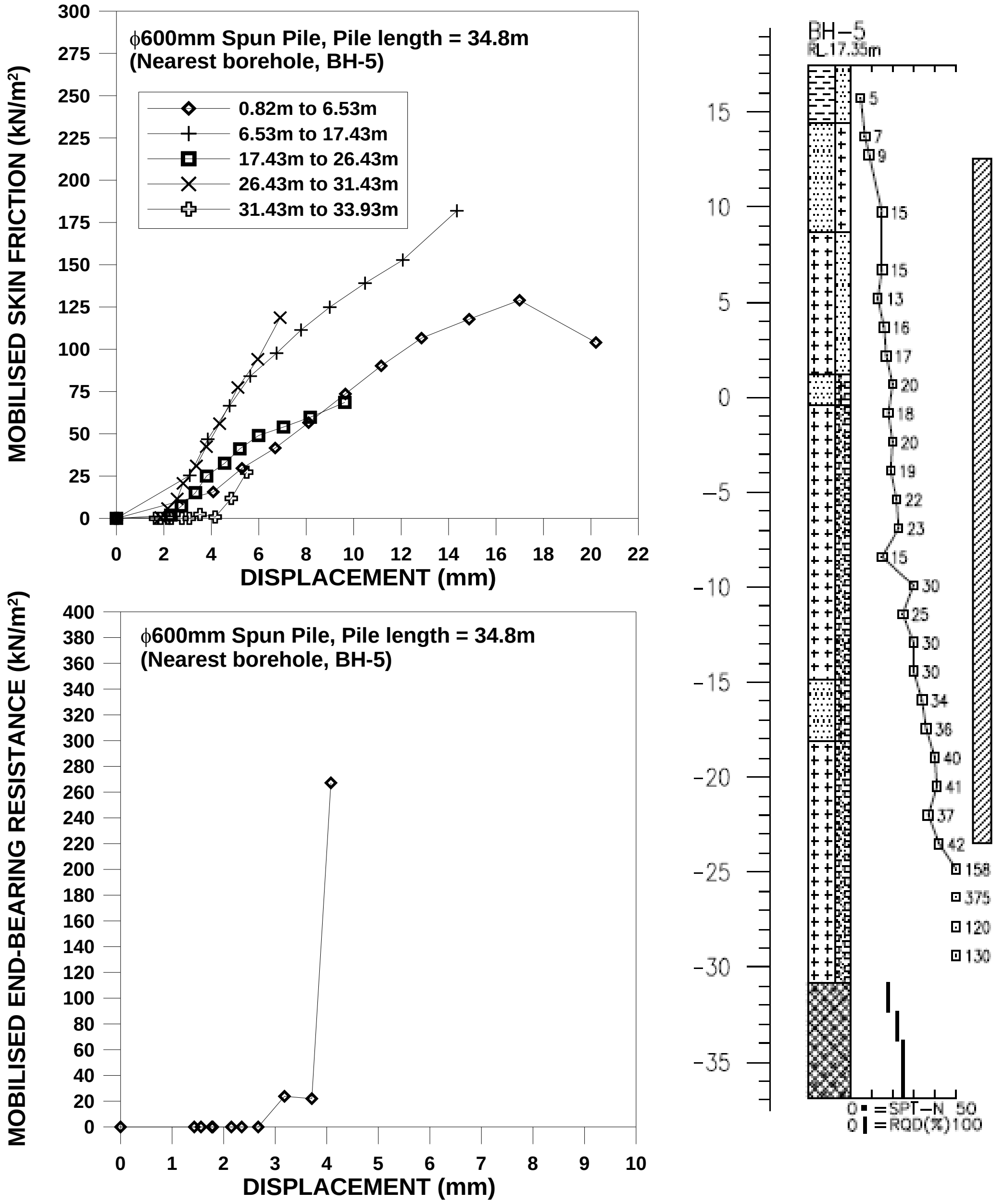


Figure 20 Mobilised shaft friction and end-bearing resistance for PTP-1 (Site D) – Borehole profile nearest to test pile shown

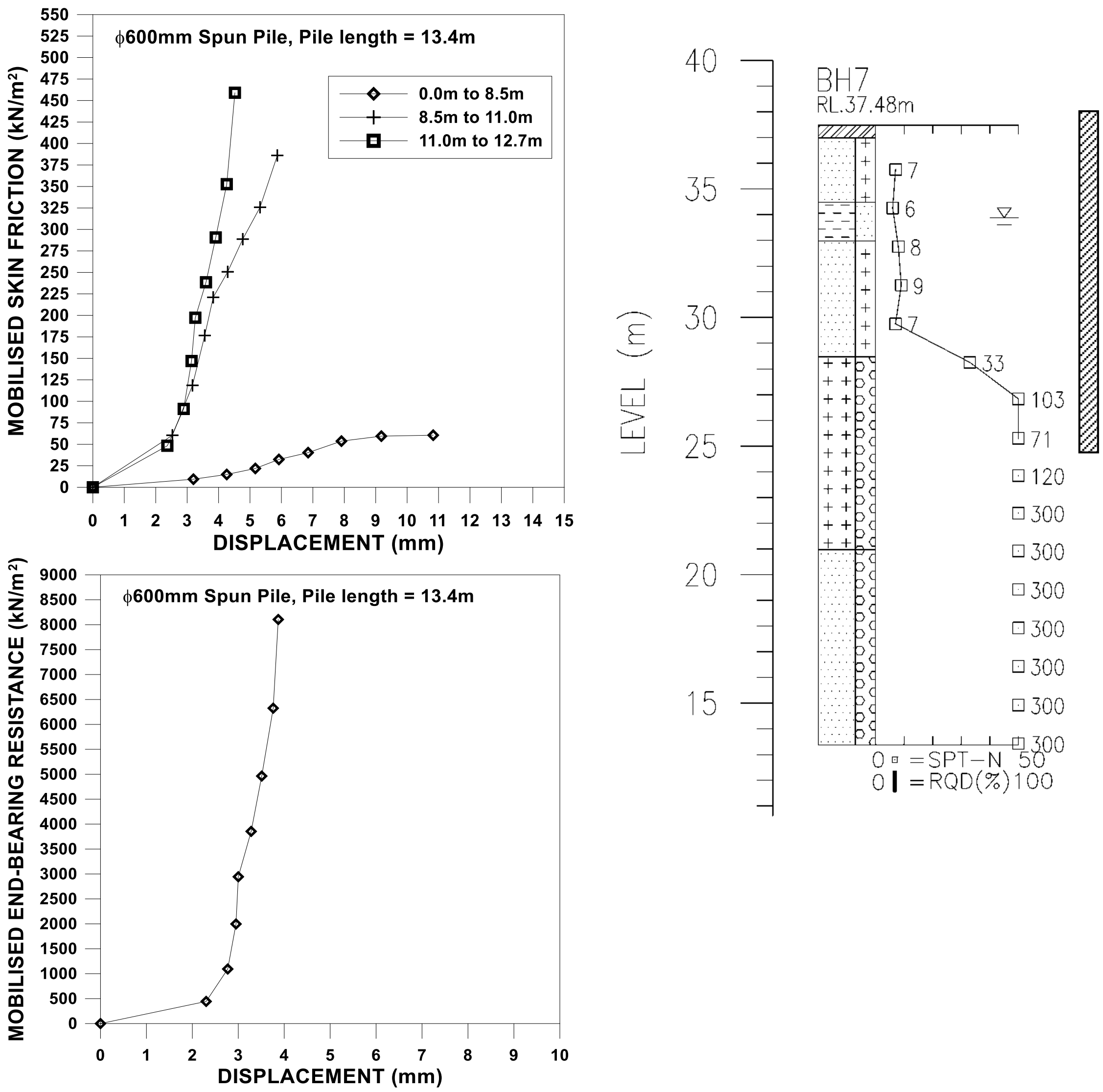


Figure 21 Mobilised shaft friction and end-bearing resistance for TP-1 (Site E) – Borehole profile nearest to test pile shown

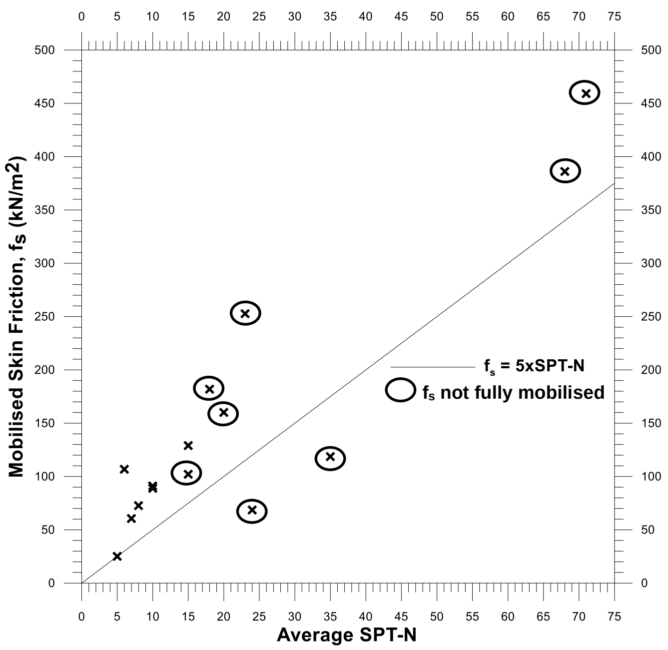


Figure 22 Relationship between mobilised skin friction, f_s against average SPT-N values from instrumented static load tests.

3.2.1 24-storey Residential Apartment in East Ledang, Nusajaya, Johor

For the first project in East Ledang, the installation of jack-in pile was carried out after preboring works to ensure minimum pile length of 5.0 m below cut-off level due to the shallow hard layer (SPT-N > 50) of the weathered sedimentary rock formation. This method required the prebored hole to be backfilled with loose soil. The specified prebore size is equal to or no larger than 50 mm of the diameter of the pile to be installed and the preboring works were carried out using conventional rotary boring rigs without any drilling fluid. Consequently, the piles were installed using jack-in method with termination criteria of jacking to a minimum of two (2) times working load, with the maximum jack-in pressure maintained for at least 20 seconds and the procedure repeated for three (3) times for each pile. Figure 23 shows actual view of the apartment which was completed in 2015 while Figure 24 shows typical borehole profiles of the site. The overburden materials mainly comprise of sandy SILT / silty SAND with increasing SPT-N with depth. Hard layer (SPT-N > 50) was encountered at shallow depths, ranging from 3.0 m to 9.0 m below the ground surface. Furthermore, weathered sandstone and siltstone were encountered at approximately 8.0 m to 15.0 m below the surface. Details of the jack-in pile adopted and tested are summarised in Table 5 while Figure 25 presents the load-settlement curves for the static load tests.

Based on the results of the static load tests conducted at site, the following observations are made:

a) The 500 mm diameter spun pile static load test stopped at 1.9x WL (4370 kN) due to complications experienced by the hydraulic jack during loading. Nevertheless, the pile head settlement at 1.9x WL was relatively small (13.8 mm) with residual settlement of 6.7 mm after unloading as shown in Figure 25(b).
b) Referring to Figure 25(c), the un-instrumented 600 mm diameter pile static load test terminated at 1.8x WL (5400 kN) with pile head settlement of 59.0 mm. In Table 5, the reported pile head settlement of 5.8 mm and 13.0 mm were at WL and 1.5x WL respectively. The pile was unable to achieve 2*WL as excessive pile head settlement was observed. In retrospect, the pile was expected to undergo excessive settlement as the imposed load approached 2*WL because the pile was designed to a global safety factor (FOS) of 2.0. Therefore, it is deemed adequate to test the pile to 1.5x WL (4500 kN) to prevent pile damage and to be consistent with the recommendations of ICE Specification for Piling and Embedded Retaining Walls [Institution of Civil Engineers (ICE), 2007).
c) In general, the results showed that the performances of the jack-in piles were satisfactory, even with preboring. All piles tested to the design working load recorded pile head settlements of 7.0 mm or less with very small residual settlement after unloading. The relatively lower ultimate pile capacity for the un-instrumented 600 mm diameter pile compared to other test piles was possibly caused by the thicker compressed fill beneath the pile toe, resulting in lower end-bearing resistance.

Figure 23 Completed apartments in East Ledang, Nusajaya, Johor, Malaysia

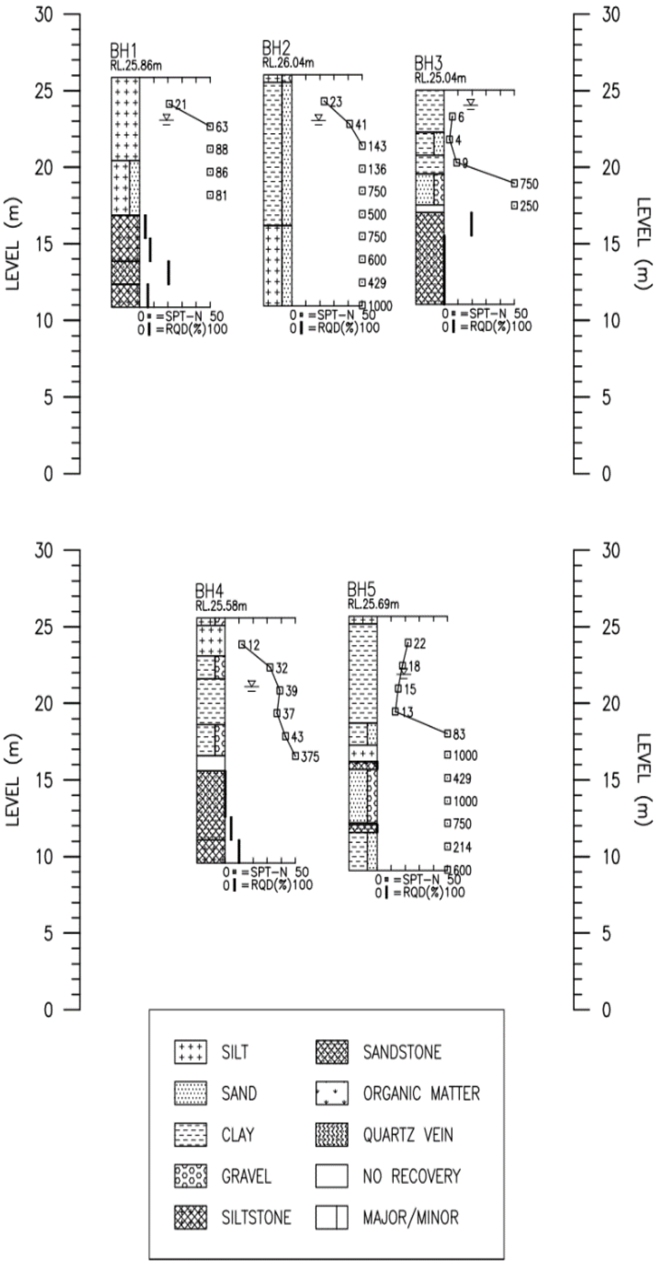


Figure 24 Borehole profiles for 24-storey residential apartment in East Ledang, Nusajaya, Johor, Malaysia

Table 5 Summary of static load test results

Pile Diameter [mm]	Pile Penetration Length [m]	Prebored Depth [m]	Pile Head Settlement [mm]		Remarks
			1x WL[1]	2x WL	
450	8.8	9.0	7.0	26.6	-
500	9.0	11.0	7.0	13.8	At 1.9x WL[2]
600	8.5	11.0	5.8	13.0	At 1.5x WL[2]
600	9.5	9.0	7.0	55.6	Instrumented

Note: [1] *WL denoted Design Working Load. The working loads for 450, 500 and 600 mm diameter piles are 1900, 2300 and 3000 kN respectively.*

[2] *Static load tests terminated at the stated applied load.*

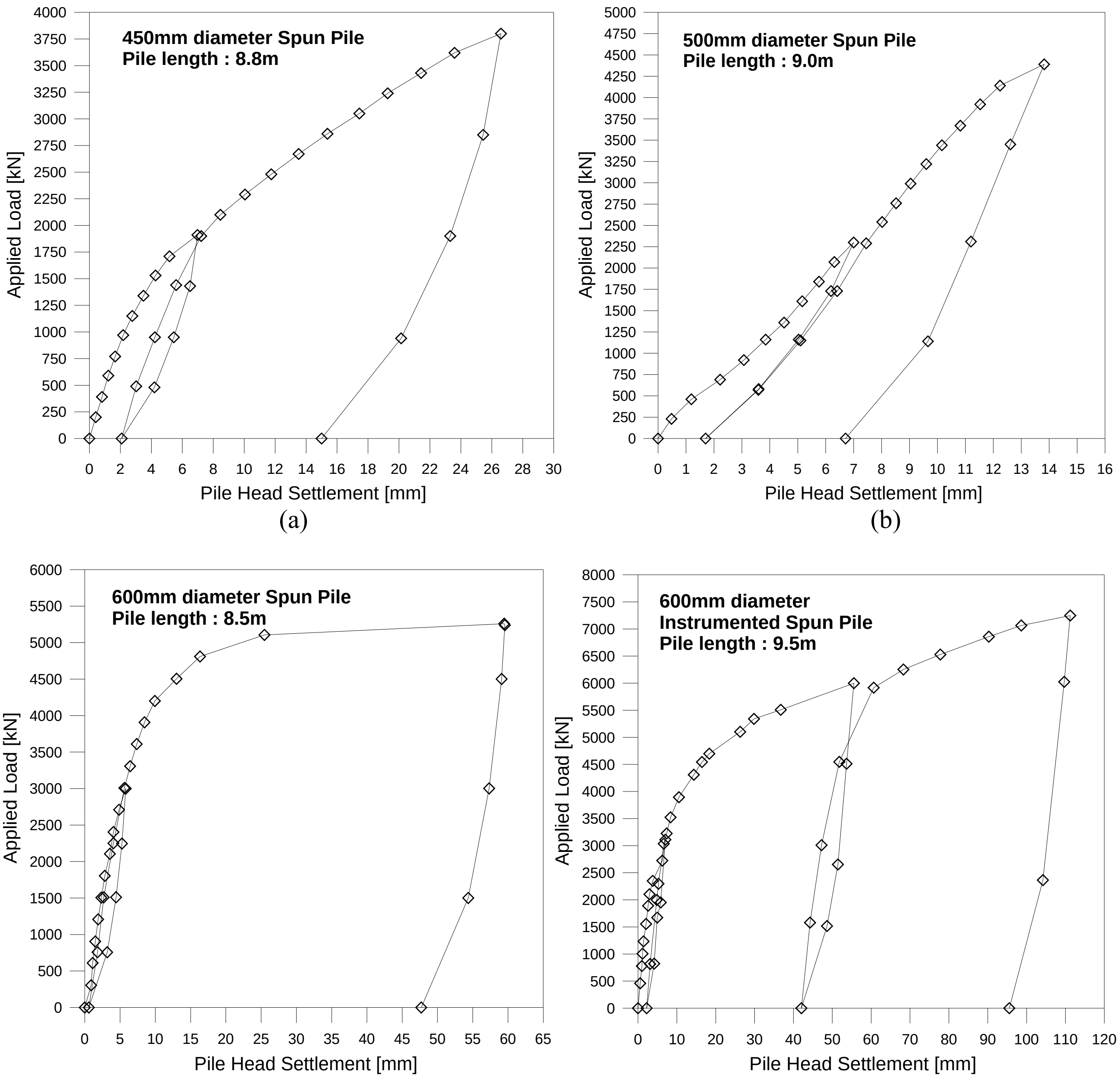


Figure 25 Load-settlement results of static load tests for a) 450 mm, b) 500 mm, c) 600 mm and d) 600 mm diameter instrumented piles

The preliminary test pile was instrumented using GLOSTREXT's global strain gauges and vibrating wire extensometers. The installed instruments allowed for measurements of mobilized shaft friction and mobilized base (end-bearing) resistance of the preliminary test pile. The load transfer curves for shaft friction and end-bearing resistance measured at two (2) times the design working load (2*WL) are illustrated in Figure 26.

From the preliminary instrumented pile static load test results, the following observations are made:

a) Chow & Tan (2010) have suggested a shaft friction correlation factor of 5*SPT-N for jack-in piles in weathered granite without preboring. Figure 26(a) suggests that the ultimate shaft friction was reached with shaft friction correlation factor of approximately 2*SPT-N of the original subsoil, which is fairly high considering the pile was installed into loosely filled prebored hole. Hence, it is evident that the shaft friction is still a function of the original subsoil condition after preboring, but with lower correlation factor compared to jack-in piles in weathered granite without preboring.
b) Figure 26(b) shows that relatively large end-bearing resistance was mobilized at small base displacements. The characteristic secant base stiffness, k_s, at base displacement of 2% pile diameter and with end-bearing resistance normalized to the ultimate end-bearing resistance is about 29. This is consistent with the findings of Deeks et al. (2005), where k_s for jack-in piles is more than two and ten times compared to driven piles and bored piles respectively.

3.2.2 35-storey Mixed Development in Puteri Harbour, Nusajaya, Johor

For the second project in Puteri Harbour, the installation of jack-in pile was carried out after preboring works as intermittent hard layer at shallow depths were detected. The specified prebore size is equal to or no larger than 50 mm of the diameter of the pile to be installed and the preboring works were carried out using conventional rotary boring rigs without any drilling fluid. Subsequently, the prebored holes were backfilled with loose soil and the piles were installed using jack-in method with termination criteria of jacking to a minimum of two (2) times working load, with the maximum jack-in pressure maintained for at least 20 seconds and the procedure repeated for three (3) times for each pile. Figure 27 shows actual view of the development which was completed in 2016 while Figure 28 shows typical borehole profiles of the site.

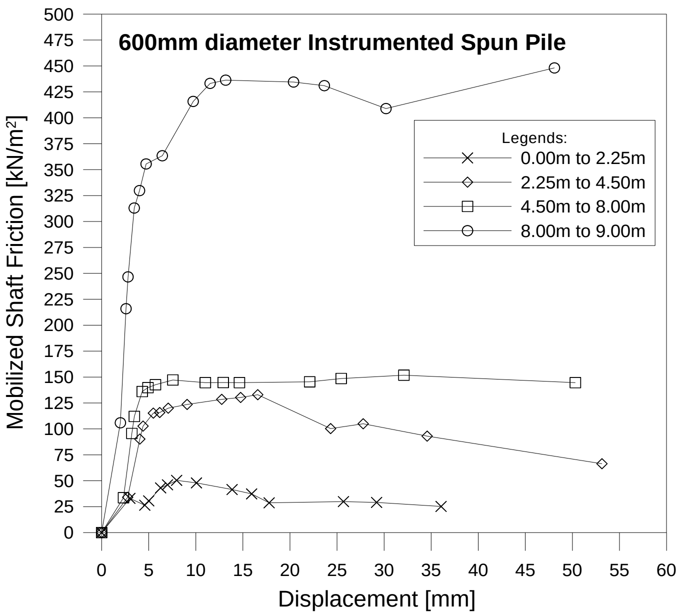
The jack-in pile sizes and capacities adopted are similar to the project in East Ledang, i.e. 450 mm, 500 mm and 600 mm diameter with working load of 1900 kN, 2300 kN and 3000 kN respectively. Results from one of the instrumented test pile (PTP-2a) are shown in Figures 29 and 30.

The following observations can be made from the instrumented test pile results:

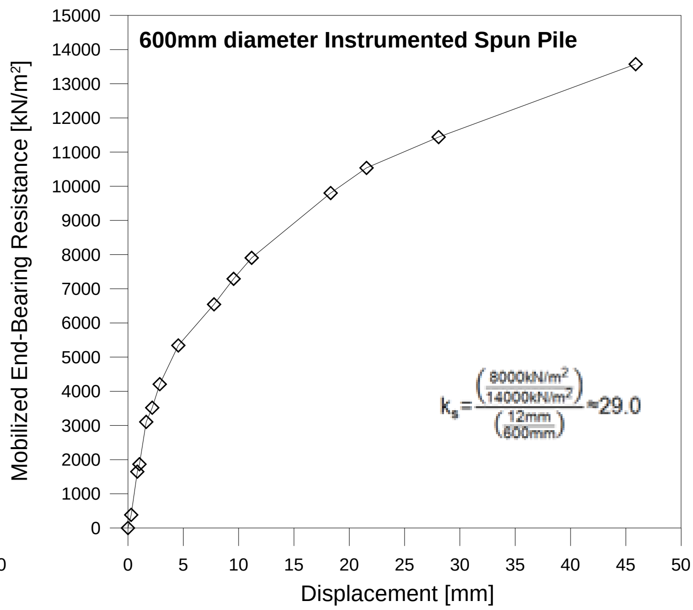
a) The pile performance is satisfactory with settlement at 1*WL and 2*WL of 5.42 mm and 14.64 mm respectively. The pile showed signs of yielding when it reached load of approximately 7000 kN or approximately 2.3*WL.

b) Significant shaft resistance is mobilised even after preboring. Even though results from the instrumented test pile seem to suggest that shaft friction correlation factor of 5*SPT-N is applicable which is similar to jack-in piles in weathered granite without preboring as reported by Chow & Tan (2010), the Authors would advise caution due to the heterogeneous nature of sedimentary formation. Based on the Authors' experiences in similar ground conditions, the shaft resistance of prebored jack-in piles in metasedimentary formation varies considerably (see Section 3.2.1) and as such, it is prudent to err on the conservative side and adopt lower shaft resistance for design purposes.

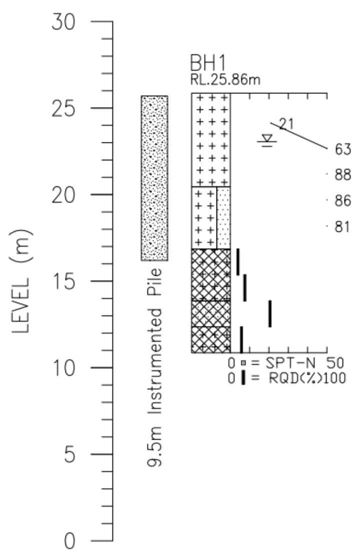
c) Figure 30(b) shows that relatively large end-bearing resistance was mobilized at small base displacements. The characteristic secant base stiffness, k_s, at base displacement of 2% pile diameter and with end-bearing resistance normalized to the ultimate end-bearing resistance is about 35. This is similar to results obtained in East Ledang (Section 3.2.1).



(a)



(b)



(c)

Figure 26 a) Mobilized shaft friction, b) end-bearing resistance for instrumented 600 mm diameter spun pile at 2*WL and c) adjacent borehole profile

Figure 27 Completed 35-storey towers in Puteri Harbour, Nusajaya, Johor, Malaysia (https://www.nst.com.my/property/2019/01/446784/puteri-harbour-potential-gem-south)

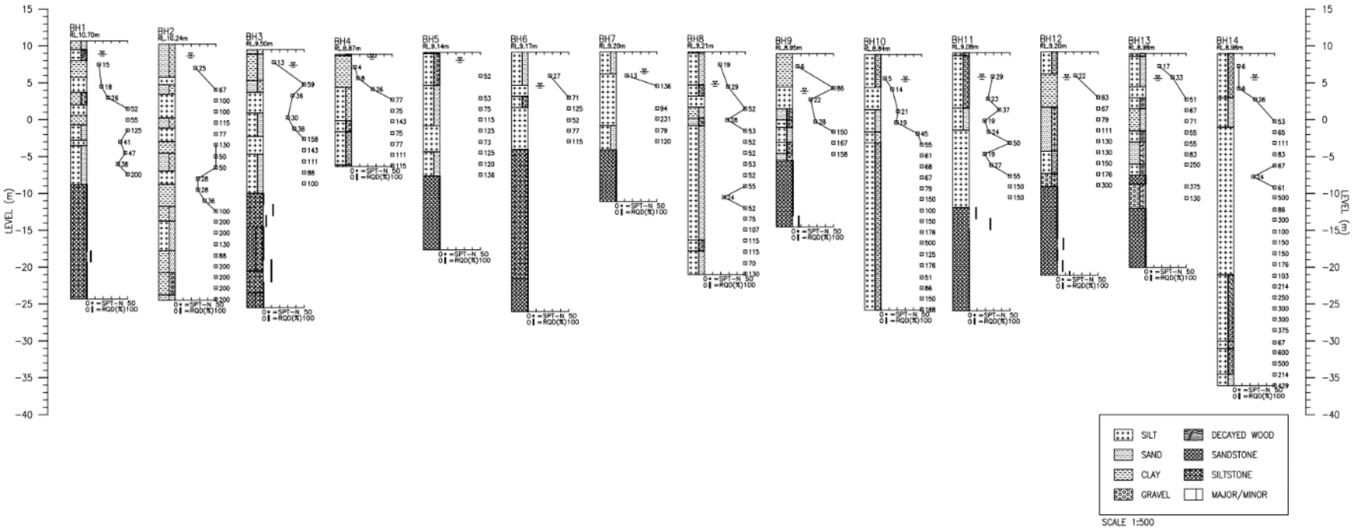


Figure 28 Borehole profiles for 35-storey mixed development in Puteri Harbour, Nusajaya, Johor, Malaysia

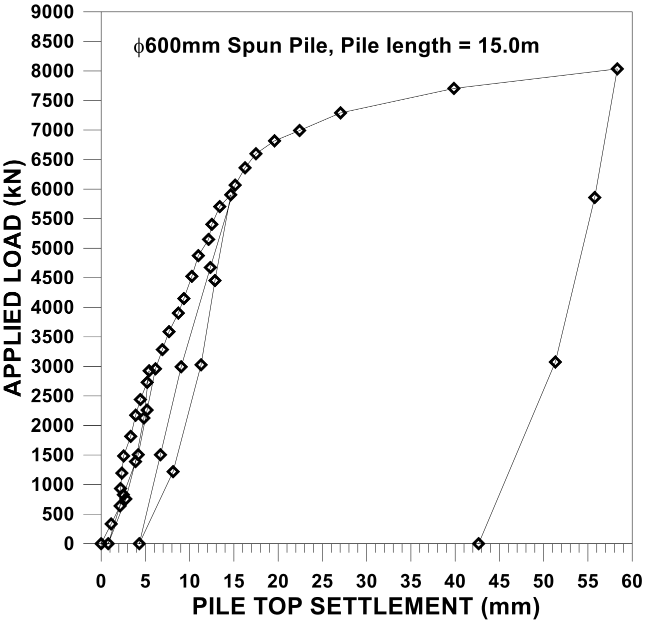


Figure 29 Load-settlement results of static load test at Puteri Harbour, Nusajaya, Johor, Malaysia

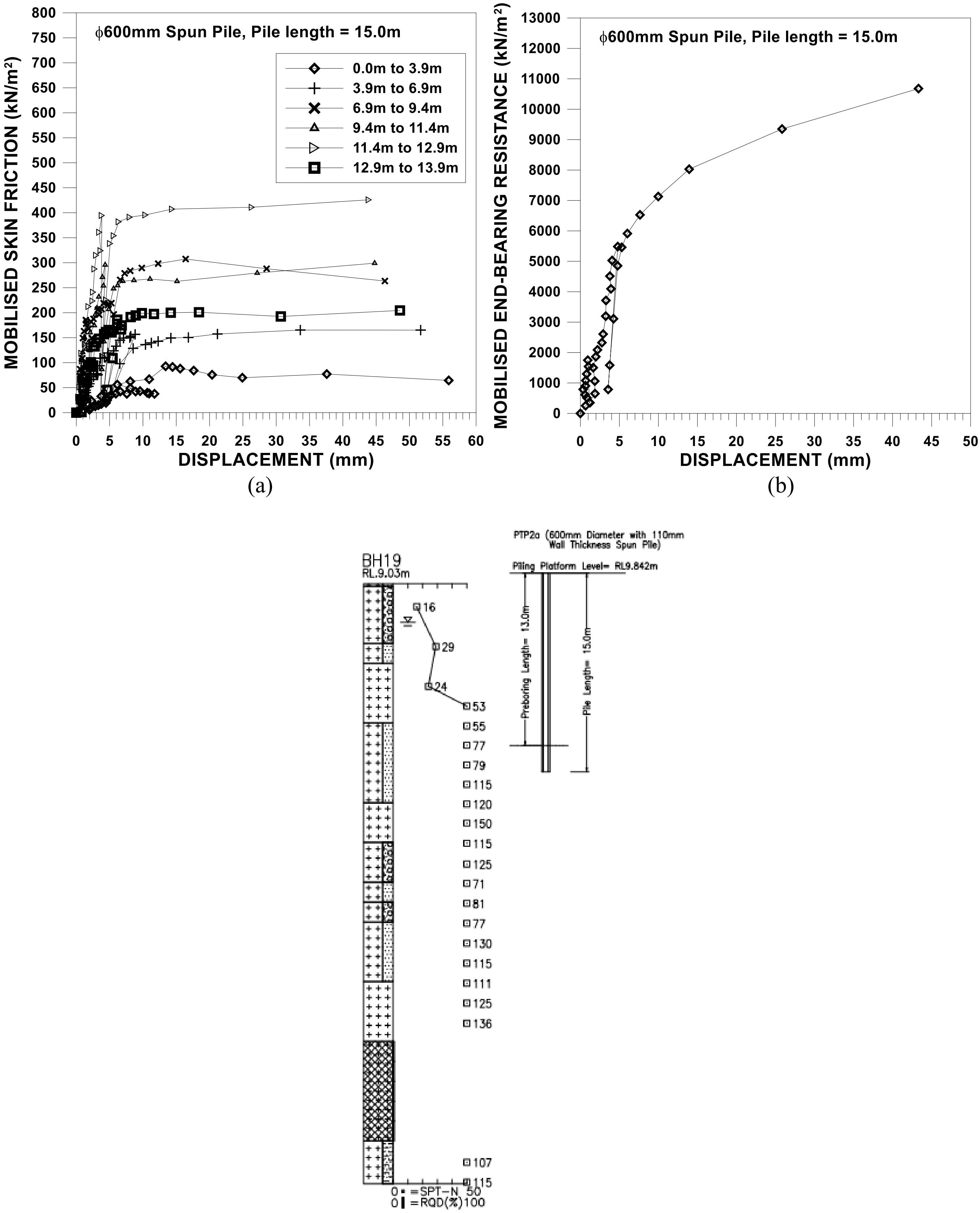
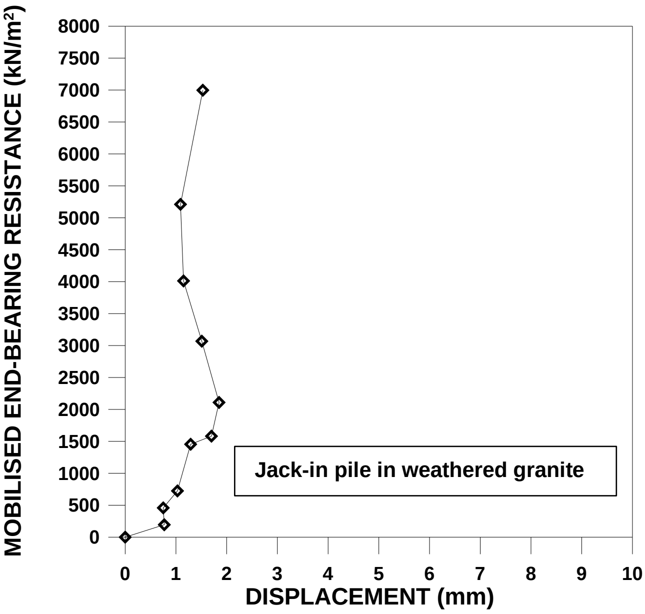


Figure 30 a) Mobilized shaft friction, b) end-bearing resistance for instrumented 600 mm diameter spun pile at 2.7*WL and c) adjacent borehole profile



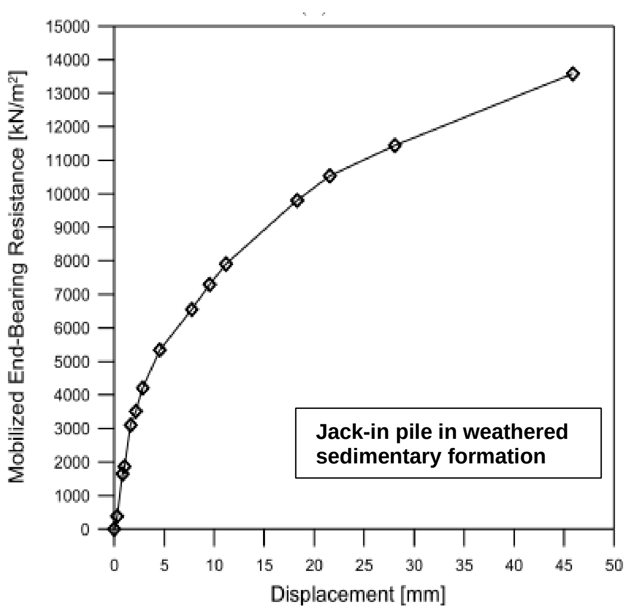


Figure 31 Comparison of end-bearing resistance-displacement curves for jack-in piles in weathered granite and weathered sedimentary formation

4. CONCLUSIONS

High capacity jack-in piles with pile diameter of up to 600 mm and capacity of 3200 kN have been successfully adopted for high-rise buildings in various types of ground conditions. In this paper, the performance of jack-in piles in weathered granite and weathered sedimentary formation is discussed and the following observations were made:

a) Jack-in piles exhibit relatively larger shaft resistance compared to driven piles due to less soil disturbance during pile installation and preliminary correlations of 5*SPT-N is recommended for jack-in piles in weathered granite. The available shaft resistance of jack-in piles even after preboring is still relatively high.
b) Jack-in piles exhibit relatively larger end-bearing resistance compared to driven piles and bored piles due to the precompression of the soil at the base during pile installation and also due to the effect of residual load.
c) The termination criteria of "*Jack the pile to 2.0 times of the design load for a minimum of three cycles with an interval of not less than 3 minutes between each reading. The corresponding pressure has to be held for minimum 20 seconds with settlement not exceeding 2 mm*" is generally adequate for various types of ground conditions. The above criteria provide a convenient reference for termination criteria of jack-in pile which is still subjected to adjustment based on geotechnical conditions of the site, static load test results, contractor's workmanship, etc.
d) Obvious differences in the behaviour of jack-in piles in weathered granite and weathered sedimentary formation are observed. The most distinct difference is in the behaviour of end-bearing resistance where even though relatively large end-bearing is mobilised compared to bored piles/driven piles, the base stiffness of jack-in piles in weathered sedimentary formation is noticeably less stiff as shown in Figure 31.
e) For design purposes, the Authors recommend ultimate end-bearing resistance for prebored jack-in piles in weathered sedimentary formation to be limited to values ranging from 10,000 kPa to 15,000 kPa.

5. REFERENCES

Australian Standard, AS 2159-2009 Piling-Design and installation.

Chow, C.M., and Tan, Y.C. (2009) "Jack-in Pile Design – Malaysian Experience and Design Approach to EC7", IEM Course on Eurocode 7 – Geotechnical Design, 16-17 July 2009, Petaling Jaya, Selangor.

Chow, C.M., and Tan, Y.C. (2010) "Performance of jack-in pile foundation in weathered granite", Proceedings 17th Southeast Asian Geotechnical Conference, Taipei.

Chow, C., Lim, J. A. H., and Tan, Y. (2015) "Performance of high capacity jack-in pile for high-rise building with preboring in weathered sedimentary rock formation", Proceedings 15th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering, Fukuoka.

Deeks, A. D., White, D. J., and Bolton, M. D. (2005) "A comparison of jacked, driven and bored piles in sand", 16th International Conference on Soil Mechanics and Geotechnical Engineering, Osaka.

Geotechnical Society of Singapore, GeoSS. (2015) "Good Practice for Installation of Jacked Foundation Piles in Singapore".

Institution of Civil Engineers. (2007) "ICE Specification for Piling and Embedded Retaining Walls (Second Edition)", Thomas Telford Publishing, London.

Jardine, R., Chow, F., Overy, R., and Standing, J. (2005) "ICP design methods for driven piles in sands and clays", Thomas Telford Publishing, London.

Krishnan, S., and Lee, S. K. (2006) "A novel approach to the performance evaluation of driven prestressed concrete piles and bored cast-in-place piles", Proceedings 10th International Conference on Piling and Deep Foundations, Amsterdam.

Li, V., and Lam, J. (2011) "Development of Jacked Piling in Hong Kong", Proceedings of the 2nd VLA Seminar: New Developments in Jacked Piling, Hong Kong, pp88-116.

Randolph, M.F. (2003) "Science and empiricism in pile foundation design", Geotechnique, 53, No. 10, pp847-875.

Research Committee on Rapid Pile Load Test Methods. (1998) "Research activities toward standardization of rapid load test methods in Japan", Proc. 2nd International Statnamic Seminar, Tokyo, pp219-235.

White, D.J. & Lehane, B.M. (2004) "Friction fatigue on displacement piles in sand", Geotechnique, 54, No. 10, pp645-658.