ABSTRACT: A mixed development consists of a shopping mall with 500 retail lots, a service apartment and a hotel tower (26 floors) is proposed to be constructed over an 18 acres land situated in Klang, Selangor. Based on geological map, the proposed site is located at interface of soft alluvium clay and Kenny Hill formation with Limestone being encountered during the course of subsurface investigation (SI). The average 25m thick soft alluvium (Klang clay), intermediate hard layer and highly uneven limestone bedrock surfaces post a great challenges in term of foundation design. The adopted pile design parameters based on SI are being verified with both instrumented and non-instrumented Maintained Load Test (MLT). Besides, comparison of pile capacity obtained from high strain dynamic pile test (e.g. PDA) during end of drive and pile capacity obtained from MLT after the pile installation is presented. The correlation of undrained shear strength, $s_u$ with shear modulus, $G$ of cohesive soil and some of the best practices adopted at the site are also discussed in this paper.

KEYWORDS: driven pile; soft alluvium; limestone; intermediate hard layer

1 INTRODUCTION

A mixed development consists of a shopping mall with 500 retail lots, a service apartment and a hotel tower (26 floors) is proposed to be constructed over an 18 acres land situated in Klang, Selangor as shown in Figure 1. This project has been divided into three phases in which the foundation works of the initial two phases involving the shopping mall and hotel tower are discussed in this paper.

Generally, the site is located approximately 50m from an existing river (Sungai Si Jangkang) and previously a palm oil plantation which has a fairly flat terrain. Based on the subsurface investigation (SI) works, the subsoil consists a layer of 1.5m thick filled material. The filled material overlying a rather homogenous soft clay (SPTN<4) with thickness of about 25m. This soft clay layer has been termed as “Klang Clay” by past researchers (Tan et al.) and post great challenges to the geotechnical engineers in term of foundation design due to its low undrained shear strength and high compressibility. Figure 2 shows the soft clay encountered during pilecap excavation. As the proposed platform level is about same as current ground level (no additional fill) and filled materials have been placed there for years, negative skin friction is not a concern in the foundation design.

Spun pile with 500mm and 600mm diameters are adopted as the foundation for the project. Based on the SI results, the competent hard layer (SPTN>50) or rock are encountered at depth of 55m to 60m below ground level. Commonly, the piles will be driven or jacked to set (founded on the competent hard layer or rock) in order to achieve the designed pile working load, which is normally same as the pile structural capacity. However, the preliminary test piles are installed to predetermined length (pile to length) using hammer-driven rigs in order to explore possibility to optimize the pile length. This paper mainly presents the design, construction and performance of driven pile in soft clay. Besides, results of Maintained Load Test (MLT) with and without instrumentation are analysed to evaluate the performance of the piled foundation. The correlation of undrained shear strength, $s_u$ with shear modulus, $G$ of cohesive soil and some of the best practices adopted at the site are also discussed in this paper.

2 GENERAL GEOLOGY

The Geological Map of Pelabuhan Klang and Klang, New Series L 7010 Sheets 93 published in 2011 by Minerals and Geoscience Department of Malaysia, indicates that the site is underlain by two different formations, namely alluvium and Kenny Hill Formation (Figure 3). In addition, the SI work revealed that limestones are encountered at deeper depth.
3 SUBSOIL CONDITION

Based on the SI results, the subsoil generally consists of 25m to 30m thick of very soft to soft CLAY/SILT overlying loose to medium dense silty SAND to SAND as shown in Figure 4. It is observed that there are intermediate hard layers (SPT-N>50) at around 35m to 40m below ground level. Meanwhile, limestones are encountered at approximately 55m to 60m below ground level.

Besides, borehole vane shears tests are carried out until 30m below ground level at specified interval to obtain the undrained shear strength of the soft clay. The undrained shear strength obtained from the vane shear tests together with laboratory testing [e.g. Unconsolidated Undrained (UU) Tests] are presented in Figure 5.

4 PILE CONSTRUCTION

4.1 Pile Installation

Circular pre-stressed spun piles of 500mm and 600mm diameters with 80MPa concrete strength and wall thickness of 90mm & 100mm respectively have been adopted as the foundation pile system for the entire project with driven method.

The designed pile working capacities for 500mm and 600mm diameter are 1800kN and 2700kN respectively and the piles are designed to be founded on hard layer or bedrock. However, maintained load tests (MLT) are carried out on piles, which are installed to predetermined length (not set) with aim to explore pile to length option as an alternative to the pile to set system.

4.2 Maintained Load Test

In overall, two maintained load tests (MLT) are carried out for this project, which consist of one sacrificial test pile (PTP2 on 600mm dia. spun pile) and one instrumented maintained load tests (PTP1-R with 500mm dia. spun pile).

Both PTP1-R and PTP2 are supposedly to be tested to 3 times of the designed pile working load (5400kN and 8100kN respectively). However, excessive settlement of pile occurred at test load of 3052kN and 4050kN for PTP1-R and PTP2 respectively. Load settlement plots for PTP1-R and PTP2 are shown in Figures 6 and 7 respectively. Whilst, Table 1 summarises the pile settlements experienced by PTP1-R and PTP2 with the load cycles. As both tests are unable to achieve 2 times of the designed working load, the pile lengths are reverted to the original pile length of 54m and 60m for 500mm and 600mm diameter pile respectively.
4.3 High Strain Dynamic Pile Test

PTP1, PTP1-R and PTP2 are driven with continuous pile monitoring (CPM) to determine the hammer drop height criteria along the pile length during installation of piles with 11 tonnes hammer. This exercise is to ensure that the driving stresses especially tensile stress in the pile during driving are within the allowable stress limit as per Table 2. Subsequently, the contractor is required to install all the working piles as per the hammer drop height criteria established via CPM results.

The CPM results of PTP1-R as shown in Figure 8, can be observed that the pile is installed successfully within the allowable driving stresses with 11 tonnes hammer and the proposed drop height. As the first 16m subsoil consists of soft clay (with SPTN less than 2), the piles are penetrated into the ground under the self-weight of the hammer. The CPM results yield that the pile experienced spike of TSX at 40m below ground even without increase in hammer drop height. It is deduced that this phenomenon (sudden increase in TSX) is contributed by the breakthrough of intermediate hard layer that results in sudden release of energy in the pile. This is tallied with the increase in SPT’N value at the similar depth, which shown that there is intermediate hard layer.

Thus, CPM is crucial in determining the maximum drop height and hammer weight with respect to the ground condition to ensure the tension force in the pile does not exceed the allowable value and to reduce the possibility of the pile being damaged during the installation process.

Whilst, high strain dynamic pile tests (HSDPT) during end of drive for PTP1-R have been carried out and compared with the MLT results carried out after 2 weeks of pile installation. The results for both tests are presented in Table 3.

Table 2. Allowable Stress Limit

<table>
<thead>
<tr>
<th>Description</th>
<th>Allowable stress limit recommended</th>
</tr>
</thead>
<tbody>
<tr>
<td>CSX</td>
<td>0.85 (f'c - fpe)</td>
</tr>
<tr>
<td>TSX</td>
<td>( f_{pe} + 0.25 \left( \frac{f_0}{f_{pe}} \right)^{1/2} )</td>
</tr>
</tbody>
</table>

Where:

\( f_0 = \) Concrete 28 day Strength (MPa)

\( f_{pe} = \) Effective pre-stress (MPa)

Based on the CPM results of PTP1-R as shown in Figure 8, it can be observed that the pile is installed successfully within the allowable driving stresses with 11 tonnes hammer and the proposed drop height. As the first 16m subsoil consists of soft clay (with SPTN less than 2), the piles are penetrated into the ground under the self-weight of the hammer. The CPM results yield that the pile experienced spike of TSX at 40m below ground even without increase in hammer drop height. It is deduced that this phenomenon (sudden increase in TSX) is contributed by the breakthrough of intermediate hard layer that results in sudden release of energy in the pile. This is tallied with the increase in SPT’N value at the similar depth, which shown that there is intermediate hard layer. Thus, CPM is crucial in determining the maximum drop height and hammer weight with respect to the ground condition to ensure the tension force in the pile does not exceed the allowable value and to reduce the possibility of the pile being damaged during the installation process.

Whilst, high strain dynamic pile tests (HSDPT) during end of drive for PTP1-R have been carried out and compared with the MLT results carried out after 2 weeks of pile installation. The results for both tests are presented in Table 3.
Table 3. Summary of CAPWAP and MLT Results for PTP1-R

<table>
<thead>
<tr>
<th>Date of Installation or Test / (Time lapsed from date of installation, days)</th>
<th>Type of Test</th>
<th>Shaft Friction (kN)</th>
<th>End Bearing (kN)</th>
<th>Total (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7th February 2017 / (0)</td>
<td>End of drive</td>
<td>1391</td>
<td>169</td>
<td>1560</td>
</tr>
<tr>
<td>22nd February 2017 / (15)</td>
<td>Instrumented MLT</td>
<td>2568</td>
<td>484</td>
<td>3052</td>
</tr>
</tbody>
</table>

Table 3 clearly indicates that the shaft friction has increased about 1.8 times after (2) two weeks of installation as confirmed by the instrumented MLT test.

Similar to PTP1-R, the restrike HSDPT on PTP1 (2 weeks after installation) also yielded that pile capacity increase from 1785kN to 3279kN, which increased by about 84% (Table 4) and this is in lined with observation by Liew & Kowng (2005). The much lower ultimate pile capacity at EOD as compared to the instrumented pile test indicates significant reduction in shear strength of soft clay that was contributed by disturbance during pile installation (i.e driving). Whilst, the significant increase in ultimate pile capacity after 2 weeks demonstrating the gained in strength with time or the commonly known as “set up” effect.

Table 4. Summary of CAPWAP Results for PTP1

<table>
<thead>
<tr>
<th>Date of Installation or Test / (Time lapsed from date of installation, days)</th>
<th>Event Analysed</th>
<th>Shaft Friction (kN)</th>
<th>End Bearing (kN)</th>
<th>Total (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20th January 2017 / (0)</td>
<td>End of drive (CPM)</td>
<td>1054</td>
<td>731</td>
<td>1785</td>
</tr>
<tr>
<td>7th February 2017 / (18)</td>
<td>Re-strike</td>
<td>2890</td>
<td>389</td>
<td>3279</td>
</tr>
</tbody>
</table>

4.4 Instrumentation Results

The instrumented test pile, PTP1-R, was equipped with ten levels of strain gauges as shown in Figure 9 and the borehole profile of nearest borehole, BH5 is indicated in Figure 9 for ease of reference. The strain gauges were installed after pile installation.

Although the MLT was unable to achieve the objective to optimise the pile length, this provide a good platform for the Authors to study the mobilised ultimate shaft resistance of the subsoil throughout the pile length and the ultimate base resistance. The instrumented test results showed that the subsoil has been mobilised to its ultimate shaft friction resistance throughout the pile length as shown in Figure 10. The SPTN values (e.g.: 4 to 27) for the pile length from 27.5m to 48m below ground level have been correlated with the mobilised ultimate shaft friction resistances recorded range from 28kPa to 132kPa. The mobilised ultimate shaft friction resistance correspondence to about 4 to 9 times of the SPTN values. Therefore, it can be concluded that a conservative correlation of shaft friction of 3 x SPT-N can be adopted for driven pile design in such subsoil condition.

Meanwhile, the mobilised ultimate shaft friction resistances for the soft clay layer at 2.0m bgl- Level B, Level B-C, Level C-D and Level D-E are about 14.5kPa, 18.8kPa, 19.6kPa and 21kPa respectively. The back-calculated empirical factor of α is lower than the theoretical empirical factor of α suggested by McClelland (1974) chart. However, it can be noted that the decreasing trend of the magnitude of empirical α factor with respect to increasing undrained shear strength is similar.

4.4.1 Load Distribution

Figure 9 Location of strain gauges for PTP1-R and BH5.
Figure 11 Load distribution curve with depth below platform level.

With the ultimate end bearing (2601.5kPa) for PTP1-R as shown in Figure 12 and the average SPT-N value (10) from nearest borehole at the pile toe, the ultimate base resistance factor which is approximately 260. Thus, the ultimate base resistance factor of 250 can be adopted to determine the ultimate base resistance. Meanwhile, Figure 12 also shows that the base resistance requires a larger magnitude of displacement to be fully mobilised as compare to the shaft friction resistance.

In addition, attempts to correlate the undrained shear strength, \( s_u \), with the shear modulus, \( G \) of the encountered soft clay has been made by using PIGLET and REPUTE. The axial deformation of piles may be estimated reasonably well by taking \( G \) in the range of \( 200 \leq G/s_u \leq 400 \) based on recommendations by Randolph (2007).

The load-settlement curves from REPUTE and PIGLET results are presented together with the actual load-settlement curve of the pile in Figure 13. The calculated pile settlements from both software are based on \( G = 200s_u \) (in kPa) for soft clay (cohesive soil) and \( G = 1000 \times SPT-N \) kPa for cohesionless soil. Based on Figure 13, the estimated settlements using REPUTE are closed to the settlements measured during the pile test for 1st cycle, which is tested up to 1 time working load.

4.5 Construction Practices

During construction stage, the following good practices are exercised to ensure the piles are installed successfully:

a) The working pile has been installed without pile shoes (open ended) with intention to reduce the displacement of the upper soft clay in horizontal direction that would cause movement to the adjacent installed piles.

b) The sequence of pile installation is also a crucial step that requires careful planning and control. The pile from a pile group shall be installed from the inner to the outer of the pile group as to avoid the displacement of soft clay to the adjacent piles during pile installations.

c) Generally, it is recommended that a maximum 5% of the total pile number shall be subjected to high strain pile load tests. In view the existence of intermediate hard layers, additional high strain pile load tests are carried out to verify the performance and integrity of the installed piles. The total number of high strain pile load tests carried out at this project is about 8% of the total pile number.

5 CONCLUSIONS

From the test pile results, the following findings can be drawn:

a) Ultimate pile capacity for PTP1-R and PTP1 of about 3052kN and 3279kN are recorded respectively after 2 weeks of pile installation which show an increased in pile capacity by almost 1.8 as compared to the capacity obtained during installation.

b) It is recommended all pile tests such as maintain load test and high strain pile load test shall only be carried out on the pile minimum 14 days after installation for similar ground condition.

c) The pile test results indicate a conservative preliminary correlation for shaft friction resistance of \( 3 \times SPT-N \) can be adopted for driven pile with similar ground condition.
However, higher shaft resistance correlation also can be adopted subjected to pile test results.

d) Although the pile is not installed to set, correlation for base resistance of 250 x SPT-N can be adopted to determine the ultimate base resistance of pile installed to length.

e) Correlation of $G=200s^u$ and $G=1000$ x SPT-N can be adopted for cohesive and cohesionless soil respectively in similar subsoil condition to predict the pile settlement at 1 time working load with good accuracy.

f) Higher percentage (8%) of high strain dynamic pile tests are recommended for project with similar ground condition (i.e intermediate hard layer) due to higher tendency of pile breakage.

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Liew S. S., Kowng Y. W., (2005), "Design, Installation and Verification of Driven Piles in Soft Ground", 11th International Conference of IACMAG, Torino, Italy
