REPORT ON THE EFFECTS OF THE BASE GROUTING / DCM ON DEEP FOUNDATION BORED PILES AT MARINA BAY BUSINESS FINANCIAL CENTRE

Report Submitted by:

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ABSTRACT

The author would like to submit his report on one of the project involved in his engineering life. The project is at Marina Bay Business Financial Centre. The author would describe his involvement in this project. The focus of this report would describe the author’s analysis on the instrumented test piles results for the deep foundation bored piles. The effects of base grouting and Deep Cement Mixing (DCM) on the pile performance would be described. Encouraging results are presented and the outcome of the analysis could help in the improvement of the deep foundation Bored Pile design in Singapore.
ABSTRACT

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EFFECTS OF BASE GROUTING ON PILES AT
MARINA BAY BUSINESS AND FINANCIAL CENTRE

Introduction of Project

Marina Bay Business and Financial Centre (MBFC) is one of the most iconic project in Singapore. The author was very grateful that he was able to involve in this large scale civil engineering works. The author was assigned as a Senior Civil Engineer with the reputable civil engineering contractor, Tiong Seng Contractors (Pte) Ltd (TSC). The scope of the construction works, which cost S$100 millions and undertaken by TSC are:

- Deep foundation works (bored piles)
- Retaining walls (contiguous bored piles & secant piles)
- Soil improvement (deep cement mixing and jet grouting piles)
- Geotechnical instrumentation
- A&A to the existing Common Services Tunnel

The project involves residential development and commercial development. Residential development which include 3 high rise tower blocks and 2 podiums.

The author was the Engineer-In-Charge and he has to manage the site execution of the engineering works and to handle technical issues together with the consultants and authorities. Design and confirmation of the founding depths for the foundation bored piles were also his major duty in this project. The author has to work together with the six geotechnical engineers, who were reported to him.
Problem Analysis

The proposed site is located at the marina bay area, which has one of the most difficult geological formations in Singapore. In this project, about 85 numbers of soil investigation bore holes had been carried out by the SI company, Moh & Associates as shown. Generally, the formation comprises reclaimed sand/hydraulic sand fill, upper marine clay, fluvial layer, lower marine clay and old alluvium. Part of the Tower 2 is located within the area of existing seawalls. The site is next to the Marina Bay Basin and surrounded by the existing Common Services Tunnel (CST). The existing MRT North-South Line (NSL) is also passing through Tower 2 and Phase 3. Both the geological formation and the strategic location determine the challenges and difficulties for the project.

Generally, the construction sequences are:

- Stage 1: Installed geotechnical instruments, such as inclinometers, water stand pipes, piezometers, vibration meters, prisms and ground settlement markers.
- Stage 2: Installed DCM (If there is, all areas have DCM except R1 & Podium block at Residential Development).
- Stage 3: Coring for grouted DCM layers after 28 days.
- Stage 4: Installed bored piles and retaining wall (secant piles & contiguous bored piles).
Soil investigation bore holes location at MBFC

FIG. 5.4 POSSIBLE EXTENT OF GRANITE / CONCRETE BOULDERS (OLD SEA WALL)
General geological formation for MBFC

<table>
<thead>
<tr>
<th>Layer</th>
<th>Description</th>
<th>Thickness</th>
<th>N-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1</td>
<td>Fill material, Very loose to medium dense hydraulic sand fill</td>
<td>~ 10 to 25m</td>
<td>≤ 30</td>
</tr>
<tr>
<td>Layer 2A</td>
<td>Very soft to soft marine clay (upper marine clay)</td>
<td>~ 10 to 15m</td>
<td>≤ 4</td>
</tr>
<tr>
<td>Layer 3</td>
<td>Loose to medium dense silty sand / clay (Fluvial material)</td>
<td>~ 5m</td>
<td>≤ 4</td>
</tr>
<tr>
<td>Layer 2B</td>
<td>Soft to stiff marine clay (lower marine clay)</td>
<td>~ 5m</td>
<td>≤ 15</td>
</tr>
<tr>
<td>Layer 4</td>
<td>Medium dense clayey to silty sand and stiff to very stiff silty to sandy clay (Old Alluvium)</td>
<td>~ 0 to 10m</td>
<td>≤ 30</td>
</tr>
<tr>
<td>Layer 5A</td>
<td>Dense, silty sand and hard, silty to sand clay with some gravels (Old Alluvium)</td>
<td>~ 0 to 10m</td>
<td>≤ 30</td>
</tr>
<tr>
<td>Layer 5B</td>
<td>Very dense, clayey to silty sand and hard, silty to sandy clay (Old Alluvium)</td>
<td>~ 5 to 15m</td>
<td>≤ 100</td>
</tr>
<tr>
<td>Layer 6</td>
<td>Very dense, silty sand and very hard, silty to sandy clay and sandy silt (Old Alluvium)</td>
<td>(&gt;&gt;40m)</td>
<td>&gt; 100</td>
</tr>
</tbody>
</table>

EGL ~ RL 103.500m
In this report, bored piles were only discussed. Bored piles were the first engineering works commenced in this project at Residential Development since there was no basement and no soil improvement was required in this area. In this project, the geotechnical design for the bored piles is the responsibility of TSC. This was clearly stated in the contract specifications as “The contractor shall be solely responsible for the geotechnical design and installation of working piles which shall support the specified loads with appropriate factor of safety”. Therefore, it was important to come out the design calculations with the reasonable and agreeable parameters.

The total numbers of the bored piles in this project. Dia 1800mm bored piles are designed for the tower blocks and dia 800mm to dia 1200mm are used for the podium blocks and basement carparks. An appropriate method to construct the deep foundation with quality control and quality assurance is also very crucial to ensure that the piles are safe to support the skyscrapers and to complete the project on time.

<table>
<thead>
<tr>
<th>Area</th>
<th>Dia 1800mm bored piles</th>
<th>800 to 1200 mm bored piles</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1 &amp; Podium</td>
<td>112</td>
<td>120</td>
<td>232</td>
</tr>
<tr>
<td>Tower 1 &amp; 4A Podium</td>
<td>107</td>
<td>95</td>
<td>202</td>
</tr>
<tr>
<td>Tower 2 &amp; 4B Podium</td>
<td>207</td>
<td>115</td>
<td>322</td>
</tr>
<tr>
<td>3A &amp; 3B Basement Car parks</td>
<td>0</td>
<td>269</td>
<td>269</td>
</tr>
<tr>
<td>Parcel A7 UPN</td>
<td>0</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Total</td>
<td>426</td>
<td>629</td>
<td>1055</td>
</tr>
</tbody>
</table>

**Numbers of foundation bored piles at MBFC**
Design and Development of Solutions

In order to handle such large extent of the bored piling works at MBFC, a systematic approach in the design and construction was required to be established prior commencement of works.

Firstly, design equations and assumed design parameters have been discussed and agreed with the C&S Consultant, Meinhardt (Singapore) Pte Ltd (MSPL), and specialist contractors, Resource Piling Pte Ltd (RPPL) and KH Foges Pte Ltd (KH). In this project, the author was very grateful to work with the following professional personnel.

- MSPL: Er. Kam Mun Wai, Dr. Junied Qureshi (Qualified Person’s representatives)
- TSC: Prof. Harry Tan (TSC’s specialist consultant), Er. Lim Kim Chai & Er. Dr. Indra (TSC’s consultants)
- RPPL: Er. Foo Hee Kang (Professional Engineer from the specialist contractor)
- KH: Er. Dr. IH Wong (KH’s specialist consultant)

The geotechnical design for the bored pile is:

Case 1: \[ Q_p \geq \frac{Q_{s,ult}}{2.0} = \frac{f_s A_s}{2.0} \]

Case 2: \[ Q_p \geq \frac{Q_{s,ult} + Q_{p,ult}}{2.5} = \frac{f_s A_s + f_p A_p}{2.5} \]

Case 3: \[ Q_p \geq \left( \frac{Q_{s,puf}}{1.5} - \eta Q_{s,ulf} \right) = \left( \frac{f_{s,puf} A_{s,puf}}{1.5} - \eta f_{s,ulf} A_{s,ulf} \right) \]

Where \( Q_p \) = working capacity the pile;
\( Q_{s,ult} \) = ultimate skin resistance (kN)
\( f_s = \) ultimate skin friction (kN/m²)  
\( A_s = \) Circumference area (m²)  
\( Q_{p,ult} = \) ultimate base resistance (kN)  
\( f_p = \) ultimate end bearing (kN/m²)  
\( Q_{s,psf} = \) positive skin resistance below the neutral point (kN)  
\( Q_{s,nsf} = \) downdrag forces or negative skin friction (kN)  
\( \eta = \) mobilisation factor for downdrag forces

The bored piles depth has to be designed to satisfy all the three cases. The assumed design parameters are shown below:

- Ultimate skin friction, \( f_s = 2N \) for soil with SPT N <100 and \( f_s = 300kN/m^2 \) for soil with SPT N>100;
- Ultimate end bearing, \( f_p = 7000kN/m^2 \);
- Negative skin friction, \( f_{s,nsf} = \beta \times \sigma' \), where \( \beta = 0.35 \) for sand and \( \beta = 0.22 \) for marine clay.

In order to verify and confirm the design parameters are reasonably correct and reliable. Six numbers of instrumented ultimate load tests had been conducted in MBFC, i.e. 2 numbers for dia 1500mm piles, 1 number for dia 1000mm pile and 3 numbers for dia 1200mm piles. The load transfer curves for all the six ultimate load tests are shown. The summaries of results of the instrumented pile loading tests are tabulated.
Ultimate load test plan at MBFC
Load Transfer Curves for Ultimate Load Test Piles at Marina Bay Financial Centre

Fig. 1 Load transfer curves for the ultimate load tests at MBFC
<table>
<thead>
<tr>
<th>Date of Testing</th>
<th>Sequence of Testing</th>
<th>Pile Ref</th>
<th>Pile Length (m)</th>
<th>Pile Diameter (mm)</th>
<th>Pile Working Load (kN)</th>
<th>Maximum Test Load (kN)</th>
<th>Pile Construction</th>
<th>Stabilising Fluid</th>
<th>Base Grouting</th>
<th>Within Improved Soil Layer (DCM)</th>
<th>Pile Top Settlement (mm)</th>
<th>Pile Top Settlement (mm) at maximum load, % of Pile Diameter</th>
<th>Residual Settlement (mm)</th>
<th>Elastic Settlement</th>
<th>Pile Toe Settlement</th>
<th>Stratum</th>
<th>Maximum Mobilised Skinfraction, σc (kN/m^2)</th>
<th>Mean Effective Stress, σv' (kN/m^2)</th>
<th>Mean SPT N Value</th>
<th>Mean End Bearing, C (kN/m^2)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>October-06</td>
<td>1</td>
<td>R1-UTP01</td>
<td>60.8</td>
<td>1500</td>
<td>13250</td>
<td>34780</td>
<td>Constructed with 23.5m long temporary casing to protect the loose and medium dense sand, boreng bucket and cleaning/bucket under water.</td>
<td>Polymer Yes</td>
<td>No</td>
<td>2.62</td>
<td>21.63</td>
<td>30.63</td>
<td>0.00</td>
<td>23.17</td>
<td>75.7%</td>
<td>1.4%</td>
<td>2.0%</td>
<td>746</td>
<td>45 65 470.00 0.69 0.10 NA NA NA</td>
<td>NA NA NA 2829.00</td>
<td>NA NA NA</td>
</tr>
<tr>
<td>November-06</td>
<td>2</td>
<td>A2-UTP01</td>
<td>54.7</td>
<td>1200</td>
<td>8450</td>
<td>26710</td>
<td>Constructed with 31.5m long temporary casing to protect the loose and medium dense sand, boreng bucket and cleaning/bucket under water.</td>
<td>Polymer Yes</td>
<td>No</td>
<td>1.16</td>
<td>20.75</td>
<td>38.63</td>
<td>12.75</td>
<td>25.34</td>
<td>65.6%</td>
<td>1.7%</td>
<td>3.2%</td>
<td>13.29</td>
<td>175 70 478.00 2.50 0.37 NA NA NA</td>
<td>NA NA NA</td>
<td>Skin friction fully mobilised. End bearing substantially mobilised.</td>
</tr>
<tr>
<td>July-07</td>
<td>5</td>
<td>A2-UTP02</td>
<td>48.9</td>
<td>1000</td>
<td>5780</td>
<td>18660</td>
<td>Constructed with 13.5m long temporary casing to protect the loose and medium dense sand, boreng bucket and cleaning/bucket under water.</td>
<td>Bentonite Yes</td>
<td>Yes</td>
<td>3.25</td>
<td>5.375</td>
<td>11.25</td>
<td>0.88</td>
<td>11.25</td>
<td>100.0%</td>
<td>0.00</td>
<td>0.00</td>
<td>375</td>
<td>NA NA NA 350.00 0.93 NA NA</td>
<td>NA NA NA</td>
<td>DCM Layer contributed about 7000kN or 40% of the total load (1.3 times WL). Therefore, skin friction at the lower layers, Layer SB &amp; Layer 6 have not mobilised.</td>
</tr>
<tr>
<td>January-07</td>
<td>3</td>
<td>A2-UTP01</td>
<td>59.3</td>
<td>1500</td>
<td>13250</td>
<td>33130</td>
<td>Constructed with 26.5m long temporary casing to protect the loose and medium dense sand, boreng bucket and cleaning/bucket under water.</td>
<td>Polymer No</td>
<td>No</td>
<td>3.50</td>
<td>32.25</td>
<td>53.75</td>
<td>35.25</td>
<td>17.15</td>
<td>31.9%</td>
<td>2.2%</td>
<td>3.6%</td>
<td>176</td>
<td>60 450.00 2.95 0.41 NA NA NA</td>
<td>NA NA NA</td>
<td>Skin friction fully mobilised. End bearing substantially mobilised.</td>
</tr>
<tr>
<td>March-07</td>
<td>4</td>
<td>A4-UTP01</td>
<td>57.5</td>
<td>1200</td>
<td>8450</td>
<td>21930</td>
<td>Constructed with 12.0m long temporary casing to protect the loose and medium dense sand, boreng bucket and cleaning/bucket under water.</td>
<td>Bentonite No</td>
<td>No</td>
<td>2.60</td>
<td>46.5</td>
<td>66.63</td>
<td>50.00</td>
<td>16.21</td>
<td>24.3%</td>
<td>3.0%</td>
<td>5.6%</td>
<td>50.42</td>
<td>30 70 450.00 0.439 0.018 NA NA NA</td>
<td>NA NA NA</td>
<td>Skin friction fully mobilised. End bearing fully mobilised. Low skin friction may due to bentonite filter cake issue.</td>
</tr>
<tr>
<td>June-07</td>
<td>6</td>
<td>A4-UTP01</td>
<td>58.3</td>
<td>1200</td>
<td>8450</td>
<td>26150</td>
<td>Constructed with 15.5m long temporary casing to protect the loose and medium dense sand, boreng bucket and cleaning/bucket under water.</td>
<td>Bentonite No</td>
<td>No</td>
<td>3.09</td>
<td>24.25</td>
<td>73.75</td>
<td>54.50</td>
<td>20.17</td>
<td>27.3%</td>
<td>2.0%</td>
<td>8.1%</td>
<td>235</td>
<td>73 450.00 3.162 0.94 NA NA NA</td>
<td>NA NA NA</td>
<td>Skin friction fully mobilised. End bearing substantially mobilised.</td>
</tr>
</tbody>
</table>

Summaries of results of the instrumented pile loading tests and interpreted results for MBFC
Back analysis and interpretation of the ultimate load tests results

The skin friction for the six load tests had been fully mobilised or substantially mobilised at a relative displacement between the pile and soil of about 1.5% to 2% pile diameter at maximum test loads, except for A2-UTP02. Generally, end bearing for the test piles was not substantially / fully mobilised due to the fact that the piles are rather long, from 49m to 60m. It was noted that substantial pile toe settlement of about 0.5% to 4.5% pile diameter was required in order to slightly or substantially mobilise the end bearing of the piles from about 2829kN/m\(^2\) to 8860kN/m\(^2\). It is also to note that A4-UTP01 (Additional) was compensated and conducted at 6m away from the A4-UTP01. This was because the pile performance for A4-UTP01 was not satisfactory and did not comply to the contract specifications.

The test results indicate a complex and erratic distribution of the relative pile soil settlements, mobilised skin friction and mobilised end bearing. Various factors would have contributed to the test results, such as base grouting, improved soil layer (DCM) and construction method (different stabilising fluids). In the following sections, factors affecting the test results would be discussed.

Effects of base grouting

Base grouting was required for all the foundation bored piles as specified in the contract specifications. It involves installation of a grouting device (dia 32mm TAM pipe) at the bottom of the steel cages or pile toe. Grouting hoses are attached to the grouting device for preparation of three stages of post grouting after the pile has been cast.

R1-UTP01, A2-UTP01 and A2-UTP02 had been base grouted at least 7days before commencement of the load tests. Refer to Fig. 2, the pile toe settlement of R1-UTP01 was 7.46mm or 0.49% pile diameter, when the end bearing had been
mobilised to 2829kN/m². For A2-UTP01, the pile toe settlement was 13.29mm or 1.1% pile diameter for 5684kN/m² of end bearing. The other three piles, which did not base grouted, required 2.44% to 4.5% pile diameter to mobilise 2829kN/m² to 8860kN/m² of end bearing. The above results show that effects of base grouting on pile toe settlements are huge. Base grouted piles required little pile toe movement to mobilise end bearing compared with non-base grouted piles as shown below. However, it was suggested that the base grouted pile would not contribute better end bearing since the cement grout strength is much lesser than the compressive strength of the pile base material. For A2-UTP02, the end bearing was only slightly mobilised at 335kN/m² with zero pile toe movement. The reason for such minimal mobilisation was due to improved soil layer (DCM).

![Fig 2. Pile toe settlement versus mobilised end bearing due to base grouting](image-url)
Base grouting was not only help to reduce the pile toe movement. It was also help to enhance tremendously on the skin friction above the pile toe. For R1-UTP01, the mobilised skin friction increased rapidly from 54m to 60.77m (4.5D from the pile toe, where D is the pile diameter) and the skin friction was about 626kN/m² as shown in Fig. 1. The mobilised skin friction was 924kN/m² from 52m to 54.7m (2.25D from the pile toe) for A2-UTP01. However, the mobilised skin friction at the pile base location was only 229 kN/m² to 314 kN/m², for piles without base grouting. Fig. 3 and Fig. 4 show the relationship between maximum mobilised skin friction and mean SPT N-value, and maximum mobilised skin friction and mean vertical effective stress, respectively. The difference between base grouted and non-base grouted piles are shown clearly in the figures and Table. For example, the factor of $f_s/N$ for layer 6 in R1-UTP01 is 5.6 and for layer 5B is only 0.69; For A2-UTP01, factors for layer 6 and layer 5B are 9.25 and 2.5, respectively. Based on the test results, it was concluded that skin friction for base grouted pile shaft at 2D to 4D from toe level would increased from (2.5~3) N to about (6~9) N or from (0.43~0.6) to (0.99~1.71) for the $\beta$-values when comparing with piles without base grouting. The relationship between beta value and effective stress is shown below.

$$ f_s = \beta \times \sigma_v' $$

$$ \beta = K_s \times \tan \delta $$

where $K_s =$ lateral earth pressure coefficient

$\delta =$ interface friction angle in degrees

$\sigma_v' =$ average effective vertical stress along the pile shaft
Fig. 3 Relationship between maximum mobilised skin friction and mean SPT N-value for ultimate test piles at MBFC
Fig. 4 Relationship between maximum mobilised skin friction and mean vertical effective stress for ultimate test piles at MBFC
Effects of improved soil layer

The 5th ultimate load test pile, A2-UTP02, was installed on 9 June 2007 at 4B Podium after the DCM had been completed at that area. The improved soil layer was from RL 94.000m to RL 87.000m (7m thick) or about 9m to 16m from EGL. The geological profile of the pile is as shown below:

- Layer 1, 0 to 15.2m (EGL at RL 103.000m): Loose sand fill;
- Layer 2A, 15.2 to 24.6m: Soft marine clay (upper);
- Layer 3, 24.6 to 27.6m: Medium stiff silty clay;
- Layer 2B, 27.6 to 31.4m: Soft marine clay (lower);
- Layer 5A, 31.4 to 35.8m: Very stiff silty clay;
- Layer 5B, 35.8 to 39.4m: Hard silty clay and dense silty sand;
- Layer 6, 40 to 49.6m: Very dense silty sand.

For this pile, majority of the DCM layer was located within the loose sand layer. The behaviour of the pile was totally different from the other five piles. The mobilised skin friction for pile shaft at DCM layer was 375kN/m², which is as good as skin friction at soil with SPT N-value greater 100 (refer to Fig. 1 and the Table above). The DCM layer had contributed about 7000kN skin resistance to the pile load, which is about 1.3 times of the working load of the pile. Therefore, the skin friction at the lower layers, such as Layer 5 and Layer 6, had not been substantially mobilised. The mobilised pile bearing capacity was also minimal, at 355kN/m². With the combined effects of base grouting and improved soil layer, the pile toe settlement is zero. As such, pile top settlement is same as the measured elastic shortening.

It was noted that all the working piles would behave similar to A2-UTP02, since DCM had to be completed prior installation of foundation bored piles. However, it was also worthwhile to note that the rate of pile top settlement was increased
rapidly from $0.3233 \times 10^{-3} \text{mm/kN}$ to $0.3739 \times 10^{-3} \text{mm/kN}$ when the pile load went beyond 7000kN/m$^2$ due to the localised effects of high mobilised skin friction at DCM layer as shown in Fig. 5.

![Graph showing rate of pile top settlement](image-url)

**Fig. 5. Rate of pile top settlement for A2-UTP02**
Effects of construction method

All the piles in MBFC were constructed under water instead of dry pile method due to the geological formation of the site. The piles were deep, ranging from 50m to 80m and the construction time for one pile was long, boring and casting needed ranging from about 18hours to 48hours.

Long temporary casings (20 to 30m depend on thickness of sand layer) were required to protect the loose sand layer when polymer was used as stabilising fluid. However, only short casing from 6 to 10m was required if bentonite was adopted to stabilise the loose to medium dense sand layer, very soft to soft marine clay layer and soft to medium stiff clay and sand layer. The reason that bentonite slurry can stabilise and prevent the loose to medium dense layer (from toe of the temporary casing up to the top of the very soft marine clay) from collapse during boring operation is because the loose to medium dense sand layer is highly permeable. Bentonite suspensions can seal the hole and provide the gel strength required to move the solids out of the hole. In other words, it would form a filter cake on those soil layers that are highly permeable to prevent loose to medium dense sand layer from collapsing. Therefore, by adopting bentonite as stabilising fluid would have the following advantages.

- Short casing (6 to 10m) instead of long casing (20 to 30m) for polymer;
- No joining and welding of casings are required for each individual piles;
- Smaller machine / crane is needed;
- No vibrator hammer or only smaller capacity of vibrator hammer (eg. 5tons hammer) is needed for installation and extraction of casings;
- Minimal vibration created (this is good for this site as MBFC is located at LTA MRT railway reserves zone and URA CST 6m protection zone);
These were the main reasons that driven the ultimate load tests for A2-UTP02, A4-UTP01 & A4-UTP01 (Additional) to be carried out using bentonite. All the 232 numbers of working piles at R1 & Podium were constructed using polymer and it required lengthy construction time of four months from October 2006 to February 2007 to complete all the piles. The purpose of carrying out the three load tests using bentonite was to prove to the Consultants that the piles performance would not be compromised by adopting bentonite slurry. The successful of this approach would ultimately shorten the construction period for the commercial development, i.e. Tower 1, Tower 2, underground carparks and podiums. Total average duration required to install a 70meter deep foundation bored piles of dia 1800mm with polymer and bentonite slurry are shown below. It shows that the duration was about 30 percent shorter for piles constructed with bentonite slurry comparing with polymer slurry.

<table>
<thead>
<tr>
<th>Stabilising Fluid</th>
<th>Duration for each activity (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1st Casing Installation (max 14m)</td>
</tr>
<tr>
<td>Polymer</td>
<td>1</td>
</tr>
<tr>
<td>Bentonite</td>
<td>1</td>
</tr>
</tbody>
</table>

**Average duration required to construction a 70meter deep foundation bored piles with polymer and bentonite suspensions**

However, bentonite suspensions do have disadvantage. The filter cake formed around the pile shaft would affect the skin friction. This was proven in the ultimate load test A4-UTP01. The fully mobilised skin frictions for this pile were only
30kN/m² for old alluvium (soil layers above layer 6) and 229kN/m² for layer 6. It was also need to note that the bore hole with bentonite suspensions was untouched for at least 24 hours when the boring was only few meters to reach the toe level. This was due to boring rig faulty during the installation. It was concluded that the thick filter cake was formed during the stoppage period and caused the lower mobilised skin friction.

In order to verify this finding, another ultimate load test A4-UTP01 (Additional) was installed and tested at 6m away from A4-UTP01. The pile was constructed in continuous sequences without any disturbance. The mobilised skin friction for this pile is much higher than the previous one. The mobilised skin frictions were 233kN/m² and 286kN/m² for layer 5 and layer 6, respectively.

**Quality control & quality assurance for construction of bored piles**

After the analysis and interpretation of the ultimate load tests results, the C&S Consultant and TSC had decided to adopt the following design parameters for the working piles. Conservatively, the effects of base grouting and improved soil layer were not taken into the consideration.

<table>
<thead>
<tr>
<th>Area</th>
<th>Skin friction for soil (kN/m²) with SPT N-value &lt; 100 blows</th>
<th>Skin friction for soil (kN/m²) with SPT N-value &gt; 100 blows</th>
<th>End bearing (kN/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1 &amp; Podium; Tower 1 &amp; 4A Podium; Tower 2 &amp; 4B Podium; Parcel A7 UPN</td>
<td>2 N</td>
<td>300</td>
<td>7000</td>
</tr>
<tr>
<td>3A &amp; 3B Basement Car parks</td>
<td>2 N</td>
<td>280</td>
<td>4500</td>
</tr>
</tbody>
</table>

**Design parameter adopted for working piles in MBFC**
The quality control and quality assurance for the foundation bored piles must be in placed in order to achieve the design. It was required to closely monitor the progress of the foundation works due to the tight construction schedule.

Several forms had been created and implemented for the site supervisors and geotechnical engineers to follow. The objective was to ensure that all the required information was recorded, such as:

- Setting out of the pile
- Casing verticality
- Time taken for each individual activities, such as casing installation, boring, lower steel cages, tremie pipes and concreting
- Quality of the bentonite / polymer suspensions (Strictly follow BS EN 1536:2000, Clause 6.5.2)
- Bored out soil classifications
- Ground level, casing level, pile penetration length, pay length and reinforcement details
- Concreting record to verify the wet concrete raising
### Sequences of the bored piles construction

<table>
<thead>
<tr>
<th>Step</th>
<th>Image</th>
</tr>
</thead>
<tbody>
<tr>
<td>Casing installation</td>
<td><img src="image1" alt="Casing installation" /></td>
</tr>
<tr>
<td>Casings had been installed</td>
<td><img src="image2" alt="Casing installation" /></td>
</tr>
<tr>
<td>Join &amp; weld additional casing if required</td>
<td><img src="image3" alt="Join &amp; weld additional casing if required" /></td>
</tr>
<tr>
<td>Seawall removal if any</td>
<td><img src="image4" alt="Seawall removal if any" /></td>
</tr>
<tr>
<td>Boring operation</td>
<td><img src="image5" alt="Boring operation" /></td>
</tr>
<tr>
<td>Testing on bentonite/polymer qualities prior/during boring and before casting</td>
<td><img src="image6" alt="Testing on bentonite/polymer qualities prior/during boring and before casting" /></td>
</tr>
<tr>
<td>Lowering steel cage with base grouting tubes</td>
<td><img src="image7" alt="Lowering steel cage with base grouting tubes" /></td>
</tr>
<tr>
<td>Tremie pipe installation</td>
<td><img src="image8" alt="Tremie pipe installation" /></td>
</tr>
<tr>
<td>Tremie concreting</td>
<td><img src="image9" alt="Tremie concreting" /></td>
</tr>
</tbody>
</table>

#### Key Points
- **Casing installation**: Installation of casing into the ground.
- **Casings had been installed**: Additional casings may be installed if required.
- **Join & weld additional casing if required**: Welding to ensure stability.
- **Seawall removal if any**: Removal if not required for the construction.
- **Boring operation**: Lowering of steel cage with base grouting tubes.
- **Testing on bentonite/polymer qualities prior/during boring and before casting**: Quality checking of soil conditions.
- **Lowering steel cage with base grouting tubes**: Essential for stability.
- **Tremie pipe installation**: Ар installation of concrete for bored piles.
- **Tremie concreting**: Placement of concrete at the bottom of the casing.
Verification of pile performance of working piles

Total 15 numbers of working load tests had been carried out on the working piles for MBFC to verify the pile performance. It is noted that all the piles had been base grouted prior the working load tests. In addition, all the piles are located within the soil improvement layer except those piles at R1. Therefore, the performances of the piles are expected to be very good as per the discussion early on the effects of base grouting and effects of improved soil layer. The author has carried out back analysis for the load tests on the working piles using Chin’s Stability Plot.

All the working load tests had been loaded to 2 times working load. The pile top settlements for the four piles at R1, whereby the piles were located outside the improved soil layer, were measured at 0.8% to 1.7% of pile dimension. Whereas, the settlements for the 11 piles located within the improved soil layer had experience lesser values, various from 0.4% to 0.8%. These results are comparable, where 1.4% and 1.7% for R1-UTP01 and A2-UTP01 (with base grouting & outside improved soil area) respectively & 0.5% of pile dimension for A2-UTP02 (with based grouting & within improved soil area).

The estimated average ultimate skin frictions for the entire pile length based on Chin’s Plot were also lesser, from 69 to 122kN/m², for piles located outside the improved soil area than the opposite with higher skin frictions from 101 to 252kN/m². As mentioned earlier, all the piles had been base grouted before the load tests. Generally, the skin frictions were only partially mobilised during the load tests (2 x WL) and the end bearings were not mobilised or only slightly mobilised. The factor of safeties for all the test piles, based on the estimate ultimate total resistance and ultimate skin friction, are much higher than the design values of 2.5 and 2.0 respectively. These were shown clearly in the Chin’s Plots and the results on Table. The results on the working test piles were agreeable with the previous on the effects of improved soil layer and base grouting. Therefore, it could be concluded that
performance of the deep foundation in MBFC is extremely good and safe. However, it also shows that the design of the bored piles was too conservative as resulted from ignoring the both effects of base grouting and improved soil layer. In the author’s opinion, the design should take into account on the effects of base grouting and this would offer a more economical, safe and effective deep foundation system. As for the other, the effects of improved soil layer shall not be considered in the design as proposed by the author. The reasons are the effects of consolidation on the piles would affect the contribution of improved soil layer and this would require further study and research.
Chin’s Stability Plots for the working load tests at MBFC
Chin’s Stability Plots for the working load tests at MBFC
<table>
<thead>
<tr>
<th>SN</th>
<th>Date of Testing</th>
<th>Area</th>
<th>Pile Ref.</th>
<th>Pile Length (m)</th>
<th>Pile Diameter (mm)</th>
<th>Pile Working Load (kN)</th>
<th>Nominates End Load (kN)</th>
<th>Max. Pile Test Settlement (m)</th>
<th>Residual Settlement (m)</th>
<th>Estimated ultimate end bearing based on CAHR (kN)</th>
<th>Estimated ultimate end bearing based on chin's plot (kN)</th>
<th>Remarks</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>9 Feb 2007</td>
<td>WLT #1 at Residential</td>
<td>R1-12-P05</td>
<td>5.22</td>
<td>1200</td>
<td>8500</td>
<td>10600</td>
<td>4.00</td>
<td>3.80</td>
<td>19678</td>
<td>13714</td>
<td>31491</td>
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<td>2</td>
<td>9 Mar 2007</td>
<td>WLT #2 at Commercial, Tower 1</td>
<td>P1C-P10</td>
<td>5.16</td>
<td>1000</td>
<td>4750</td>
<td>9080</td>
<td>4.80</td>
<td>2.80</td>
<td>5625</td>
<td>5947</td>
<td>11574</td>
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<td>10 Mar 2007</td>
<td>WLT #1 at Residential</td>
<td>R1-18-P01</td>
<td>7.16</td>
<td>15000</td>
<td>50000</td>
<td>20000</td>
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<td>2.80</td>
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<td>36264</td>
<td>55009</td>
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<td>4</td>
<td>17 Apr 2007</td>
<td>WLT #4 at Residential</td>
<td>R1-10-P10</td>
<td>7.22</td>
<td>15000</td>
<td>50000</td>
<td>30000</td>
<td>4.80</td>
<td>2.80</td>
<td>50000</td>
<td>56250</td>
<td>156250</td>
</tr>
<tr>
<td>5</td>
<td>17 Sep 2007</td>
<td>WLT #1 at Commercial, Tower 1</td>
<td>P1C-P08</td>
<td>6.87</td>
<td>1000</td>
<td>5000</td>
<td>10000</td>
<td>4.00</td>
<td>2.80</td>
<td>9579</td>
<td>748</td>
<td>100%</td>
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<tr>
<td>6</td>
<td>2 Oct 2007</td>
<td>WLT #1 at Commercial, Tower 1</td>
<td>P1C-P09</td>
<td>6.27</td>
<td>1000</td>
<td>5000</td>
<td>10000</td>
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<td>2.80</td>
<td>8468</td>
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<td>15394</td>
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<td>7</td>
<td>2 Oct 2007</td>
<td>WLT #1 at Commercial, Tower 1</td>
<td>P1A-T10</td>
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<td>1000</td>
<td>5000</td>
<td>10000</td>
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<td>2.80</td>
<td>65385</td>
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<td>8</td>
<td>14 Nov 2007</td>
<td>WLT #4 at Commercial, Tower 2</td>
<td>P1A-T17</td>
<td>7.03</td>
<td>15000</td>
<td>50000</td>
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<td>1.50</td>
<td>67324</td>
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<td>9</td>
<td>10 Nov 2007</td>
<td>WLT #1 at Commercial, Tower 2</td>
<td>P1A-P16</td>
<td>5.09</td>
<td>3000</td>
<td>5000</td>
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<td>10</td>
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<td>P1A-P02</td>
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<td>3000</td>
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<td>5000</td>
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<td>11</td>
<td>17 Dec 2007</td>
<td>WLT #1 at Commercial, Tower 2</td>
<td>P2B-P06</td>
<td>6.61</td>
<td>900</td>
<td>4750</td>
<td>9080</td>
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<td>2.80</td>
<td>65385</td>
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<td>0</td>
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<td>12</td>
<td>15 Feb 2008</td>
<td>WLT #1 at Commercial, Tower 2</td>
<td>P2A-P71</td>
<td>6.64</td>
<td>1000</td>
<td>5000</td>
<td>5000</td>
<td>4.80</td>
<td>2.80</td>
<td>67222</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>13</td>
<td>22 Mar 2008</td>
<td>WLT #2 at Commercial, Tower 2</td>
<td>P2A-P11</td>
<td>6.64</td>
<td>1200</td>
<td>8500</td>
<td>17600</td>
<td>4.00</td>
<td>2.80</td>
<td>63893</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>7 Mar 2008</td>
<td>WLT #1 at Commercial, Tower 2</td>
<td>P3A-P08</td>
<td>6.57</td>
<td>1100</td>
<td>5000</td>
<td>11000</td>
<td>4.80</td>
<td>2.80</td>
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<td>2052</td>
<td>11475</td>
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<tr>
<td>15</td>
<td>22 Jun 2008</td>
<td>WLT #1 at Commercial, Tower 2</td>
<td>P3A-P51</td>
<td>6.80</td>
<td>1200</td>
<td>8500</td>
<td>17600</td>
<td>4.80</td>
<td>2.80</td>
<td>53129</td>
<td>0</td>
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</tr>
</tbody>
</table>

**Summaries of results for the working load tests and back analysis results for MBFC**
Evaluation of Outcomes and Impacts

The project is situated at the Marina Bay, an artificial bay formed by reclamation, which will be developed to further support Singapore’s continuing growth as a major business and financial hub. Marina Bay Business Financial Centre is the first few developments in this area. Future developments around Marina Bay would also have the similarities as the current development, i.e. high rise buildings supported by deep foundation and deep basements which required soil improvements works to form the earth retaining or stabilising structure. Thus it was important to understand the deep foundation and soil improvements behaviours and to develop more reliable and economical in the design and construction methods in Marina Bay.

In this section, the author discussed the behaviour of the bored piles at MBFC. The findings are useful and would have great impacts in the future projects if there are adopted in the design and construction. The findings are summarised below:

*Foundation bored piles*

- **Effect of base grouting** – Take into account of the contribution of base grouting on the skin friction, i.e. base grouted pile shaft at 2D to 4D from toe level, adopt 6~9N or 0.99 to 1.71 (β-value).

  *Impacts: Pile penetration depths would have been reduced by 10 to 30%, that will save cost and construction duration.*

- **Effect of DCM** – Take into account of the contribution from the improved soil layer, i.e. skin friction of 375kN/m² for the pile shaft within the improved soil layer.

  *Impacts: Pile penetration depths could be reduced.*
Effect of construction methods – Excavation of bored pile under bentonite suspension would be faster compared with polymer suspension in Marina Bay area. This is because shorter temporary casing and smaller machinery are only required under bentonite suspension.

*Impacts:* The construction duration for the deep foundation works could be reduced by at least 30%.

**Responsibility for Decisions**

In this large scale engineering project, the author, as Senior Civil Engineer, was responsible for the supervision of the Geotechnical Engineers, site supervisors and sub-contractors to ensure all the engineering activities to be carried out safely and smoothly. The author was also involving in the decisions on the various works methods to solve the problems encountered at MBFC including getting approval from the authorities, such as LTA, URA and BCA. The examples are:

- To use Down-the-Hole method and Casing Oscillator method at the seawall area to break through and clear off the seawall in preparation for the soil improvement and bored piling works as shown below.

- To carry out load tests adjacent to the excavation area and MRT reserve zone (refer to the figure below)

The author took accountability and responsible for the decisions which he had made during the project period. The author was pleasure that the project was able to hand over satisfactory to the client.
Casing Oscillator was in operation to remove the existing seawall
(a) Working load tests using Kentledge method adjacent to MRT line and excavation area
Working load tests using Kentledge method adjacent to MRT line and excavation area
Managing Engineering Activities

This project involved a lot of engineering activities and all the activities would have to be carried out closely and simultaneously. The engineering activities are:

- Geotechnical instrumentation;
- Deep cement mixing;
- Jet grouting;
- Bored piles;
- Continuous bored piles;
- Down-the-hole hammer;
- Casing oscillator;
- DCM coring tests.

The overall view of the site can be seen in the following. Some of the activities are shown. The author had to plan the daily activities based on 24-hour a day basis. The aim was to avoid unnecessary down time for all the heavy machineries and man powers from the sub-contractors. Various considerations had to be taken care for the planning purpose. Such as, bored piles can only be installed after DCM has been completed; effects of jet grouting on completed bored piles need to be taken into considerations; etc.

Site utilities plan was also a very important issue. This was because almost all the engineering works located on the entire site. Allocation of utilities, such as water pond, bentonite / polymer silos, cement silos, mixing plants, machineries, boring tools, etc, was the great challenge in this particular site, whereby existing MRT line and existing CST are located within the site boundary. Therefore, the site utilities plan had to be cleared and approved by LTA & URA and to make sure that the effects on the existing tunnels are minimal due to the additional loads created. The site utilities plan is shown also.
An overview of the site showing various on-going activities
Site utilities plan for MBFC for silos, batching plants, etc, located within the MRT 2nd & 3rd reserve zone and URA 6m reserve zone
Exercising Sound Judgement

The author had exercise sound judgement during his involvement in the project. He worked together with all the professional personnel in the design and construction of the deep foundation bored piles. He analysed the load tests results and confirmed the design parameters with the fellow consultants for the construction of the working piles. The design parameters were reasonably correct and all the load tests on the working piles had passed according to the criteria. His analysis on the effects of base grouting and DCM on the foundation bored piles could be continued with the research and adopted in the future projects in Marina Bay area. By adopting this approach, the design and construction of the deep foundation bored piles would be more economical and safer. He was also exercised sound professional engineering judgement for adopting of down-the-hole hammer and casing oscillator methods to overcome the existing seawall problems in MBFC.

Communication

During the whole project period, the author communicated well with all range of people, such as authorities, consultants, his colleagues at site, sub-contractors and suppliers. He assisted his Project Manager in chairing the daily site meeting with all the sub-contractors for all the site works. He also involved in the consultants’ progress and technical meetings to solve all the site issues. In addition, he played a very proactive role in getting URA/LTA’s clearance for all the engineering works within their protection zone.
CONCLUSION

The author describes his project involvement in the Project BFC. The effects of base grouting on the deep foundation bored piles are heavily described. The impacts of the outcome of the current analysis could have great impact in the future’s deep foundation design in Singapore.

31 July 2012