Case History

The Pinnacle Tower – Geotechnical Challenges

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The Pinnacle Tower is one of a cluster of towers being constructed in the heart of the City of London. When complete it will be 62 Storeys high – taller than any other building in the UK. The design and construction of the tallest building in the UK, on a central London site occupied by 3 existing buildings presented special challenges. The approach the design and construction team took to these challenges earned them the best geotechnical project over £1M at the recent GE awards.

The new development

The new building is to be 62 storeys with a 3 level basement (Figure 1) occupying a retail and commercial office space of about 1.4M sq ft. Demolition of the previous 10 storey buildings to ground level started in mid 2007. Pile construction started in July 2008 from the ground level slab, over an existing three level basement which occupied much of the site. Piling is now complete, demolition and basement excavation continues as with pile cap construction progresses. The new substructure and superstructure is planned for completion in 2012.

Figure 1: The Pinnacle Tower (copyright KPF web site)

In London, tall buildings are typically less than 200m high and have traditionally been founded on large diameter bored piles (including under-reamed piles) in London Clay typically 25 to 35m deep. Canary Wharf Tower at 235m, is founded characteristically on 25m deep base grouted bored piles in the Thanet Sand, supporting maximum loads of about 30MN. The Pinnacle, has typical column loads up to 45MN with some extreme loads of up to 70MN and cannot be supported on any currently known piling system drilling into just London Clay. For this reason the only sensible solution was to found into the Thanet Sand, which at this site is about 63m below street level. The very high loads resulted in piles having diameters up to 2.4m.

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Most of the experience on base grouted piles in Thanet Sand has come from projects at Canary Wharf and therefore there is very limited experience of piling larger than 1.8m diameter, into Thanet Sand, within the City of London. Base grouted Thanet Sand piles at The Pinnacle were a much greater diameter and depth than any experience gained from past projects using base grouted piles. This posed significant design and construction challenges, which are described in this paper.

The project team and its organisation are detailed in Figure 2.

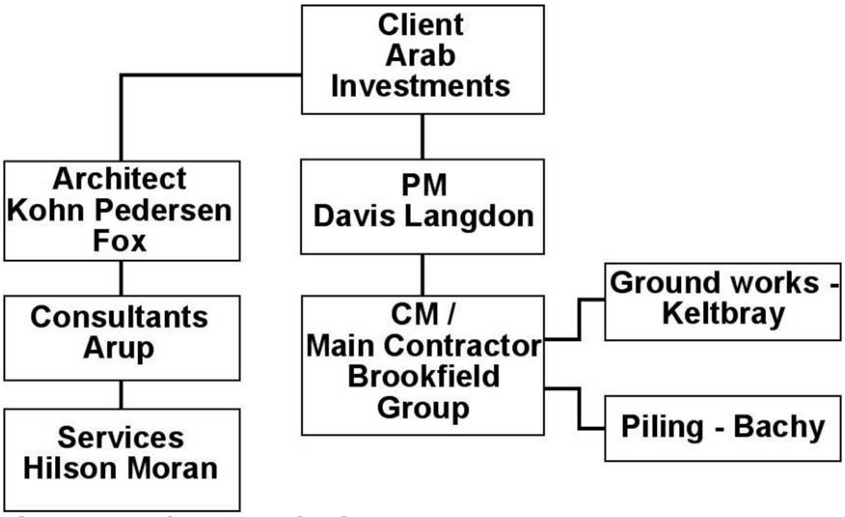

Figure 2: Project Organisation

<u>The Site</u>

The plan area of the site is approximately 140m by 70m and covers the footprint of three previous buildings. Surrounding street levels are approximately +16.8mOD on the west falling to +15.4mOD on the east side. Previous buildings on the site had a 14m deep basement (38 Bishopsgate, cc 1985), a 12m deep basement (22-24 Bishopsgate, cc 1975) and a single level basement for the oldest structure (4 Crosby Court, cc 1908). The largest of the three is Standard Chartered Bank, which was founded on up to 1.5m diameter bored piles with underream bells at 35m below ground level 4.5m in diameter in the London Clay. The existing base slab is a minimum 1m deep raft, in places up to 2.5m thick.

The footprint of The Pinnacle covers all three buildings with one tower leg sitting in the pavement of Bishopsgate. There will be a common 14m deep basement across the whole of the site formed within the existing basement walls and a new secant pile wall to be constructed in the southeast of the site underneath Crosby Square where there is currently no basement and Crosby Court where there is only a single level basement

The existing Standard Chartered Bank Building already has a basement at about +3.0mOD, and the new base slab will be 0.8m thick to be cast on top of this old slab. The new base slab will extend to the other parts of the site which have been excavated to the same level.

The Pinnacle abuts two buildings, a 24 storey structure (6-8 Bishopsgate) founded on a piled raft and 1 Great St Helens, a 10 storey structure founded on a mini-piled raft. Immediately to the south east there is also 122 Leadenhall, the site of a future 225m tall tower (Figure 3).

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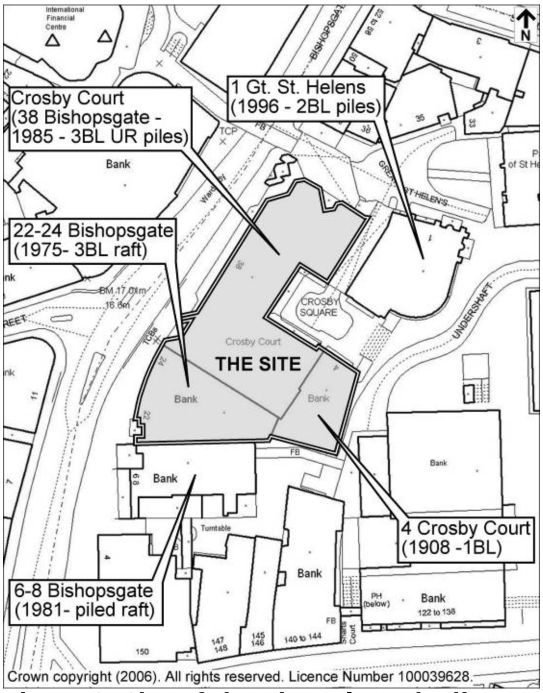

Figure 3: Site of the Pinnacle and adjacent buildings (BL = no of basement levels)

Figure 4: Anticipated layout of underream piles based on original plans

<u>Mitigation of ground risk and challenges</u>

Old foundations

Major project risks were posed from foundations of the previous developments and temporary piles used to form the original basement the extent and nature of which were not fully understood. It was important to establish the extent and location of these old foundations and temporary works to minimise adverse impact on the project and to understand better whether any benefit could be gained through foundation re-use. Arup undertook rigorous research and consultation of various consultants, previous main contractors of the existing buildings, piling contractors and Building Control departments were consulted to obtain old design and construction records.

The previous consultant's tender information was useful as they recorded structural loads and underream piles. Temporary works construction sequences and plans for a 14m deep bottom up basement construction were also obtained. The contractor also provided photographs of the basement construction which clearly showed that there would be a large number of temporary king post piles in the ground, which were utilised in 1985 to support the basement construction – these could obstruct the construction of new piles.

Unfortunately, founding levels of the existing foundations had not been recorded though indicative pile toe levels of -20.0mOD were given for some piles. No definitive design or pile records were available. The best estimates of the position of these underream piles and sizes are given on Figure 4. Intrusive investigation was required to confirm the locations and founding levels of the existing piles.

From talking to the original contractor of the Standard Chartered Bank, it was revealed that the northern half of the site had only short (6m deep) reinforcement cages installed below the trim level of the underream piles. It was found during basement excavation in 1985 that all these piles cracked just below the reinforcement cage, and before the building could be built these piles had to be remediated by coring through the undeream piles and grouting to close the cracks.

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Without the as-built sizes of the shafts and under-ream bases the cost and time associated with concrete coring during piling works was still considered a major risk and would have a severe impact on the overall piling programme. To minimise this risk, early in the design process, a probing and coring exercise was carried out to investigate the location, depth and size of the underream bases and the strength of the concrete. This used low headroom Fondedile (now Keller Geotechnique) piling rig, operating within the basement and while the building was still occupied (Figure 5). An investigation of the RC perimeter walls, including old diaphragm walls, was also made. Concrete cores and strength tests allowed the temporary works contractor to design his propping scheme for the existing basement demolition and the piling contractor to determine the most appropriate coring equipment/piling rig.

This information allowed the designers to mitigate the piling risk at an early stage of the design, by minimising the number of new piles that would encounter the existing piles. The pile removal costs and programme implications could then be more accurately assessed before tendering the main contract. This was extremely important as the piling was to be carried out from ground slab level through three floors of existing basement. Therefore adjusting new pile locations once piling works has started was not an option and would have been prohibitively expensive, time consuming and disruptive.

Figure 5: Probing and coring of existing UR piles

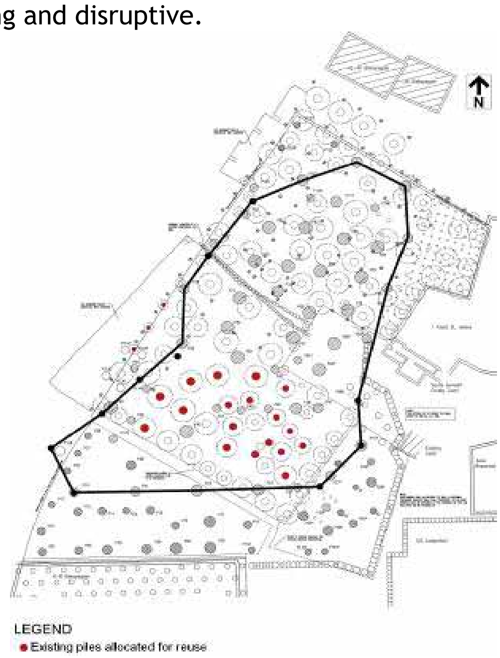

Figure 6: New pile layout and megaframe piles (also shown, extended basement within new secant pile wall to southeast)

The foundation scheme

The new foundation layout (Figure 6) also posed an engineering challenge. The outline of the megaframe, which is a fundamental part of the superstructure stability system, was spatially curved and twisted and did not lend itself to foundation reuse. Some megaframe columns also landed close to the boundary of the perimeter walls with one column sited in the street. Early design schemes considered reusing all the 1985 underream piles to support the new internal podium and substructures. All the piles in the southern half of the site were fully reinforced over the shaft and did not suffer from the cracking that the northern piles had. The cracks in the northernmost piles could be expected to reopen due to an average short term net unloading of the site of about 200kPa. As a consequence, only the southern half of the site could be considered for foundation reuse. A mixture of new large diameter bored piles and minipiles, founded in London Clay, were used in the northern half of the site, see Figure 6.

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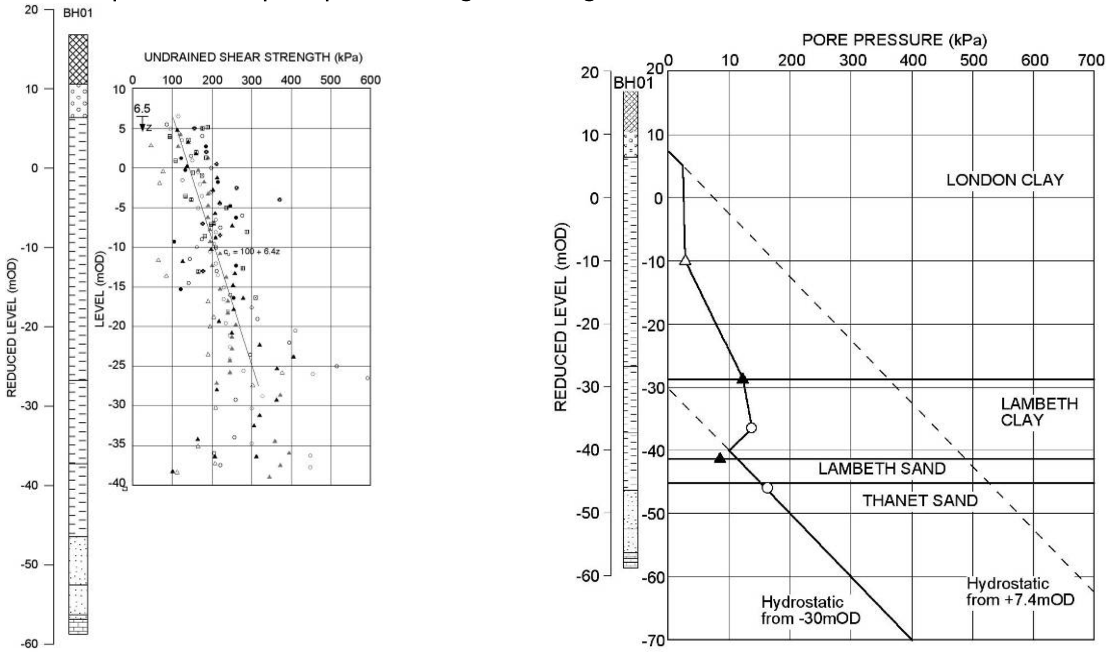
The megaframe column loads were between 20MN and 45MN. At early design stage, the use of pairs of 1.8m diameter piles per column was considered as an alternative to the single large diameter piles per column solution. However, this would have substantially increased shaft and base coring of existing underream piles (some shafts were fully reinforced), required more drilling out of steel king post obstructions, and more pre-drilling of the existing thick base slab. It would also have introduced significant pile caps and hence larger openings in the existing base slab. The Construction Managers also wanted to start superstructure construction off the pile heads whilst demolishing the basement top down, therefore large pile caps would have been time consuming to construct and would have delayed this programme. A piled raft solution was also considered but again the perimeter megaframe carried the majority of the structural loads and this frame was not sympathetic to such a foundation solution. Therefore a decision was taken to found the structure on single piles per column, using 1.5m to 2.4m diameter base grouted piles founded about 65m into the Thanet Sand stratum.

Ground conditions
The Pinnacle site stratigraphy is summed up in Table 1:

Table 1: Stratigraphy at The Pinnacle site

Stratum	Thickness (m)
Made Ground	6
Brickearth/ River Terrace Gravels	4.5
London Clay	35
Lambeth Group	18
Thanet Sand	11
Chalk	2 (proven)

The clays are underdrained due to the low groundwater table in the lower aquifer of the Chalk in Central London. A summary of the stratigraphy of the site with undrained shear strength is also plotted on Figure 7a. The piezometric pore pressure is given in Figure 7b.



(a) (b)

Figure 7 Ground Investigation data: (a) Undrained Shear strength profile; (b) Piezometric pressures

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Arup experience at Canary Wharf showed that it was important to understand the mineralogy of the Thanet Sand, as low bearing capacities could occur in sand with high clay content. For this reason, the site investigation at The Pinnacle considered profiling of the Thanet Sand as a crucial part of the pile design. This was achieved by carrying out Ménard Pressuremeter tests (Figure 8a) and frequent pipette / sieve analysis of the Thanet Sand from high quality rotary cored samples (Figure 8b).

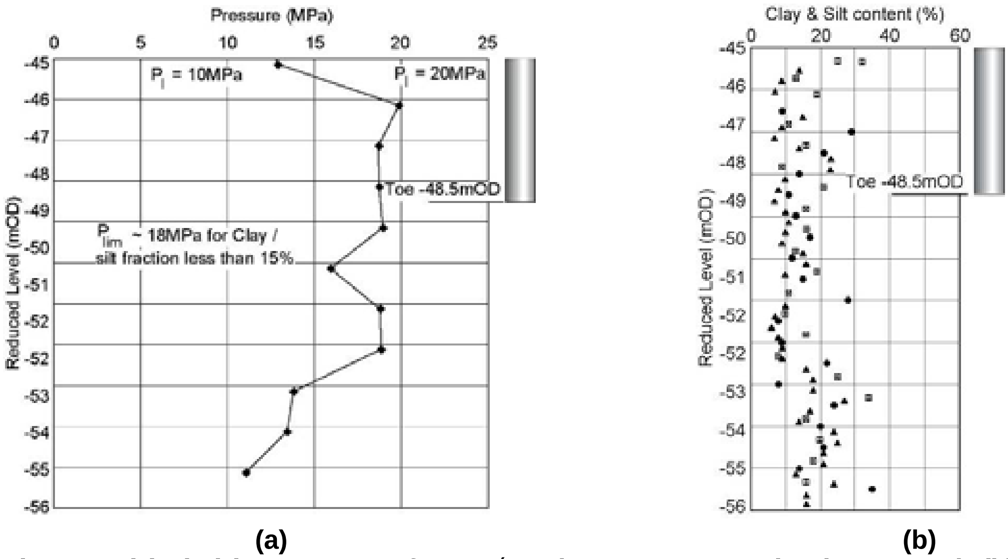

Figure 8: (a) Limiting pressures from Ménard pressuremeter in Thanet Sand; (b) Clay /silt fraction (%) of Thanet Sand

The results of these tests show that the upper 7m of the Thanet Sand recorded high limiting pressures (19MPa) and correspondingly low clay/silt mineralogy of less than 15% (referred to as "clean" sand). The lower 4m of the sand, referred to as "dirty" sand, has a higher mineralogy (> 20%) and limiting pressures reduce to about 11MPa. These observations are similar to the conclusions made by Nicholson et al (2002) in the Thanet Sands at Canary Wharf. From this investigation, the decision was taken to found all The Pinnacle base grouted piles at least 2m below the sand surface at -48.5mOD. The risk of piles not founding into the Thanet Sand, due to varying surface levels across the site, was not considered a major risk as there was a clear marker bed, the Pebble Beds of the Upnor Formation, separating the interface between the Lambeth Group and the Thanet Sand.

Pushing boundaries – design of base grouted piles

The first major use of base grouted piles in Thanet Sand was developed for the buildings at Canary Wharf, Docklands in the 1980's (Troughton 1989). This form of piling was well suited to these sites as the Thanet Sand was only about 30m below ground with mean effective stresses at about 300 – 400kPa. Two methods of pile design evolved on these sites, one based on effective stress design, and the second using self boring and/or Ménard Pressuremeter testing as described in more recent works (Chapman et al 1999, Nicholson et al 2002). The base grouted piles at Canary Wharf did not exceed 1.8m diameter and base grouting was carried out using a maximum of four grouting tube circuits or tube à manchettes (i.e. using 8 grouting tubes) attached to a reinforcement cage. It was also possible to build these piles generally within 12- 24hrs. Maximum loads on the piles were 32MN, assuming a working stress of 12.5MPa. The early Thanet Sand piles at Canary Wharf were constructed under bentonite, but later projects were constructed in dry Thanet Sand, as it was dewatered for basement construction. The use of pile drilling augers and digging buckets under bentonite was thought to loosen the Thanet Sand, and base grouting was employed to restore the base stiffness (Yates and O'Riordan, 1989).

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In the City of London, there is very limited experience of piling up to 65m into saturated Thanet Sand. The Moorhouse development (Yeow et al, 2005) is the closet site to The Pinnacle where 1.8m diameter base grouted piles were formed supporting a maximum of 35MN column loads. Pile loads on The Pinnacle are significantly higher, up to 45MN, meaning up to 2.4m diameter piles founded 65m below ground are required. Therefore this posed challenges to both the design and construction, which is discussed below.

Early workshops with potential piling contractors indicated that piles of this size and depth would take about 4 days to build, even longer if shaft or base coring of underream piles had to be carried out - much longer than at Moorhouse. As a result there was concern that low shaft frictions may occur in the overlying London Clay and Lambeth Clay strata, compared with piles which typically took 12-24hrs to install.

The pile design strategy developed for The Pinnacle therefore had to consider all these risks and the final design is illustrated in Figure 9.

Initial design was carried out using experience gained at Canary Wharf and Moorhouse, where the end bearing capacity factor Nq*, ranged between 30 and 60, from pile testing. At The Pinnacle site, the mean effective stress at the pile toe is about 800 kPa, and using the lower Nq* factor results in an ultimate base stress of about 24MPa. Thus, piles would be limited by the working stress on the concrete for an overall factor of safety of 2.5. Base grouted piles, which support the megaframe column loads, range between 1.5m and 2.4m diameter. For the largest pile diameters, up to 50% of the working load is carried on the grouted base.

An alternative design approach is to calculate the ultimate base stress from the limiting pressure derived from the Ménard Pressuremeter test, using the approach below:

$q_b = \lambda .\ p_{lim}$

where
λ = factor to convert the Ménard limiting pressure to end bearing coefficient
p_{lim} = limiting pressure from Ménard pressuremeter

For this design approach, preliminary pile tests would have to be carried out to select an appropriate λ value.

Heave and settlement

Heave forces were generated in all the piles due to (a) demolition of the existing buildings which weighed between 80kPa and 260kPa (b) areas of the site where new basements up to 14m were to be excavated (e.g. 4 Crosby Court) and (c) heave induced swelling pressures acting under the ground bearing slab due to long term changes in pore pressures. A simplified approach modifying the work of O'Reilly et al (1990) was used to calculate the heave forces in the new base grouted piles, London Clay piles and minipiles, and full length reinforcement was placed to avoid cracking in the piles. A 3D Finite Element model of the basement (Figure 10) was also carried out to check this design, to assess ground movements, the impact on adjacent buildings, the raft design and to investigate the response of the tower to soil-structure interaction.

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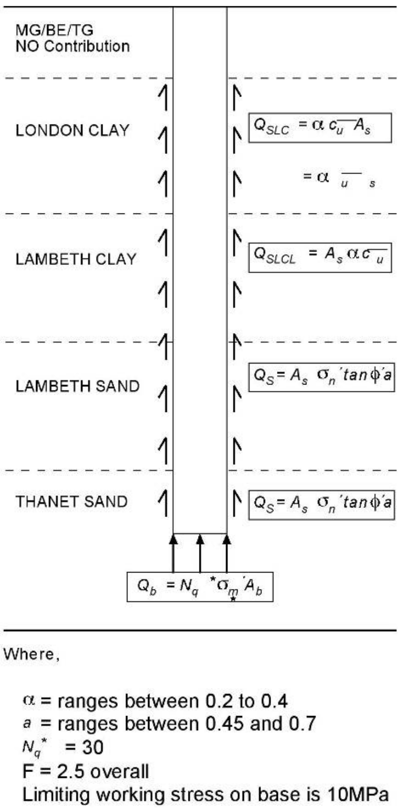

Figure 9: Pile Design Methodology

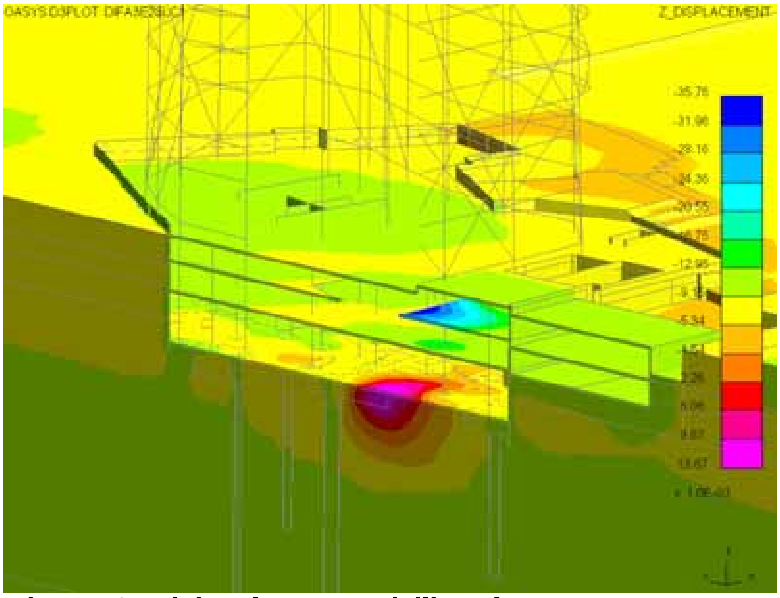

Figure 10: Finite Element Modelling of Long Term Ground Movements (Vertical Displacements)

Preliminary test pile

A 900mm diameter, 64m long preliminary pile test was carried out at The Pinnacle site to confirm the design parameters for the base. The pile was double sleeved to about 11m into the London Clay and single sleeved with a bitumen coated permanent casing to about 51m (-35mOD), approximately 7m into the Lambeth Group, to eliminate the shaft resistance of overlying soils. Figure 11 shows the test pile instrumentation layout.

Incremental maintained load testing to about 25MN took place 14 days after casting the pile. The load settlement performance of the test pile is shown on Figure 12. Also, shown is the test conducted on a similar size pile and embedment length (56m) at Moorhouse (Yeow et al). Both piles exhibit similar load settlement behaviour. The ultimate pile capacity was not achieved in the third cycle of loading to 24.5MN where the pile head settlement was 105mm. About 60% of this movement was due to elastic shortening of the pile.

The extrapolated ultimate pile capacity was determined from Fleming's (1992) analysis, and also checked using the simplified Chin (1970) method, which as expected gave a slightly higher capacity. The Fleming method predicted an ultimate base capacity of 29MN and an ultimate base stress of 45.6MPa was deduced. The backfigured end bearing capacity factor was deduced as N_q * = 57 and this value compares favourably with the N_q * = 60 derived from the Moorhouse pile test.

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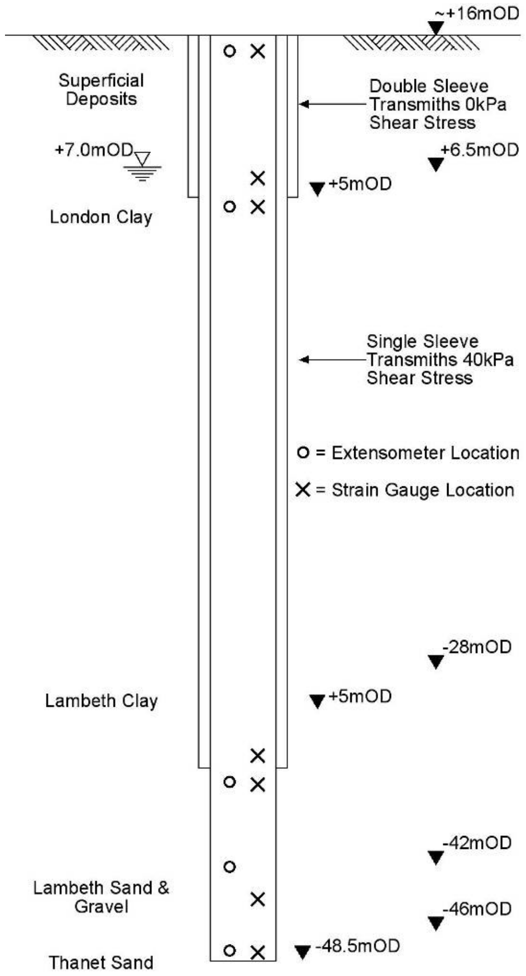

Figure 11: Pinnacle Test pile instrumentation

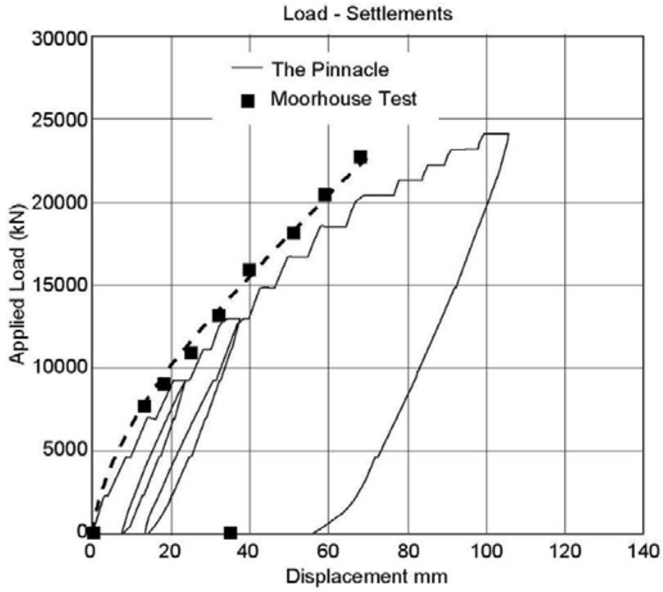

Figure 12: Load settlement plot of test pile

These two pile test data were also compared with the results of a large number of recent pile tests carried out by Arup at Canary Wharf on up to 1.5m diameter piles embedded at different depths in the Thanet Sand, see Figure 13. At less than 5m embedment the N_q* is greater than 60, while below 9m, N_q* is less than 35. Both the Pinnacle and Moorhouse test data in the City, are piles with less than 3m embedment and show high end bearing capacity factors, N_q* ≥ 57, consistent with the Canary Wharf results (circled in Figure 13). Nicholson et al 2002, showed that the reduced N_q* factors with increasing embedment depth was due to an increase in clay minerals in the lower part of the Thanet Sand at Canary Wharf.

Using the Ménard Pressuremeter and a limiting pressure, p_{lim} = 19MPa, a λ factor of 2.4 was deduced from the extrapolated ultimate base capacity.

In summary, good quality zoning of the Thanet Sand is important for pile design and this can be easily done using the Ménard pressuremeter plus taking frequent pipette/sieve analysis of the Thanet Sand.

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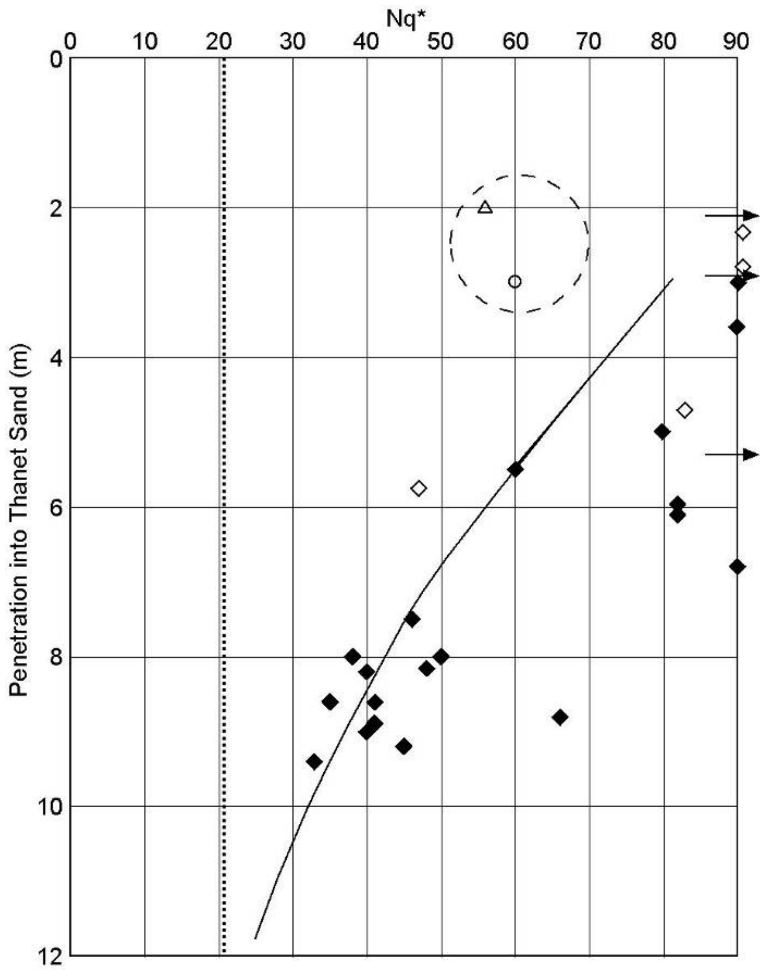

Figure 13: Base Factor, N_q* from base grouted test piles in the City and Canary Wharf

Estimating base settlement

The load-settlement curves of preliminary pile tests at Canary Wharf, The Pinnacle and Moorhouse were studied and a normalised base load against normalised settlement plot produced, as shown in Figure 14. These represent load tests conducted on pile sizes from 0.9 to 1.5m diameter. The applied load on the base can be calculated from the working load (WL) and the ultimate base capacity from $Q_b = N_q^*. \sigma'_m . A_b$.

The total pile settlement can then be deduced, using Figure 14 to estimate the base settlement and adding this to the calculated elastic shortening of the pile concrete. This approach was used to calculate the individual settlement of the base grouted piles for The Pinnacle at the end of the construction phase. Numerical techniques were used to calculate the long term settlements of the building, due to changes in pore pressures in the London Clay caused by unloading and reloading of the site, and pile group effects.

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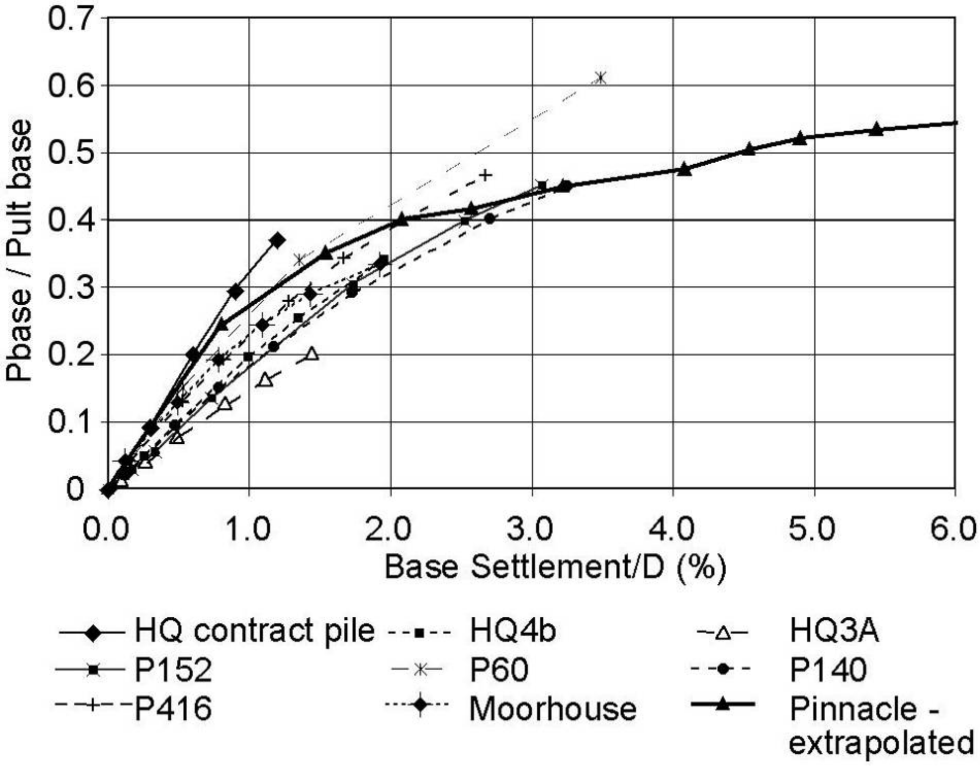

Definitions:
P_{base} - load applied on base ; $P_{ult\ base}$ – ultimate base capacity (Q_b) ; D – Base diameter

Figure 14: Normalised base load and settlement plot

Construction Issues
The construction of the base grouted piles in a congested City site posed many engineering challenges. The major risks associated with potential softening of the shaft and in particular the base was:

- not leaving a soil plug before final cleaning;
- leaving pile bores open for too long between cleaning the base and concreting;
- disturbing the base unnecessarily after base cleaning;
- not carrying out the proper checks on the base stiffness; and
- not controlling the quality of bentonite.

These risks were all judged to be unacceptable for self certification by a piling contractor and therefore Arup had two Resident Engineers (day shift and night shift) monitoring the works and alerting Arup designers to any potential problems on site. This proved to be important as a close working relationship between Arup and Bachy allowed piling construction problems to be quickly resolved on site, minimising delays.

At scheme design stage various options for basement demolition and propping were considered. In addition a decision had to be taken on whether piling should commence from base slab level or at ground level. The Construction Managers opted for piling from existing ground floor slab level (+16.5mOD) once the buildings had been demolished.

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This meant that the Bauer BG40 piling rig sat on the ground floor slab above three levels of basement that were temporarily back propped, as shown in Figure 15. Holes were cut through all the basement levels and the base slab to allow 18m deep temporary casings to be installed ready for piling.

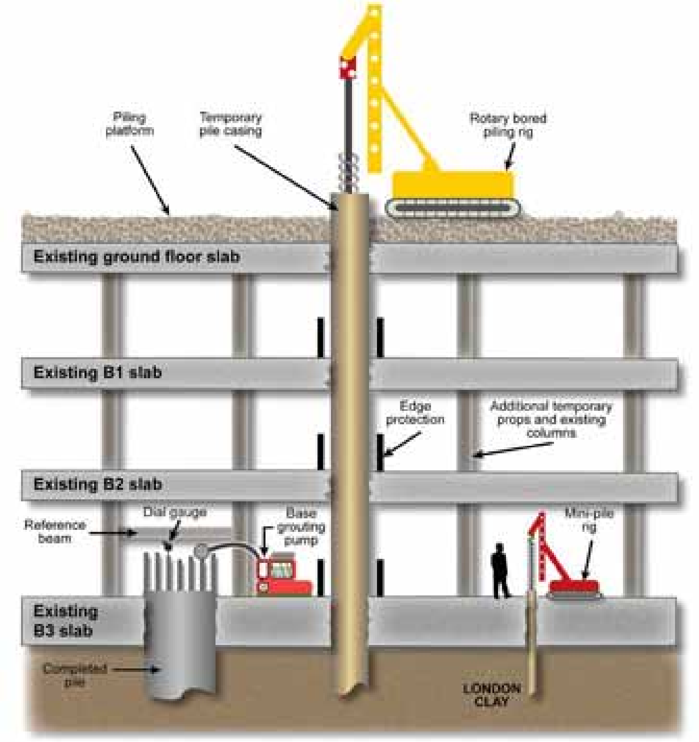

Figure 15: Piling from existing basement ground slab

Piles were constructed over two working shifts per day (working 17hrs out of 24hrs) and each base grouted pile took at least 2 days to construct, provided there was no shaft and base coring of old piles.

Some piles had piling cut-off levels close to the existing B3 slab, in which case the bentonite polluted concrete was brought up into a temporary formwork box constructed at B3 level (Figure 15) to allow the temporary casing to be removed. The polluted concrete was carefully removed, 1-2 days later, with an excavator bucket. All the piles were installed with grout tubes (doubling as sonic logging tubes) and extra pairs of extensometer tubes were installed with the pile cages to measure pile toe uplift, during base grouting.

Tube à manchette (TAM) arrangements

Previous experience with successful base grouting of piles was for piles up to 1.8m diameter, where 4 grout circuits (8 tubes total) are used (Figure 16). The maximum grout area potentially covered by these circuits is about 0.6m^2, and the maximum grout reach is about 0.6m to the pile centre.

To ensure the same coverage of grout area and reach, the 2.1m diameter piles were fitted with 6 TAM's, and the 2.4m diameter piles with 8 TAM's, as shown on Figure 16. A second reinforcing cage was avoided by 'joggling' four of the outer 8 TAMs into the centre of the pile over the bottom 10m, as shown in Figure 16. The outer 4 TAM circuits continued to the base and were also used to sonic log each pile before grouting.

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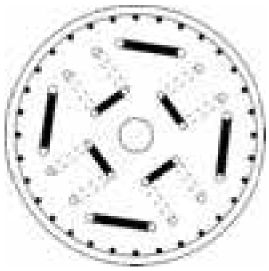

Figure 16: TAM arrangements for 1.8m and 2.4m diameter piles and sketch showing 'joggle'

Bentonite Quality Control
The piling contractor tightly controlled the quality of the bentonite through all stages of the piling and Table 2 shows the results of these site tests against the specification limits, as given in BS EN 1538:2000.

Table 2: BS EN 1538:2000 Bentonite Limits

Property	Stages			
	Fresh	Ready for re-use	Before concre-ting	Site Results
Density (g/ml)	<1.10	<1.25	<1.15	**1.05 - 1.1**
Marsh Value (s)	32 to 50	32 to 60	32 to 50	**30-40**
Fluid Loss (ml)	<30	<50	N/A	**14-18**
pH	7-11	1-12	N/A	**As spec**
Sand Content	N/A	N/A	<4	**0.25 - 2.0**
Filter Cake (mm)	<3	< 6	N/A	**<1**
After BS EN 1538: 2000 Table1 - Execution of Special Geotechnical Works - DWs				

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Base Cleaning and Ranking System for base grouted piles

A non-circular flat bladed cleaning bucket was used to cut the final 150mm of the pile base. This special bucket reduced the suctions generated at the base during bucket extraction and it also had holes on the side so that bentonite fluid could runaway. Following this operation, a 100mm square metal plate attached to a length of fabric tape measure was lowered to the base of the pile to check the base hardness. This was done immediately after base cleaning and after installation of the cage (just prior to concreting). The last measurement was taken to score the base hardness using a ranking system developed specifically for The Pinnacle site, see Table 3.

Scores were given for an OK, Firm or Hard base by the Resident Engineer. In the same way marks for grout pressures, grout take and base uplift (measured with extensometers located at the pile toe), were combined to give an overall ranking score. Grout volume was estimated for each pile size and ranked according to the actual grout take. If the peak grout pressure was less than 30 bar on each circuit during the first grouting phase then the pile was to be regrouted, up to a limit of three grouting operations including the initial operation. A minimum of three hours was allowed between each round of grouting. Using this ranking system a minimum score 7 out of a possible 15 was considered as an acceptable pile.

Conclusions

The Pinnacle is founded on some of the deepest and largest diameter base grouted piles ever built in the City of London. Single piles support loads of up to 45MN and were built through three levels of existing basement in a congested city site. The base grouted piles also had to be drilled through the bases (sometimes the shafts) of underream piles from the previous development, as well as king posts from earlier temporary works left in the ground. This made the construction very challenging. A preliminary instrumented pile test to about 25MN was carried out to confirm the design parameters. The results of this test showed good correlation with design of base grouted piles at the Moorhouse and Canary Wharf sites. Rigorous site controls were implemented checking the quality of the bentonite, base stiffness, grout volume and pressure, and base uplift for all the base grouted piles, using a ranking system that was specially developed for this site.

Acknowledgements

The success of the construction work at Pinnacle could only be achieved through innovation and collaboration between the design and construction teams. Accordingly the authors wish to acknowledge Soil Mechanics, Bachy Soletanche, Mace and Brookfields team for their contribution and co-operation throughout the project.

References

Chin FK. (1970) Estimation of the Ultimate load of piles not carried to failure. Proceedings of the 2nd Southeast Asian Conference on Soil Engineering, pp 81-90

Chin FK. (1971) Discussion on pile test. Arkansas River Project. American Society of Civil Engineers, ASCE, Journal for Soil Mechanics and Foundation Engineering, Vol. 97 SM6, pp. 930 – 932

Fleming, WK. (1992) A new method for single pile settlement prediction and analysis. *Geotechnique* Vol XLII No. 3 pp 441-425

Troughton, VM & Platis A (1989) The effects of changes in effective stress on a base grouted pile in sand. Piling and deep foundations, London

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Table 3: Base grouted pile ranking system

<table>
<tr><th>Parameter</th><th colspan="5">Ranking System Criteria</th><th>Rank</th></tr>
<tr><td rowspan="3">1. Base uplift</td><td colspan="5">>0.15 mm</td><td>3</td></tr>
<tr><td colspan="5">0.1 - 0.15 mm</td><td>2</td></tr>
<tr><td colspan="5"><0.1 mm</td><td>0</td></tr>
<tr><td rowspan="4">2. Base Stiffness</td><td colspan="5">Hard (Grade I)</td><td>3</td></tr>
<tr><td colspan="5">Firm (Grade II)</td><td>2</td></tr>
<tr><td colspan="5">OK (Grade III)</td><td>1</td></tr>
<tr><td colspan="5">No information/soft/very soft (Grades IV & V)</td><td>-2</td></tr>
<tr><td rowspan="6">3. Grout volume, litres</td><td colspan="5">Pile diameter (m)</td><td></td></tr>
<tr><td>1.2</td><td>1.5</td><td>1.8</td><td>2.1</td><td>2.4</td><td></td></tr>
<tr><td>>150</td><td>>200</td><td>>300</td><td>>400</td><td>>500</td><td>3</td></tr>
<tr><td>100 - 150</td><td>150 - 200</td><td>225 - 300</td><td>300 -400</td><td>375 - 500</td><td>2</td></tr>
<tr><td>75 - 100</td><td>100 - 150</td><td>150 - 225</td><td>200 - 300</td><td>250 - 375</td><td>1</td></tr>
<tr><td><75</td><td><100</td><td><150</td><td><200</td><td><250</td><td>-1</td></tr>
<tr><td rowspan="4">4. Max grout pressure (mean on final phase), bar</td><td colspan="5">>70 bar</td><td>3</td></tr>
<tr><td colspan="5">40 - 70 bar</td><td>1</td></tr>
<tr><td colspan="5">30 - 40 bar</td><td>0</td></tr>
<tr><td colspan="5"><30 bar</td><td>-2</td></tr>
<tr><td rowspan="4">5. Av. Residual pressure (mean on final phase), bar</td><td colspan="5">>30 bar</td><td>3</td></tr>
<tr><td colspan="5">20 - 30 bar</td><td>2</td></tr>
<tr><td colspan="5">15 - 20 bar</td><td>0</td></tr>
<tr><td colspan="5"><15 bar</td><td>-2</td></tr>
</table>

Notes:

1. The pile base stiffness is to be measured at the following times during boring:
   - Directly after base cleaning. A minimum stiffness of 'OK' must be achieved at this stage.
   - After reinforcement cage installation.
   - If the time between completion of cage installation and start of concreting is greater than 1 hour then the pile base shall be rechecked immediately prior to placing the concrete.

   The last measurement taken shall be used for the score in the ranking system.
2. Pressure measurements for peak and residual pressure criteria will only be accepted if a minimum volume of 5 litres of grout (after allowing for the compliance of the delivery system) has been injected.
3. If a peak pressure of 30bar and residual pressure of 15bar are not achieved on each circuit during the first grouting phase then the pile shall be re-grouted, up to a limit of three grouting operations including the initial operation. A minimum of 3 hours must be allowed between each round of grouting.
4. Pile head uplift shall not exceed 2mm.
5. A maximum of three grouting operations (including the initial operation) shall be carried out.

Case History

The Pinnacle Tower – Geotechnical Challenges (continued)

Chapman TJP, Connolly M, Nicholson DP, Raison CA and Yeow HC(1999). Advances in understanding of base grouted pile performance in very dense sand, International symposium and exhibition in tunnelling construction and piling, London.

Nicholson DP, Chapman TJP, Morrison P (2002). Pressuremeter proves its worth in Londons Docklands, Ground Engineering March 2002

O'Reilly, M.P. (1990) Heave induced pile tension: a simple one dimensional analysis Ground Engineering, (June, 1990)

Yates and O'Riordan, (1989) "The design and construction of large diameter base-grouted bored piles in Thanet Sand, London." *Proceeding of the Conference of Piling and Deep Foundations*. Balkema, Rotterdam, 1, pp455 – 461.

Yeow et al (2005) "The design and construction of the deepest base-grouted bored piles at Moorhouse, London." *Deep Foundations Institute 30th Annual Conference on Deep Foundations*. September 2005.