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Pushing the boundaries – the use of innovative design, testing and instrumentation to deliver the highest loaded piles installed in the UK to date

Repousser les limites - utiliser une conception, des tests et une instrumentation innovants pour fournir les pieux à la charge la plus lourde du Royaume-Uni à ce jour

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ABSTRACT: 21 Moorfields is an over site development between eight and sixteen stories spanning Moorgate Station in the City of London. The site is situated directly above the existing London Underground Moorgate Station and also spans new Crossrail tunnels running in and out of Liverpool Street Station. Due to the complex subterranean nature of the site, two new buildings are supported on only 15nr new piles of 1800mm and 2400mm diameter. All piles are constructed while working on a suspended steel decking above the roof of the existing station while trains continue to run as normal below. Piles are constructed through the existing station under support fluid (bentonite) up to 60m, founding in the underlying Thanet Sand Formation. All piles are base grouted and incorporate sophisticated instrumentation, allowing monitoring during the construction phase and over a long term period of at least two years, providing a rare opportunity to understand long term performance of such complex foundation systems. Piles are subjected to very high loads, up to 82.3MN (STR) believed to be the highest loaded piles constructed in the UK to date. To validate the geotechnical design, a sacrificial test pile has been undertaken and loaded to 50MN using a bespoke top down static load test. This has aided validation of the design parameters and provided information on the predicted performance of the piles under axial load. All piles (including test pile) are monitored using the CemOptics system for integrity and fibre optics to monitor strain. Both the size of the maintained load test and level of validation of pile performance using new technology is unprecedented, particularly on a complex, inner city development.

RÉSUMÉ: 21 Moorfields est un projet en développement de huit à seize étages dans la gare de Moorgate à Londres. Ce site est directement au-dessus de la station de métro londonienne Moorgate existante, s'étendant également sur de nouveaux tunnels Crossrail la reliant à la station de Liverpool Street. Les souterrains du site étant de nature complexe, deux nouveaux bâtiments ne sont supportés que par 15 nouveaux pieux de 1800 mm et 2400 mm de diamètre, tous construits sur un tablier métallique suspendu au-dessus du toit de la gare, tandis que les trains continuent de circuler normalement.

Ils sont construits à travers la station déjà existante sous de la bentonite jusqu'à 60 m, se fondant dans la structure sous-jacente de Thanet Sand. Tous ces pieux, avec injection par leur base, possèdent des instruments sophistiqués, permettant une surveillance pendant la phase de construction, puis pendant une période d'au moins deux ans, offrant une occasion rare de comprendre la performance à long terme de tels systèmes de fondations complexes. Ils sont, en outre, sont soumis à des charges très élevées, jusqu'à 82.3MN (STR), considérés comme étant ceux supportant les plus lourdes charges au Royaume-Uni à ce jour. Pour valider la conception géotechnique, on a chargé un pieux-test à 50MN à l'aide d'un test de charge statique sur mesure de haut en bas, ce qui a facilité la validation des paramètres de conception et fourni des informations sur les performances prévues des pieux sous charge axiale. Tous les pieux (y compris ceux des tests) sont contrôlés à l'aide du système CemOptics pour vérifier qu'ils restent intacts et de la fibre optique pour surveiller leur pression. La taille du test de charge maintenu et le niveau de validation de la performance des pieux à l'aide de la nouvelle technologie sont sans précédent, en particulier en ce qui concerne les constructions complexes en centre-ville.

Keywords: Deep foundations; piling; load testing; design, base grouting

1 INTRODUCTION

The 21 Moorfields project is situated in the City of London, directly over Moorgate tube station and adjacent to the Barbican and the C501 Moorgate access shaft for Crossrail. The project consists of 4nr 1800mm diameter piles, 11nr 2400mm diameter piles and a single sacrificial test pile of 1200mm diameter. All piles are constructed using the rotary bored piling technique, formed under bentonite support fluid and found in the Thanet Sand Formation up to 60m in length and are base grouted. All piles are constructed from a suspended grillage level over Moorgate Station, constructed through the station area and existing London Underground (LU) platforms using permanent casing to the top of the London Clay Formation. Piles are subjected to vertical loads (ULS STR) between 44MN and 82.3MN. The piles will support a commercial office development between eight and sixteen stories in height. All contract piles were completed by November 2018, construction of the main structure is due to commence in 2019.

2 GROUND CONDITIONS

A total of 6nr boreholes were undertaken in two phases; these were undertaken using cable percussion and rotary techniques and extended between 39mbl and 85mbgl. Broadly the underlying stratigraphy is typical of the London Basin, comprising River Terrace Deposits underlain by the London Clay Formation, the Lambeth Group and the Thanet Sand Formation. The site investigation extended below the Thanet Sand Formation into the Bullhead Beds and the Newhaven Chalk Formation.

Local variations in Thanet Sand level occur across the site (by up to 7.5m). In addition, the boreholes show a local absence of the Lower Shelly Beds in the Lambeth group and the presence of the mid Lambeth hiatus in the form of calcrete deposits in some of the boreholes. To the east of the site a drift filled hollow was confirmed during construction of the Moorgate Box, although noted as a potential design risk, this was not encountered on the Moorfields site.

All piles are installed from a suspended grillage level around 16.2mOD. Ground level and stratum levels can be seen in Table 1. All piles were installed with a permanent liner to +3.70mOD to allow the pile cut off level to be brought above ground level. Robert Bird Group designed the liner requirements which took into account installation tolerances and any potential buckling effects.

Stratum	Levels
Made ground	LU platform level between +9.600mOD and +8.250mOD. Made ground encountered up to +7.91mOD
River terrace deposits	+7.91mOD to +5.49mOD
London Clay Formation	Encountered between +8.40mOD and -23.16mOD. Design levels taken as +6.00mOD to -20.00mOD
Harwich Formation	Not present in all boreholes. Up to 1.5m thick and encountered between -17.16mOD and -24.16mOD
Lambeth Group including Upnor Formation	Encountered between -18.66mOD and -42.66mOD.
Thanet Sand Formation	Encountered between -35.16mOD and -53.16mOD. Top of formation varies across the site. Between 10.46m and 13.05m thick.

Table 1. Summary of ground conditions on site

3 DESIGN

We believe that the piles at 21 Moorfields are the highest loaded piles constructed in the UK to date. As a result, the design of the piles was critical in terms of both their structural and geotechnical capacity as well as their performance under loading.

A common approach to the design of large diameter piles installed within London and founding within the Thanet Sand Formation is to have a minimum factor of safety on the shaft to limit settlement. However, as the piles were so highly loaded at Moorfields, a significant amount of the load under working conditions relied on end bearing rather than shaft friction. As a result it became critical as part of the design process to understand not only the variation in Thanet Sand levels across the site but also the properties of the Thanet Sand with depth.

3.1 Profiling of the Thanet Sand Formation

It is usual to limit the toe levels of piles in this stratum to the top 2m to 3m to ensure that piles found in 'clean' sand as the formation tends to increase the fines content, particularly silt, with depth, thus significantly affecting the end bearing (Nicholson et al, 2002). A review was undertaken using the particle size distribution (PSD) results and the pressuremeter testing in the Thanet Sand Formation to see if it was possible to determine when the end bearing capacity of the piles might be reduced as a result a higher fines content.

From the pressuremeter testing and the PSD data it was evident that 'clean' sand (<20% fines) extended to between 6m and 7m below top of formation level. This allowed a further review to be undertaken of the achievable load capacity of the piles should they found up to 4m into the Thanet Sand Formation. This was particularly relevant as the level of the Thanet Sand varied across the site by up to 7m and constructability issues meant that cages were fabricated off site with little ability to change the length once they had been delivered.

Furthermore, due to the high axial loads acting on the piles, in the majority of cases the factor of safety on the shaft against the SLS load was less than 1.0. This meant that the piles were heavily reliant on end bearing in the Thanet Sand Formation therefore understanding capacity and depth of clean sand was paramount.

3.2 Preliminary test pile requirements

Large diameter piles installed in London and founding within the Thanet Sand Formation are usually designed with resistance and model factors sufficient to negate the need for load testing. Due to the confined nature of the 21 Moorfields site, limited space was available for individual pile locations resulting in the load on the piles having to be maximised.

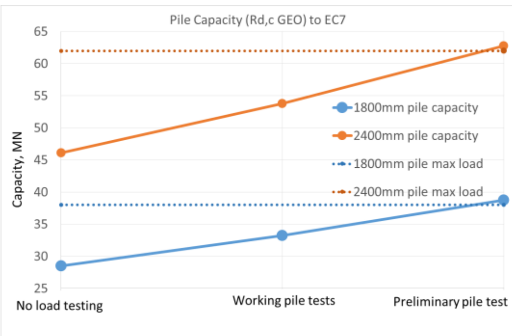

Figure 1. Capacity of piles with and without load testing

From Figure 1 it can be seen that by utilising model and resistance factors from EC7 for preliminary pile testing, the ultimate geotechnical capacity of the piles increased by greater than 25%. This approach was essential in being able to demonstrate sufficient ultimate pile capacity, irrespective of serviceability requirements.

3.3 Design parameters

Design parameters are shown in Table 2. Both the Lambeth Group and the London Clay Formation had their alpha values down rated to allow for the potential build up of filter cake in the pile bore during the construction period. Due to the variable nature of the Lambeth Group a uniform shaft friction was taken along the length of the pile in the formation and it was treated as a cohesive material. From sensitivity checks on interbedded cohesive and granular strata in the group, it was felt that this approach allowed a uniform and slightly conservative approach to be taken rather than trying to determine specific changes in the Lambeth Group at each pile location, which would have been extremely challenging. Contribution to skin friction was ignored to +3.7mOD (toe level of the permanent liner).

Stratum	Levels and parameters
Made ground	Ignored for shaft friction
River terrace deposits	Ignored for shaft friction
London Clay Formation & Harwich Formation (if encountered)	+3.7mOD to -20.00mOD γ = 20kN/m3 Cu at top = 100kPa Cu at bottom = 275Kpa α = 0.4 (piles under bentonite) Average α.Cu not to exceed 110kPa
Lambeth Group including Upnor Formation	-20mOD to -40mOD (typically) γ = 20kN/m3 Cu at top = 350kPa Cu at bottom = 350kPa α = 0.3 (piles under bentonite) Average α.Cu not to exceed 140kPa
Thanet Sand Formation	-40mOD (typically) γ = 20kN/m3 Φ' = 38 degrees End bearing limited to 20,000kN/m^2 Shaft friction limited to 250kPa

Table 2. Geotechnical design parameters

3.3.1 Thanet Sand Formation parameters

Due to the high loads acting on the piles there was significant discussion and review of the end bearing capacity of the Thanet Sand Formation. The Moorhouse development situated immediately adjacent to the 21 Moorfields site was reviewed where 1800mm piles were constructed and base grouted by Cementation Skanska in 2001 and a preliminary test was constructed (Yeow et al, 2006). The Pinnacle is a more recent example of large diameter base grouted piles founding in the Thanet Sand Formation (Patel et al, 2015). However, based on the review of these projects, it was not felt that increasing the ultimate base capacity of the Thanet Sand greater than 20MPa was justifiable.

3.4 Single pile settlement predictions

Single pile settlement predictions were carried out for all piles using the CemSet method of analysis. Usually the design of large diameter piles founding in Thanet Sand is based on ensuring that the factor of safety on the pile shaft against unity is >1.0 (typically 1.2) in order to limit settlement of the pile. Due to the high loads acting on the piles, this was not possible and single pile settlement predictions at SLS varied between 25mm and 50mm. With collaborative working between Cementation, RBG and GCG these settlements were able to be accommodated in the frame design and the building construction.

3.5 Design sensitivity checks

The authors had not to date worked on a project where alternative pile positions were not available, even in a central London site. Due to this limiting nature in terms of viable pile locations, a process of design risk review was undertaken to determine pile capacities in several scenarios:

Scenario	Detail
1	High Thanet Sand level (-37.00mOD)
2	Low Thanet Sand Level (-41.00mOD)
3	Scenario 1, pile left open >4 days
4	Scenario 2, pile left open >4 days
5	Thanet Sand end bearing 18.5MPa
6	Thanet Sand end bearing 15.5MPa
7	Piles founding in Newhaven Chalk Formation

Table 3. Design scenarios considered

From Figure 3 it can be seen that there were several scenarios considered where the ultimate geotechnical capacity of the piles did not meet the required vertical load. As a result, a further mitigation measure was taken where larger diameter piles (2700mm) were considered which would found in the Thanet Sand Formation. In this instance 4m penetration into the Thanet Sand Formation meant that the piles could achieve the maximum load of 63MN (ULS GEO).

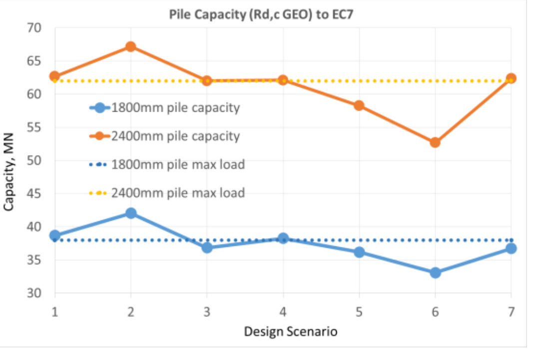

Figure 2: Capacity of piles for considered design scenarios

3.6 Base Grouting

The first significant use of base grouted bored piles in the UK was in the 1980's for the Canary Wharf, London Docklands development. Piles in this area were routinely founded in the Thanet Sand, encountered at depths of 20 to 30m (Troughton, 1992) and high base capacities were generated within this dense cohesionless material, where insitu effective stress at the pile toe were typically 300 to 400kPa.

Over recent years, the use of base grouting in large diameter bored piles has been adopted over much wider areas of London, the City of London in particular. In these areas piles continue to found within the Thanet Sand but at much greater depth, with Thanet Sand encountered at almost twice the depth of Canary Wharf with a commensurate increase in effective stress at the pile toe.

There remains limited experience of testing these larger, deeper and higher capacity piles and the load test at 21 Moorfields provided a significant opportunity to further our understanding of such piles, tested to a load well in excess of any top loaded pile in the UK to date.

Table 4 below summarises the test loads achieved on piles to date in the UK (specific to bored piles founding in Thanet Sand and top loaded).

Location	Dia. (mm)	Length (m)	Max SLS Test Load

Canary Wharf	Up to 1500	<30	<25MN
Moorhouse	900	56	23MN
Pinnacle	900	64	25MN
Shard*	1500	54	29MN
21 Moorfields	**1200**	**59**	**50.5MN**

*Table 4 Summary of Top Loaded Thanet Sand load tests (*not base grouted)*

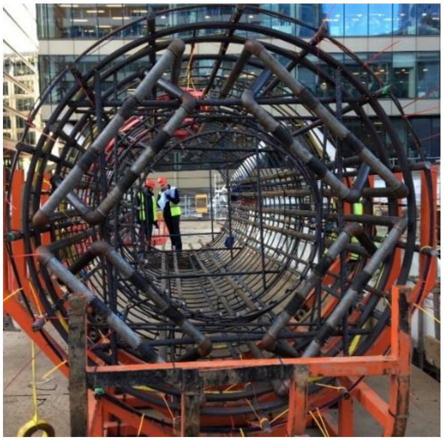

Figure 3. Pile cage with base grouting tubes shown

Figure 3 shows an 8 circuit base grouting system adopted at 21 Moorfields.

4 PRELIMINARY TEST PILE

Options for the preliminary test pile were discussed at length and it was decided that a top loaded static pile test would be undertaken rather than installing a bi-directional load test cell. There were several reasons for this decision; it was felt that on occasion bi-directional load tests can yield anomalous results which are difficult to interpret. With only one possible location for the preliminary test pile it was felt that the risk was too high to rely solely on a test pile that may have challenging results which are difficult to interpret; It was felt that a top loaded traditional pile test would provide a better understanding of how the pile would work when vertical loads were applied to it as part of the construction in a similar way; The stress change in the ground induced by bi-lateral load tests is not well understood, particularly in poorly cemented granular deposits such as the Thanet Sand Formation (compared to competent rock in geographical areas where this type of test is commonly used) and it was felt that this could have an effect on both the performance of the test pile and the strain measured as the result of any stress regime change at depth; There was further concern that the ultimate shaft friction calculated above the load cell would not be sufficient to provide the reaction required to test the Thanet Sand Formation up to/beyond 20MPa. Therefore a static top loaded test was undertaken to a maximum load of 50MN. A load well in excess of any top loaded pile test completed to date in the UK.

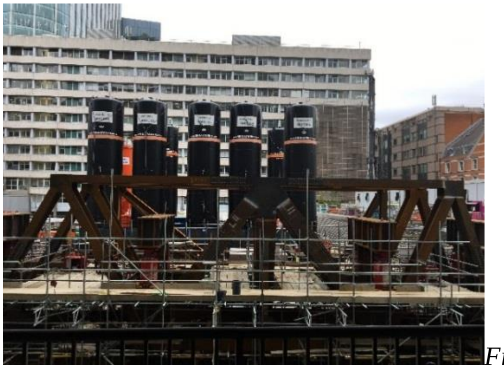

Figure 4: Test pile reaction frame with bentonite silos in the background (also used as ballast during the test)

The preliminary pile test was undertaken on a 1200m pile as EC7 allows meaningful interpretation from pile tests up to 50% of the diameter of the largest scheme pile. In addition to this, test loads would have had to be in excess of 120MN if the load test was carried out on a 2400mm pile, which was not achievable given site constraints and the significant challenges associated with a 50MN test.

4.1 Anchor piles

Due to space constraints on the site, permanent works piles were used as reaction piles for the load test. Four permanent works piles were used with SLS tension loads between 10.9MN and 14.5MN. High strength steel tension bars were be cast into the reaction piles to allow the application of the test load.

4.2 Reaction frame

A bespoke reaction frame was designed by RBG to facilitate the pile test. The 200t , 6m high steel truss spanned over the four reaction piles and the test pile. Tension loads were applied to the reaction piles using pairs of hydraulic jacks mounted on the reaction truss and load cells were installed at the head of the test pile to confirm the force being applied. A bracing system connected the test truss and the retained deck to stabilise the truss during its construction as well as the pile test. This bracing system required concrete ballast to resist overturning of the truss during the pile test.

Figure 5: Test pile reaction frame showing permanent piles used as anchor piles.

4.3 Instrumentation

Sophisticated instrumentation was installed into all piles, including the test pile in the form of extensometers, vibrating wire strain gauges (VWSG) and fibre optics (CemOptics™ system). Both distributed fibre optics sensors (DFOS) and Brillouin Optical Time Domain Reflectometer (BOTDR) fibre optics were installed for both quality and integrity. Instrumentation was utilised at the following stages of the test pile construction (and main works pile construction):

i) During construction: DFOS used to monitor concrete flow during construction and thermal integrity profiling over a 48 hour period (Figure 6).
ii) During base grouting: Extensometers used to measure movement at pile base, VWSG used to monitor strain during base grouting process.
iii) During Load testing: VWSG and BOTDR fibre optics used to monitor strain in the pile during load test
iv) Long term monitoring of the permanent works piles using BOTDR fibre optics will be undertaken to assess the performance of the piles over the entire build period, which as yet is unprecedented for long term pile performance monitoring.

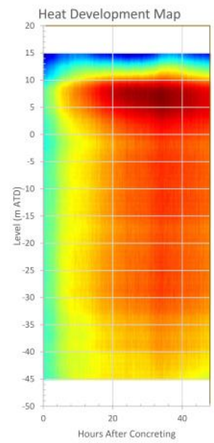

Figure 6: Heat development map using CemOptics™ during concreting of the test pile.

4.4 Test pile settlement predictions and performance

Prior to the test pile being undertaken single pile settlement predictions were undertaken by Cementation, GCG, Byrne Looby and RBG (Table 4). The preliminary test pile was designed with a SLS capacity of 19,500kN and an ultimate geotechnical capacity (ultimate shaft friction plus ultimate end bearing) of 39,769kN. Pile toe level installed 2m into the Thanet Sand Formation at -43.10mOD. The pile was installed between 4th and 7th June 2018 and the load test undertaken between 11th and 12th September 2018.

Load	Settlement predictions**	Actual settlement
19,500kN (DVL)	20 to 30mm	22mm
39,000kN (Frep + DVL)	80 to 150mm	53mm
Max load 50,500kN	Up to 250mm	78mm

*Table 4. Test pile settlement predictions against measured settlement.**predicted settlement range across all four parties.*

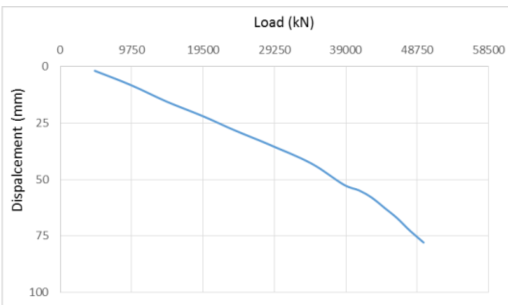

Figure 7: Test pile load vs Displacement graph

5 CONCLUSION

The piling works at the 21 Moorfields has been a success both in construction challenges, design validation and design risk management. The key to this success has been the strong and continued collaboration of all parties involved.

From the results of the preliminary test pile (see Figure 7), it is evident that the decision not to use a bi-lateral load test for the project was the right one. The use of a top loaded static load test has provided the opportunity to better understand the performance of highly loaded, large diameter piles formed under support fluid and founding in the Thanet Sand Formation. It is clear from the recorded settlement of the test pile that the performance of the pile far exceeded both the settlement response and the ultimate capacity expected using current industry parameters for design of piles and single pile settlement predictions. (Table 4)

It is the authors' intent to publish a further paper on the detailed analysis of the test pile undertaken at 21 Moorfields and the potential implication for the design of similar piles within the London area.

6 ACKNOWLEDGEMENTS

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