Moorhouse foundations designed for future Crossrail wins DFI’s Outstanding International Project Award

Constructing London’s deepest base grouted piles on logistically challenging Moorhouse site
Moorhouse, London –
Designing for Future Crossrail

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BACKGROUND

The new 19-storey high Moorhouse was commissioned by Moor House Limited Partnership and is another new Central London landmark building by the British architect Foster and Partners. Two of the four facades feature complex geometry to fulfill the city’s planning requirements. The building’s steel frame structure is stabilised by a reinforced concrete core. The complex geometry of the superstructure requires a diagonal “bandolier” to transfer floor loads to perimeter columns then down to the foundations. The development has one level of basement covering the entire footprint of the building with a second basement level over approximately the eastern half of the building footprint.

The proposed Crossrail will provide a rail link between the east and the west of the City of London. In the Moorgate area, where Moorhouse is located, the alignment dips to its deepest point to avoid existing underground tunnels. The Moorhouse footprint is within the safeguarded zone of this proposed rail link. The safeguarding directions made in 1991 by the then Department of Transport made Crossrail a statutory consultee in the Moorhouse planning application. This is to ensure Crossrail is protected against any detrimental impact of its development.

Interaction of Crossrail with Moorhouse

The new rail link will have a new ticket hall at Moorgate and an upper plant room, which lies in the northeast of the Moorhouse site. There is also an 8.2m (37 ft) internal diameter 40m (131 ft) deep temporary draught relief shaft built as part of the Moorhouse development to facilitate future construction of a ventilation shaft belonging to the proposed Crossrail project. Due to future access constraints, these structures were built as part of the Moorhouse project.

The new Crossrail’s Moorgate ticket hall will be constructed with a 40m (131 ft) deep box that will form the access, both during construction and in the future, for the Crossrail’s Moorgate Station and will provide the necessary space for other essential utilities. Two 6.6m (21.6 ft) external diameter running tunnels north of the footprint of Moorhouse will be bored at about 35m (114.8 ft) below street level. Another two 6.1m (20 ft) diameter cross passage tunnels will be constructed linking the running tunnels to the ventilation shaft. Figures 1 and 2 show the plan and section through the basement and future Crossrail’s structures.

Figure 1. Plan of Moorhouse site

Figure 2. Section of Moorhouse basement and Crossrail’s structures
The construction of the temporary draught relief shaft and future Crossrail’s deep box and tunnels will cause ground movements. In line with the Crossrail safeguarding requirements, the Moorhouse foundations were designed to tolerate these movements without compromising the performance of the superstructure. Figure 3 shows a 3D schematic of the Moorhouse development and the Crossrail temporary draught relief shaft and running tunnels.

**GROUND CONDITIONS**

The Moorhouse site is underlain by variable thicknesses of Made Ground that are up to 5m thick. Underlying the Made Ground is about 2m (6.5 ft) of Terrace Gravel, 32m (105 ft) of London Clay, 18m (59 ft) of Lambeth Group, 10m (33 ft) of Thanet Sand and Chalk proved to 5m depth. The clays are underdrained due to the low groundwater level in the lower aquifer of chalk underlying Central London. A summary of the stratigraphy of the site can be seen in Figure 2.

**DESIGN OF FOUNDATION AND DRAUGHT RELIEF SHAFT**

Piled foundations

Two key issues for the design of the Moorhouse foundations’ were speed of construction and the need to allow for the effects of the proposed Crossrail rail link adjacent to the development.

In order to achieve speedy construction, a semi top-down bottom-up construction option was adopted. This led to a foundation scheme consisting mainly of columns supported on 35 no. single piles up to 1800 mm (6 ft) in diameter, except in the area under the central core where a pile group with 19 no. 1500mm (5 ft) diameter piles was used. These piles were installed using two state-of-the-art heavy-duty Bauer rigs by Cementation Foundations. To clear the location where the new bearing piles were to be installed, Cementation Foundations removed a number of existing, reinforced, cast in place 600mm diameter piles. This was done using the Bauer BG36 piling rig and segmental casing screwed in around the old pile. The pile was then crushed and removed by boring through it using a heavy-duty rock auger, guided by the perimeter segmental casing. Once the pile had been completely removed the bore was backfilled with a cement/bentonite, clay type soft mix and casing extracted.

Plunge columns were used in some parts of the site to facilitate construction. As a result of heavy structural loading and the effects of potential ground movements from construction of the proposed Crossrail rail link, base grouted bored piles founded in the underlying Thanet Sand with bitumen coated sleeve (see Figure 4) in London Clay were chosen as the most appropriate foundation scheme. With a toe level of -43mOD (-141 ft), these piles are about 56m (184 ft) below street level, compared with 25-35m (82-115 ft) long piles normally installed in Central London in London Clay. Table 1 shows a comparison of foundation schemes with and without the influence of Crossrail.
Base grouting is used in bored piles founded in Thanet Sand to reinstate the stiffness of pile base loosened by piling operation (Yeats and O’Riordan, 1989). For the base grouted bored piles at Moorhouse, four circuits of grouting tubes (i.e. a total of 8 grouting tubes) were installed with the reinforcement cage to enable the base grouting operation. Grade 50 concrete was also specified in order to achieve a maximum working stress of 12.5MPa (1800 psi) in the piles to support the heavy vertical column loads of up to 32MN (3,600 tons). This was the first use of such high-grade concrete in bored piles in the UK. Details of design of these deep piles are reported in Yeow et al. (2005).

Temporary draught relief shaft

The temporary lining for the Crossrail draught relief shaft was designed to accommodate the constraints imposed by the Moorhouse foundations and the future Crossrail works. With respect to the Moorhouse foundations, the performance of which relies on beneficial shaft friction in the lower levels of the London Clay and below, it was necessary to construct the shaft with minimal disturbance (stress relief) to surrounding ground. To address this constraint the shaft construction was subjected to detailed finite element calculations allowing the potential ground and groundwater conditions to be modeled (in geotechnics this is not an exact science yet). The results of these calculations allowed a set of acceptable ground movements to be established against which the actual shaft construction was monitored (The Observational Method approach). Contingency measures were designed into the shaft in the event of worse than anticipated ground and groundwater conditions being encountered.

With respect to the design details to accommodate the future Crossrail construction, the shaft was detailed with low friction circumferential packers to allow shear distortion thereby prevent bending stresses (and localized damage) that would occur when the adjacent deep box is installed and steel fiber reinforcement to limit spalling of concrete that would result from the inevitable distortions that Crossrail will cause to the shaft prior to the permanent lining being installed. Details of the design and construction of the temporary draught relief shaft are reported by Morrison et al. (2004) and Figure 5 shows the constructed segmental lined shaft.

| Table 1. Comparison of foundations with and without the influence of Crossrail |
| Structure | Piles in Moorhouse with influence of Crossrail | Piles in structure similar to Moorhouse without influence of Crossrail |
| Foundation depth | Bored base-grouted piles constructed under bentonite to 50m depth into the Thanet Sand | Dry bored piles to 30 m depth within the London Clay |
| Method of carrying working load | Combined pile skin friction in Lambeth Group and end bearing in Thanet Sand | Pile skin friction in London Clay |
| Working load | Structural load and negative skin friction as well as bending moment due to ground movements | Structural load only |
| Governing design criteria | Structural capacity of reinforced concrete of the pile (see Test Pile) | Limiting capacity of the London Clay |

Figure 4. Installation of bitumen-coated sleeve

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Figure 5. Completed segmental temporary draught relief shaft
Finite element modeling

Complex finite element assessment using Oasys SAFE program was undertaken to compute potential ground movements due to the construction of the 40m deep Crossrail box (Yeow et al. 2005). Ground movements due to Crossrail tunnelling work were assessed using Oasys TUNSET program. These two components of ground movements were superimposed to produce the final predicted ground movements in three-dimensional space and were then imposed onto the Moorhouse foundations. In the pile design, the effect of reduction in bending stiffness due to ground movement induced curvature was allowed to avoid the need for excessive reinforcement steel for a designed lateral displacement of up to 75mm (3 in.).

A separate finite element modeling of the 40m (131 ft) deep temporary draught relief shaft using Oasys SAFE program (Morrison et al. 2004) was undertaken to investigate the “de-stressing” effects of the construction of such structure on piles adjacent to the shaft.

TEST PILE

A 900mm (36-inch) diameter 56m (184 ft) long test pile was used to confirm the design parameters for the piles at Moorhouse. This diameter of test pile had been used at Canary Wharf to confirm the design parameters of piles up to a diameter of 1500mm (5 ft), and this had been successfully proved by subsequent contract pile tests. Although the maximum size of piles at Moorhouse is 1800mm (6 ft) diameter, it was considered appropriate to apply the same approach.

In order to test the 900mm (36-inch) diameter pile using a commonly available test frame with a maximum applied test load of less than 30MN (3,372 tons), sleeving of the pile over the top 26m length, between ground level and -13mOD (-43 ft), was necessary. The test pile was also designed to assess the performance of a 22m (72 ft) length of bitumen coated permanent casing, between -13 and -35mOD, (-43 to –115 ft) which was to be used to reduce downdrag resulting from ground movement caused by Crossrail construction. The last 8m (26 ft) in the Lambeth Bed sand and the Thanet Sand, between -35 and -43mOD, (-115 to –141 ft) allowed the assessment of the skin friction of these soils. Figure 6 shows the temporary casing used for the test pile. Details of the sizes of casings and instrumentation fixed to the test pile are shown in Figure 7.

Temperature measurements taken from the pile showed that hydration heat during concrete curing peaked at 49°C (120°F) 18 hours after casting of the pile. The temperature in the concrete stabilised after about 4 days.

Figure 8 shows the load-settlement behaviour of the pile after the third cycle of loading to 22.9MN (2,574 tons) where the measured pile head movement was about 77mm (3 in.). The test load of 22.9MN (2,574 tons) represents 2.5 times the working load and the majority of this movement was due to elastic shortening of the sleeved section of the pile.

A reasonably conservative approach was taken in the interpretation of the shaft resistance of the test pile, giving an equivalent shaft capacity of the test pile of 6MN, (675 tons)
excluding any contribution from the bitumen coated section. Frictional resistance of the bitumen-coated sleeve was shown to be dependent on pile settlement. A conservative estimate value of 40kPa (5.8 psi) was observed when the relative movement between the pile shaft and the soils was 25mm (1-inch). When this relative movement is less than 10mm (0.4 in.) the frictional resistance measured during the test was negligible. This gave an end bearing capacity of 38MN (4,271 tons), or 60MPa (8.7 ksi), compared to 30MPa (4.35 ksi) assumed in the preliminary design.

The test pile also showed that the capacity of the pile was governed by the structural capacity of the reinforced concrete instead of the geotechnical capacity of the foundation soils. However, the piles could not be shortened as the soils above the Thanet Sand would not have the required bearing capacities to support the design load.

CONSTRUCTION ISSUES

Pile foundations

Installation of the deepest base grouted bored piles at the congested Moorhouse site in Central London posed many logistical and environmental challenges. The risks associated with potential softening of the base when the pile bore was left open overnight before concreting and the time required to perform critical activities during the last day of the piling work were carefully evaluated by the team prior to commencement of construction activities.

In order to limit the environmental impact of the piling works on local residence, the project team had to reduce the amount of digging required on the day the pile was to be concreted. Cementation Foundations conducted “Non-standard” penetration tests (NSPT) in the base of the bores at Stratford and Canary Wharf and the trials showed that the NSPT penetration resistance in Thanet Sand varied within an acceptable range when the Thanet Sand was exposed for durations greater than 19 and 20 hours respectively. Finite element analyses of the pile bore were also undertaken and showed the bore to be stable, even without formation of bentonite cake, and that under homogeneous condition the base of the pile remains stable with an adequate factor of safety.

Further drilling trials were undertaken during the initial phase of the contract piling work to determine the optimum thickness of the plug and to investigate the effectiveness of the cleaning bucket used. The tests were undertaken using a probing weight attached to the end of a strong (and very stiff) measuring tape. The “impact” response while dropping the weight was used to gauge the cleanliness of the pile base before base cleaning. The trials revealed a satisfactory progress rate in boring and cleaning out of the last 2m (6.6 ft) of the pile base. The use of clean bentonite also prevented the need to desand the pile after base cleaning operation, hence speeding up the construction time of the pile.

Reinforcement cages for the Moorhouse piles were manufactured off site in four sections and delivered to site just in time for installation. Couplers were used to connect the sections of the cages together. The use of two rat holes, i.e. temporary cased holes about 25m (82 ft) deep, allowed pairs of reinforcement cage sections to be joined together in advance. This left only one joint to be made once the cage was being lowered into the pile bore. Even with only one joint to connect, coupling between 18 and 24 main reinforcement bars (T20, T25 or T32), eight 50mm (2-inch) diameter grouting tubes, two 15mm (0.6 in.) extensometer tubes and, in some piles, a 100mm (4-inch) sleeve and three additional 15mm (0.6 in.) extensometer tubes, took up to 4 hours to complete.

Although concreting operations took a significant amount of time, the process was more controllable. Typical concreting durations for a 1500mm (5-ft.) diameter pile (i.e. approx. 90m$^3$ (118 c.y.) concrete) was about 4 hours and for a 1800mm (6-ft.) diameter pile (i.e. approx. 120m$^3$ (157 c.y.) concrete) was about 6 hours. This is equivalent to about 20-25m$^3$ (26 to 33 c.y.) of concrete per hour.

Temporary Draught relief shaft

The draught relief shaft was constructed within the basement of the newly finished building in order to achieve the cost benefits of an overall programme savings of 3 months. This had posed tremendous logistic problems with respect to muck-away and ring delivery.
Prior to the commencement of construction instrumentation in the form of inclinometers and piezometers were installed around the shaft to provide information for comparison with the design assessments. Thereafter the primary dewatering system (an ejector well system) was installed in the Thanet Sand and the Lambeth Group, the system was designed by WJ Groundwater following a detailed pumping trial at the site. A secondary emergency dewatering measure was also designed to be installed from within the shaft to tap remaining pockets of water in the Lambeth Group. Advanced probing ahead of the excavation also allowed the constructor the opportunity to confirm the presence of any water-logged pockets beneath the advancing shaft. An Observation Method approach was used to monitor the work and provide feedback to the contractor of how to limit ground movements. The shaft was constructed without the need for secondary dewatering within the acceptable trigger ground movements.

CONCLUSIONS

The design and construction of the then longest base grouted bored piles and the 40m (131 ft) deep temporary Crossrail draught relief shaft in Central London posed many challenges to the designer and the constructor. The single column single pile solution necessitated the first use of Grade 50 concrete in piles and the need to allow for future construction induced ground movement required the piles to be designed as base grouted bored piles founded in the Thanet Sand with some piles to be sleeved permanently to minimise downdrag.

The open-minded approach adopted by all parties allowed the piling and draught relief shaft excavation to be undertaken under the least disruption with respect to construction related problems. The use of Observational Method in the construction of the temporary draught relief shaft was a success and this allowed the excavation in the Lambeth Beds without the need of the secondary dewatering measures. Other observations are:

- Higher end bearing can be taken for base grouted piles in Thanet Sands at higher in situ stresses,
- The bitumen liner reduced friction to 40kPa (5.8 psi), when relative movement between the soil and casing was about 25mm (1-inch),
- The use of high strength concrete did not introduce any construction difficulties,
- The use of sonic logging test is essential to confirm the integrity and quality of the piles, especially when the design is governed by the stress in the high strength concrete.

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References

Bitumen coated casing

Installation of test pile casting

Cage with base grouting circuit

Left photo: Placing bitumen-coated casing to reduce downdrag
Top right photo: Setting temporary casing for splicing
Lower right photo: Rebar cages with eight 50mm tubes forming base grouting circuit