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Field measurements of ground movements associated with circular shaft construction

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ABSTRACT: Circular shafts are an integral component of infrastructure development schemes which exploit underground space. However, limited design guidance exists for such structures and the cautious approach often adopted by designers can have significant impact on the shaft construction costs and the protective measures implemented for adjacent buildings and services. In the UK, Crossrail is a major tunnel construction project underway to improve transportation links across London and the South East. Several deep circular shafts were constructed to facilitate access and egress of plant and personnel to and from the tunnel horizon and to provide ventilation and emergency access. This paper describes the findings from a comprehensive review of field observations associated with construction of four of the Crossrail shafts. The data is invaluable to understanding the behaviour of circular shafts and the adjacent ground. Different techniques for constructing shafts are evaluated and the important effect of dewatering is highlighted.

1 INTRODUCTION

1.1 *Background*

Shaft construction may cause movement of the ground adjacent to the shaft. Estimates of the magnitude and extent of such ground movement influence the precautionary protective measures adopted for buildings and buried pipelines located near to the shaft. Few published case histories of circular shaft construction exist and as a result, there is limited guidance to estimate ground movement due to excavation of circular shafts. Finite element analyses can be used but representative input parameters are needed as well as comparison with field observations to validate the numerical results.

A well-documented UK shaft case history, Bowers (1994), provides an empirical correlation to predict ground movement due to shaft excavation. The empirical correlation is independent of the shaft diameter and is only applicable to circular shafts constructed in London Clay with similar geometry and construction method to their case history shaft, pre-cast segments and a sprayed concrete lining (SCL). Consequently, British practitioners use the Bowers (1994) correlation together with some engineering judgement to account for different shaft diameters or construction methods. The cost implication for tunnelling projects is that protective measures that may not necessarily be needed are sometimes implemented for buildings and services located near to the shaft.

This paper describes field observations of ground surface movement during construction of four deep circular shafts built in London to enable construction of a new £15 bn railway, Crossrail. A plan view of the Crossrail route beneath London is shown in Figure 1.

2 PUBLISHED CASE HISTORIES

Five publications relating to circular shaft construction in the UK were identified, four of which were built in London.

Schwamb et al. (2014) monitored a 30 m diameter and 73 m deep diaphragm wall shaft for a wastewater pumping station. The ground conditions were primarily the Lambeth Group, Thanet Sand and Chalk. They demonstrated that fibre optic instrumentation can be used to measure bending and hoop strains in circular diaphragm wall shafts.

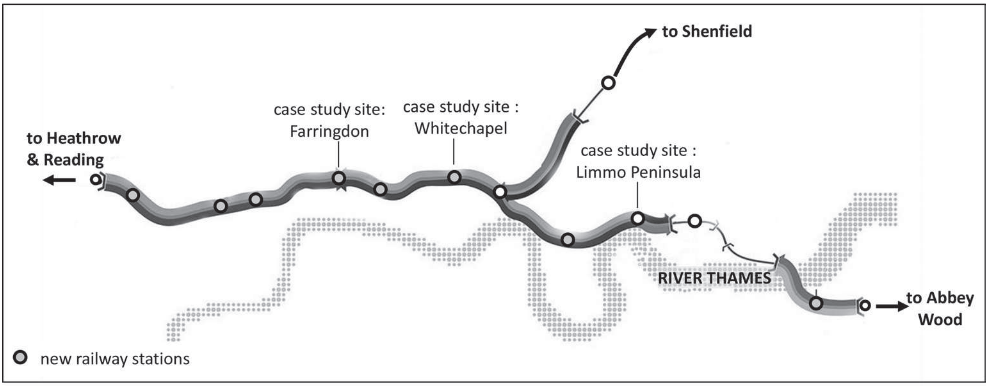

Figure 1. Plan view of the Crossrail tunnel route across London showing the locations of the four case history shafts.

McNamara et al. (2008) and Morrison et al. (2004) reported on the design and construction of a 8.2 m diameter and 40 m deep ventilation shaft constructed below basement level using pre-cast segments. The shaft was sunk through London Clay and Lambeth Group. Subsurface horizontal movements measured using an inclinometer were presented.

Cabarkapa et al. (2003) compared observed and predicted wall deflections for a 57 m diameter and 28 m deep tunnel boring machine (TBM) launch and reception shaft for the Dublin Port Tunnel Project. The ground conditions were Dublin Boulder Clay.

Powderham (2000) highlighted cost and time savings for the construction of a circular cofferdam using an observational approach.

New and Bowers (1994) assessed ground movements observed during excavation of a 10 m diameter and 26 m deep shaft for the Heathrow Express trial tunnel. The shaft was constructed in stiff relatively homogeneous London Clay using a combination of pre-cast concrete segments followed by sprayed concrete lining. A cross-section through the shaft and ground movements observed during excavation of the shaft are shown in Figure 2.

A curve fitted to the data is described by Equation 1, where S_v is the settlement at a distance x from the shaft lining, H is the shaft excavation depth and α is an empirical constant dependent on the ground conditions and construction method. A value of $\alpha = 0.0006$ reported indicates that the maximum settlement induced in the ground around the shaft is 0.06% of the shaft excavation depth.

In plan, the ground movements extended to a distance of one shaft depth away from the shaft lining (1.0H).

$$S_v = \frac{\alpha(H-x)^2}{H} \tag{1}$$

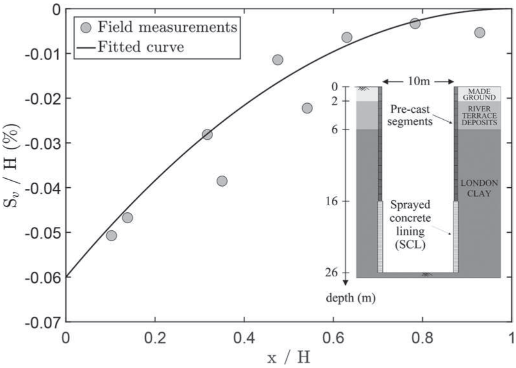

Figure 2. Measured settlement for shaft excavation in London Clay, New & Bowers (1994). The top section of the shaft was constructed using pre-cast concrete segments and the bottom section of the shaft was constructed using SCL.

3 CROSSRAIL CASE STUDY SHAFTS

Crossrail is a new transportation railway under construction in the UK. When open in 2018, it is forecast to make 200 million journeys per year between London and the South East. A plan view of the 42 km central tunnelled section which crosses beneath London at depths of up to 40 m below ground level (bgl) is shown in Figure 1. The 6 m diameter Crossrail tunnels are founded at such great depths to avoid existing underground lines, sewers, utility tunnels, building foundations and other underground infrastructure.

Several deep circular shafts were constructed to facilitate access and egress of plant and personnel to and from the tunnel horizon and to provide ventilation and emergency access to the completed tunnels. Details of four case study

Table 1. Overview of four Crossrail shafts reviewed for this study.

		Shaft geometry			
Shaft location	Type of shaft lining	Diameter (m)	Depth (m)	Wall thickness (m)	Long term shaft use
Limmo Peninsula main shaft	Diaphragm wall	30	44	1.2	Ventilation and emergency access
Limmo Peninsula auxiliary shaft	Sheet piles	28	14	–	None
	Sprayed concrete	28	25	0.6 to 1.0	
Whitechapel shaft (Cambridge Heath)	Diaphragm wall	28	32	1.5	Ventilation and emergency access
Farringdon shaft	Secant bored piles	15	24.7	1.2	Ventilation and emergency access; mechanical and electrical room

shafts, reported in this paper, are given in Table 1 and shown in Figure 1. Two of the Crossrail shafts located at Limmo Peninsula were used to launch the TBMs and provided access to the tunnel horizon. The other two shafts at Whitechapel and Farringdon provided access to the tunnel horizon.

3.1 *Typical ground conditions*

The Crossrail case study shafts at Limmo Peninsula, Whitechapel and Farringdon were mainly constructed in London Clay and the ground conditions at the shaft sites were typical of the London Basin strata. It generally comprised Made Ground and Superficial Deposits (Alluvium and River Terrace Deposits) overlying stiff relatively homogeneous London Clay having a low permeability. The London Clay was underlain by highly variable Lambeth Group sands and clays, Thanet Sand Formation and Chalk.

3.2 *Typical groundwater conditions*

There are two main aquifers in the London Basin: a shallow aquifer within the Superficial Deposits and a deep aquifer which spans the lower permeable units of the Lambeth Group, Thanet Sand and Chalk.

Shafts may be excavated under dry conditions by either lowering the deep aquifer groundwater levels or using depressurisation wells or sumps located within the shaft.

At Farringdon, the groundwater level was located below the base of the shaft and no groundwater control measures were implemented. At Whitechapel, the groundwater level was controlled using depressurisation wells and a sump. At Limmo Peninsula, an extensive dewatering scheme was carried out to lower the deep aquifer water level by approximately 30 m to below the shaft excavation level. The dewatered piezometric profiles and the duration of the shaft excavation are shown in Figure 3.

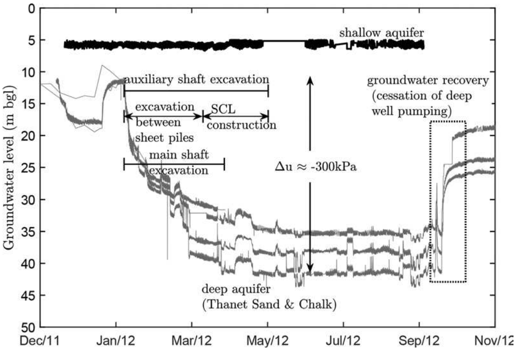

Figure 3. Dewatered piezometric levels at Crossrail's Limmo Peninsula shaft site.

3.3 *Shaft construction methods*

The different methods used to construct the Crossrail shafts can be classified into two groups: shafts constructed using a pre-installed shaft lining and shafts constructed progressively by concurrently excavating the ground and installing the shaft lining.

Pre-installed shaft linings are constructed before the shaft is excavated; these may comprise diaphragm walls, secant bored piles, sheet piles or jacked pre-cast segments. The shaft is excavated once the pre-installed shaft lining is complete. The pre-installed shaft construction technique is generally adopted in ground that is considered not stable or competent or in areas where groundwater ingress is a concern.

Diaphragm walls are included in this category because the excavated panel is supported by bentonite slurry. If the quality of workmanship is high then the bentonite slurry can support the walls of the excavated panel.

Jacked pre-cast segments are also included in the pre-installed shaft construction category because, like diaphragm walls, they limit in-situ horizontal stress relief of the ground during shaft excavation.

Figure 4 shows the construction process for Crossrail's 30 m diameter shaft built to launch the tunnel boring machines at Limmo Peninsula. Fourteen diaphragm wall panels were installed in a circular arrangement to a depth of 52 m bgl between October and December 2011. The shaft was subsequently excavated between February and May 2012.

A cross-section through the Limmo Peninsula main shaft after the diaphragm walls were installed is shown in Figure 4(i). A similar cross-section after the shaft was excavated to a depth of 44 m bgl is shown in Figure 4(ii). The completed pre-installed diaphragm walled shaft is shown in Figure 5.

Three of the Crossrail shafts, located at Whitechapel, Farringdon and Limmo Peninsula, were constructed using pre-installed shaft linings. Details of these three pre-installed shafts are given in Table 1.

The second shaft construction category is to progressively excavate the ground in sections, or segments, and install the shaft lining to form a ring. Typically, the height of the excavated section is 1.0 m to 1.2 m. This concurrent shaft construction is comparable to tunnel excavations ahead of the tunnel face. Like tunnels, the concurrent shaft lining is either pre-cast segments or a sprayed concrete lining (SCL). When a ring is complete the process is repeated for the underlying ring. This sequence continues until the desired shaft depth is achieved.

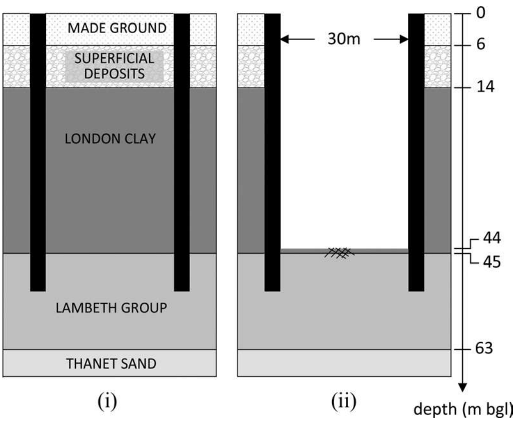

Figure 4. Construction sequence for Crossrail's main shaft at Limmo Peninsula which was supported by 53 m long and 1.2 m thick pre-installed diaphragm walls.

Figure 5. View from the bottom of Crossrail's 30 m diameter 44 m deep main TBM launch shaft at Limmo Peninsula.

The concurrent excavation and installation technique is employed in more stable ground where groundwater ingress is not a concern.

In London, it can be beneficial to use a combination of both shaft construction methods if there is considerable thickness of Made Ground or Superficial Deposits overlying the London Clay: a pre-installed construction is used in the Superficial Deposits and a concurrent shaft construction is employed in the London Clay.

A dual shaft lining involving sheet piles and SCL was adopted for the auxiliary TBM launch shaft at Limmo Peninsula, as illustrated in Figure 6. Installation of pre-installed sheet piles through the Made Ground and Superficial Deposits overlying the London Clay is shown in Figure 6(i). The 14 m long sheet piles were embedded approximately 1 m into the London Clay to create a watertight seal. The upper part of the shaft was then excavated as shown in Figure 6(ii). The shaft construction method was then changed to a concurrent excavation and installation sequence using sprayed concrete. The more stable London Clay was excavated in sections (Figure 6(iii)) and each section was supported with sprayed concrete before excavating the next section (Figure 6(iv)). When a complete sprayed concrete lined ring was formed the process was repeated for the underlying rings to a final shaft excavation depth of 39 m bgl.

A cross-section through the completed dual-lined auxiliary shaft involving sheet piles and SCL is shown in Figures 7 and 8.

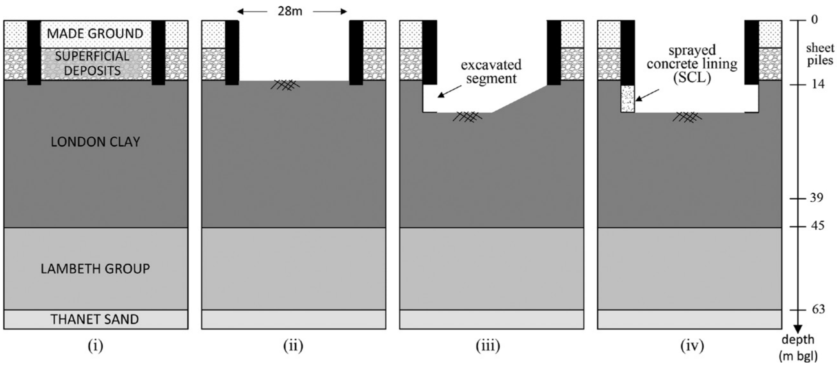

Figure 6. Construction sequence for Crossrail's auxiliary shaft at Limmo Peninsula which was built using a dual shaft lining.

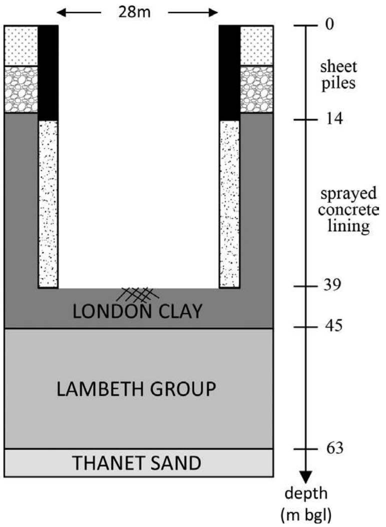

Figure 7. Cross section through the completed auxiliary shaft at Limmo Peninsula.

Figure 8. Crossrail's 28 m diameter, 39 m deep auxiliary shaft constructed using a combination of pre-installed sheet piles and a sprayed concrete lining.

4 GROUND MOVEMENTS OBSERVED DURING CIRCULAR SHAFT CONSTRUCTION

Some factors that influence the magnitude and extent of ground movement during circular shaft construction are the geometry of the shaft, excavation depth, ground conditions, construction method and quality of workmanship. Other site activities like dewatering can also have an effect on the shaft-induced ground movement.

Field observations during construction of the four Crossrail shafts at Limmo Peninsula, Whitechapel and Farringdon are used to examine some of these factors. Further details are given in Faustin (2017).

4.1 *Shaft installation effects*

The construction process for pre-installed shaft linings inherently causes some displacement of the adjacent ground. This movement can be reasonably expected to vary depending on the ground conditions and quality of workmanship. Observations of ground surface movement during installation of secant piled and diaphragm wall shaft linings are shown in Figures 9 and 10 respectively.

Figure 9 shows the shaft construction progress and observations of ground surface movement recorded during construction of a 15 m diameter and 25 m deep access shaft at Farringdon. This shaft was supported by large 1.2 m diameter secant bored piles. A maximum settlement of approximately 4 mm was observed during installation of the bored piles.

Figure 10 shows the construction progress and ground surface displacements recorded during construction of a 28 m diameter and 32 m deep ventilation and emergency access shaft at Whitechapel. This shaft was supported by 1.5 m

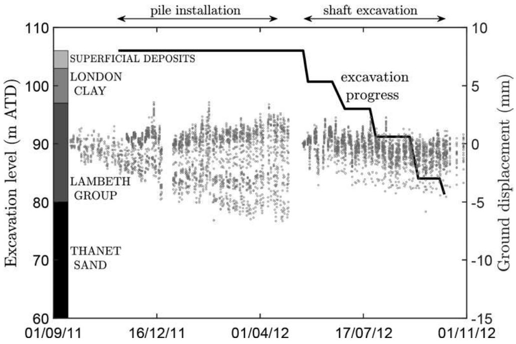

Figure 9. Construction progress and ground surface displacements for Crossrail's 25 m deep secant piled access shaft at Farringdon.

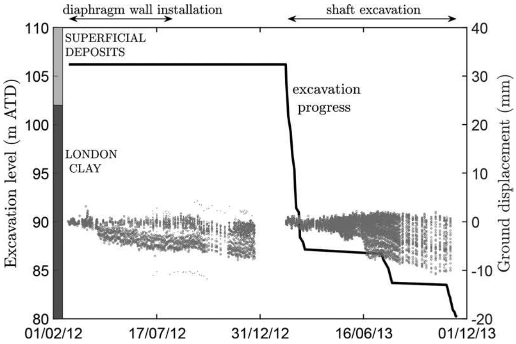

Figure 10. Construction progress and ground surface displacements for Crossrail's 32 m deep diaphragm wall shaft at Cambridge Heath.

thick diaphragm walls. A maximum settlement of approximately 7 mm was observed during installation of the diaphragm wall panels.

4.2 *Influence of shaft excavation depth*

Field observations during excavation of the auxiliary shaft at Limmo Peninsula were used to examine the effect of shaft excavation depth. This effect was accounted for by normalising the observed settlement by the shaft excavation depth.

Figure 11 shows the settlement measurements normalised by excavation depth plotted against distance from the auxiliary shaft also normalised by excavation depth. The predicted ground movement based on the New and Bowers (1994) empirical correlation is shown for comparison. The 28 m diameter Limmo Peninsula auxiliary shaft and the 10 m diameter New and Bowers (1994) shaft. were constructed using similar techniques: pre-cast segments and SCL versus pre-installed sheet piles followed SCL.

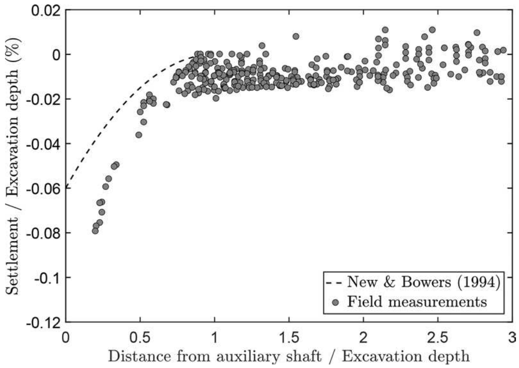

Figure 11. Observed and predicted settlement during excavation of Crossrail's auxiliary shaft at Limmo Peninsula.

Figure 11 shows that the New and Bowers (1994) relation underestimates the ground movement around the auxiliary shaft at Limmo Peninsula. The reasons for this may be attributed to the larger diameter of the case study shaft; the diameter of the Limmo Peninsula auxiliary shaft is almost three times greater than the New and Bowers (1994) shaft.

4.3 *Influence of shaft construction method*

The top section of the auxiliary shaft at Limmo Peninsula was constructed using pre-installed sheet piles to a depth of 14 m bgl. The lower section of this shaft was constructed using concurrent excavation and installation of a sprayed concrete lining for a further 25 m. This case study shaft therefore provides a unique opportunity to examine the effect of different shaft construction methods on adjacent ground movement. It is particularly advantageous that the effect of varying ground conditions and shaft diameter are eliminated (the sheet piled section and SCL section having very similar diameters).

Ground movements observed during excavation of the auxiliary shaft are shown in Figure 12. For comparison, the dewatered piezometric profile and excavation progress are also shown. The groundwater levels were lowered at the same time as excavation of the soil in front of the sheet piles. A maximum total settlement of 10 mm was generated due to excavation of the shaft between the sheet piles and the dewatering operations.

The magnitude of settlement increased considerably during SCL construction to a maximum of 40 mm upon completion of the shaft. The depressed deep aquifer water level was maintained during the construction of the sprayed concrete lining

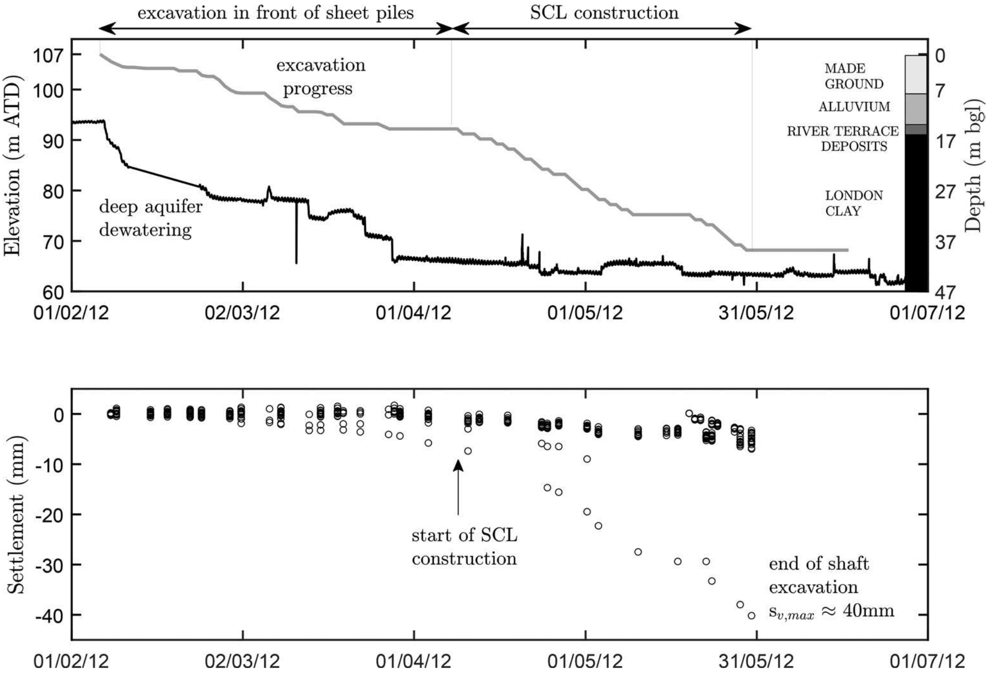

Figure 12. Observed settlement during excavation of Crossrail's auxiliary shaft at Limmo Peninsula.

(Figure 12). Therefore, the observed increase in settlement during SCL construction could be attributed to the shaft construction method, excavation depth and the quality of workmanship. Due to the experience and reputation of the Crossrail contractors a good quality of workmanship was achieved.

The effect of the different shaft construction methods on the observed soil movements can be explained. The pre-installed sheet pile lining, used for the top section of the shaft, caused relatively small changes in in-situ total horizontal soil stress and stiffness leading to relatively smaller settlement being observed. In contrast, the concurrent excavation and installation shaft construction method, employed for the lower section, locally reduced the in-situ total horizontal soil stresses to zero prior to placing the sprayed concrete lining. This reduction in stress and stiffness of the ground caused greater settlement around the shaft.

4.4 *Dewatering effects*

Dewatering operations and excavation of the Limmo Peninsula main shaft were undertaken at the same time (Figure 3). The dewatering happened over a relatively short period of time and it can be assumed that pumping caused immediate compression of the Lambeth Group sands and Thanet Sand. This combined sand layer had a thickness of approximately 20 m. Dewatering settlements were evaluated from pore-water pressure measurements using an iterative procedure to obtain an average stiffness for the sand layer.

A reasonable average stiffness for the combined sand layer was used to make in initial estimate of the settlement and strain in the combined sand layer. The strain value was then used to derive the elastic modulus from stiffness degradation curves. These curves were obtained from pressure meter tests carried out during the Crossrail site investigations. The average stiffness was updated and the process repeated until there was convergence of the elastic modulus. This iterative process suggested that the average stiffness of the combined Lambeth Group sands and Thanet Sand layer is 500 MPa.

Based on the analysis approximately 10 mm of the total measured settlement can be attributed to dewatering. This magnitude of dewatering settlement compared well with measurements from displacement sensors located outside the zone of influence of the shaft excavation, more than 90 m from the shaft.

The total observed settlement at the end of excavation of the main shaft was approximately 15 mm. If 10 mm of dewatering settlement is discounted then the actual settlement due to excavation of the main shaft is in the region of 5 mm (see Figure 13).

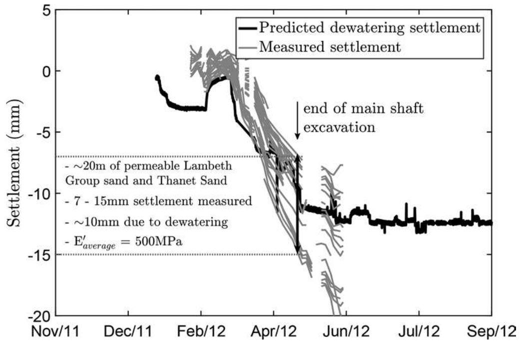

Figure 13. Comparison of observed and predicted dewatering settlement during excavation of the Limmo Peninsula main shaft.

The magnitude of excavation-induced settlement at Limmo Peninsula (5 mm) is comparable to settlement observations during excavation of the 28 m diameter and 32 m deep diaphragm wall shaft at Whitechapel shaft (Figure 10). Both shafts are of similar dimensions, constructed in London Clay and supported by pre-installed diaphragm walls.

5 CONCLUSIONS

Ground movement due to shaft construction is dependent on the ground conditions, diameter of the shaft, excavation depth, shaft construction method and the quality of workmanship. Few published case histories on circular shafts exist and none of the publications cover all of these factors. As a result, there is limited guidance for the design of circular shafts.

Field observations during construction of four circular shafts recently built in London for Crossrail has helped to progress the understanding of ground movement due to shaft construction.

The different shaft construction methods can be grouped into two categories: shafts constructed using a pre-installed shaft lining and shafts constructed progressively by concurrently excavating the ground and installing the shaft lining. The ground movement mechanisms during excavation are different for each category. Smaller ground movements were observed during excavation of shafts supported by pre-installed shaft linings compared to those built progressively by concurrently excavating the ground and installing the shaft lining.

Field observations indicate that less than 10 mm of settlement can be expected due to installation of a pre-installed diaphragm wall or bored pile shaft lining in London Clay.

The influence of shaft diameter on the magnitude of excavation-induced ground movements was highlighted. Greater ground movements were observed during excavation of larger diameter shafts constructed using similar techniques.

The effect of dewatering activities on field observations can be significant. At Crossrail's Limmo Peninsula TBM launch shaft site, dewatering settlements associated with a 30 m reduction in groundwater level were approximately double the ground movements due to excavation of a 30 m diameter and 44 m deep pre-installed shaft.

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