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Accepted manuscript doi:
10.1680/jgeen.17.00166

Submitted: 25 September 2017

Published online in 'accepted manuscript' format: 25 May 2018

Manuscript title: Case studies of circular shaft construction in London

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Accepted manuscript doi:
10.1680/jgeen.17.00166

Abstract

At present, there are few well-documented case studies of circular shaft construction. This makes it difficult for designers to estimate reliable ground movements arising from circular shaft construction. This paper describes field observations of ground surface settlement assembled during construction of 27 circular shafts built for three major tunnelling projects in London: Crossrail, National Grid's London Power Tunnels project and Transport for London's Northern Line Extension. Two categories of shaft construction were identified: support before excavation (SBE) and excavation before support (EBS). For the support before excavation category, the shaft was first supported by pre-installed walls followed by excavation of the soil between the pre-installed walls. For the excavation before support category, the ground was progressively excavated in sections followed by construction of the shaft lining. Interpretation of the field observations showed the importance of the shaft construction method on ground movements. Settlements are much more significant for EBS shaft construction than for SBE shaft excavation, although settlement arising from installation of pre-installed walls or dewatering operations should not be overlooked. Normalised charts are presented to help industry make estimates of settlements due to circular shaft construction in London, with due consideration for different shaft geometries and construction methods.

Keywords: Excavation/ Field testing & monitoring/ Geotechnical engineering

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1. Introduction

There is great uncertainty regarding the magnitude and extent of ground movements arising from circular shaft construction. Such movements occur during installation of pre-installed shaft linings and during excavation of the shaft. Other factors like the presence of soft ground or dewatering can also cause ground movement. Data available during construction of diaphragm wall shafts for the Dublin Port Tunnel (Menkiti and Long, 2015) and Crossrail (Faustin et al., 2017) show that dewatering settlements can be much more significant than excavation-induced settlement.

The limited number of well-documented circular shaft case studies has made a proper investigation into the parameters influencing shaft construction ground movements, including the potential influence of shaft construction category, very challenging. Estimates of ground movements in the UK to date are based mainly on observations from the excavation of the Heathrow Express trial tunnel (New and Bowers, 1994) or obtained from finite element analyses. Yet, the finite element results are often not validated against field observations and the New and Bowers (1994) settlement prediction method is only applicable to shafts with a similar size and construction approach to the Heathrow Express shaft. Designers conservatively account for these shortcomings which can have a direct effect on the cost of tunnelling projects. For example, protective measures that may not necessarily be needed are sometimes implemented for nearby buried utility pipelines and buildings.

In recent years, several circular shafts have been constructed in London to facilitate tunnelling works for transportation and electricity infrastructure projects. The geometry of these shafts ranged from 5 m to 30 m in diameter and 15 m to 44 m in depth. Ground surface settlements from precise levelling pins positioned around 27 case study shafts have been assembled and carefully examined in this paper. Very little information was available for horizontal movement of the ground or of the shaft lining and hence these measurements are not included in this paper. Two distinct categories of circular shaft construction were identified and field observations of surface settlement are presented in simple normalised charts that could be useful to a wide range ofconstruction professionals.

1.1 Published settlements during excavation of circular shafts

Published ground surface settlements during excavation of four circular shafts, reported by Wong and Kaiser (1988), New and Bowers (1994), Muramatsu and Abe (1996) and Schwamb et al. (2016), are shown in Figure 1. Due to the limited range of excavation depth to shaft diameter ratios (H/D) it was thought more reasonable to present the data in plots of settlement normalised by the shaft excavation depth versusdistance from the shaft also normalised by the shaft excavation depth (i.e. S_v/H versus x/H), for different ground conditions.

A maximum settlement of approximately 0.01% of the shaft excavation depth i.e. 0.01%H was reported during excavation of the diaphragm wall shafts (Muramatsu and Abe, 1996; Schwamb et al., 2016). In contrast, the maximum settlement reported by Wong and Kaiser (1988) and New and Bowers (1994) was at least four times greater, 0.04%H and 0.06%H respectively. The variability in maximum settlement is likely to be due to different ground conditions and different shaft construction categories.

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Figure 1 also shows that the settlements reduce to zero at a distance of 0.4H to 1.0H from the edge of the shaft. This zone of extent could be influenced by the ground conditions, shaft construction category and the diameter of the shaft.

1.2. Existing ground movement prediction models for circular shafts

New and Bowers (1994) proposed an equation to predict settlement based on field observations during excavation of the 11 m diameter and 26 m deep Heathrow Express shaft in London Clay. The shaft was constructed progressively by concurrent excavation of the ground and erection of the shaft lining (pre-cast segments for 16 m followed by a sprayed concrete lining (SCL) for a further 10 m). The curve fitted to the field measurements, shown in Figure 1c, is described by Equation 1.

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

where S_v is the settlement at a distance x from the shaft wall, H is the shaft excavation depth and α is an empirical constant dependent on the ground conditions and shaft construction method. The recommended value for α of 0.0006 indicates that the maximum settlement induced in the ground around the shaft is 0.06% of the shaft excavation depth i.e. $S_{v,max}$ = 0.06%H.

Equation 1 provides a useful estimate of the settlement that may occur during excavation of circular shafts in clay that have similar dimensions and construction method to the Heathrow Express shaft. However, its applicability for shaftswith diameters greater than 11 m or built using diaphragm walls, bored piles or sheet piles is questionable. For example, it was difficult to estimate reliably settlements due to excavation of the 30 m diameter Crossrail TBM launch shaft at Limmo Peninsula which was considerably larger that the Heathrow Express shaft, as illustrated in Figure 2.

Given this uncertainty, designers of shafts in London sometimes develop bespoke variations of the New and Bowers (1994) relation to conservatively account for larger diameter shafts in similar ground conditions. On the other hand, published field observations for circular shafts, shown in Figure 1, suggest that Equation 1 might be particularly conservative for pre-installed shafts: a maximum settlement of 0.01%H was reported by Muramatsu and Abe (1996), due to excavation of a 28 m diameter diaphragm wall shaft in granular soil, compared with a maximum settlement of 0.06%H suggested by Equation 1. Schwamb et al. (2016) also report significantly smaller movements of less than 0.01%H during excavation of the 30 m diameter and 73 m deep diaphragm wall shaft in Lambeth Group, Thanet Sand and Chalk. Greater settlements were reported during installation of the 84 m deep diaphragm wall panels themselves before any shaft excavation.

2. Overview of the circular case study shafts

Field records of recent circular shaft construction have been assembled from three tunnelling projects in London: Crossrail (CRL), London Power Tunnels (LPT) project and Transport for London’s Northern Line Extension (NLE). A description of these projectsis given below and details of the 27 case study shafts are summarised in Tables 1 to 3. Further details of these shafts are given in Faustin (2017).

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2.1. Northern Line Extension (NLE)

Transport for London commissioned an extension of the existing Northern Line underground line to Battersea to regenerate part of South London. The 3 km extension included two permanent circular shafts at Kennington Green and Kennington Park, located approximately 300 m apart, as shown in Figure 3 and detailed in Table 1. These shafts were built between April and August 2016 to facilitate the main tunnelling works. In the long-term they will provide ventilation,cooling and emergency access to the new tunnel extension.

2.2. London Power Tunnels project

London Power Tunnels is a project commissioned by National Grid Plc to upgrade electricity cables which were located just below the road surface in London. New high voltage electricity cables were routed in 32 km of new tunnels (3 m to 4 m diameter) at depths of up to 60 m. Fourteen deep circular shafts were built across London, between March 2011 and July 2013, to launch the tunnel boring machines, as shown in Figure 4 and detailed in Table 2. The shafts provided access to the new tunnels, facilitated removal of spoil from the tunnel horizon and provided ventilation.

2.3. Crossrail

Crossrail is delivering the Elizabeth line, a new east-west railway in the UK. Figure 5 shows a plan view of the route which connects London with Reading and Heathrow in the west and Shenfield and Abbey Wood in the east. The railway is currently Europe’s largest infrastructure project and when fully complete in 2019, it is expected to carry 200 million people each year between London and the South East.

The 21 km twin-tunnelled section of the new railway crosses beneath London at depths of up to 40 m below ground level, to avoid existing underground lines, sewers, utility tunnels, building foundations and other underground infrastructure. To facilitate the new Crossrail tunnels several large circular shafts were constructed across London. The shafts serve a variety of uses including access for equipment and personnel to the tunnel horizon, ventilation and removal of spoil. A number of relatively smaller 5 m diameter shafts were also built to enable compensation grouting works. In the long-term, some of the shafts will be backfilled and others will be used to provide ventilation or emergency access and exit to the completed tunnels. Field observations forseven access and ventilation shafts and four compensation grout shafts are presented in this paper. Details of these shafts are given in Table 3.

3. Typical ground conditions

The case study shaft locations were limited to London where the ground conditions are typical of the London Basin strata. This generally comprised varying thickness of Superficial Deposits (Made Ground, Langley Silt, Alluvium and River Terrace Deposits) overlying stiff relatively homogeneous London Clay (LC) of very low permeability. These strata were underlain by the Lambeth Group (LG), Thanet Sand (TS) and Chalk (CK). A thin layer of Harwich Formation, typically less than 1.5 m thick, was encountered below the London Clay at some shaft sites. For the purposes of this paper, the Harwich Formation has been grouped together with the London Clay.

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Most of the case study shafts were founded in the London Clay and a few extended further to the Lambeth Group and Thanet Sand Formation. The stratigraphy at individual shaft sites is summarised in Tables 1 to 3.

4. 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.

4.1. Dewatering

Dewatering was carried out when the base of the case study shaft, or the invert of the tunnels that extend from the shaft, was located very close to or in the underlying permeable units of the Lambeth Group or Thanet Sand. Dewatering operations at Limmo Peninsula in east London, to facilitate construction of two deep circular shafts to launch the Crossrail tunnel boring machines (TBMs) are described in Faustin et al. (2017). Passive groundwater control measures comprising sumps or depressurisation wells within the shaft were sometimes employed for case study shafts that were constructed mainly in London Clay.

With the exception of the deep shaft excavations that extended into or close to underlying permeable strata, there was apparently little drainage of groundwater associated with the construction of the case study shafts and hence settlement due to groundwater lowering outside of the excavation is likely to be very small.

5. Shaft construction categories

The case study shafts can be classified into different categories of shaft construction: support before excavation (SBE), excavation before support (EBS), or a combination of these two methods (SBE and EBS).

It is common practice to describe circular shafts using terminologies like ‘‘segmental shafts’’, ‘‘caisson shafts’’ or ‘‘segmentally lined shafts’’. However, these descriptions do not indicate whether the segments are jacked-in the ground or installed using a concurrent excavation and installation sequence. This differentiation is important as the mode of shaft construction greatly influences ground movements around the shaft during excavation.

5.1. Support before excavation (Pre-installed shaft linings)

For the SBE shaft construction category, the soil is supported by a pre-installed shaft lining before excavation between the pre-installed shaft lining is carried out. SBE shaft construction for the case study shafts involved pre-installed diaphragm walls, bored piles and steel sheet piles. This type of shaft construction is generally adopted in ground that is not stable or competent or where groundwater ingress is a concern. The support provided to the ground prevents large reductions of in-situ horizontal soil stresses and stiffness during excavation.

Figure 6 shows the SBE shaft construction adopted for Crossrail’s 44 m deep main shaft at Limmo Peninsula. The pre-installed shaft lining comprised 53m long and 1.2m thick diaphragm wall panels.

Three relatively smaller 5 m diameter case study shafts were built using jacked pre-cast segments to enable compensation grout works for Crossrail. This type of shaft construction is included in the SBE shaft construction category because they provide support to the soil before it is excavated. The only exception would be if the excavation is carried out ahead of

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the lead cutting ring to aid the jacking in process, as shown in Figure 7. In such instances, there would be some in-situ horizontal stress relief of the ground during excavation which can cause additional ground movement. It is difficult to quantify the effect of any unloading due to excavation ahead of the lead cutting ring because it is done on an *ad hoc* basis depending on the site conditions and is often not formally reported. For this reason, settlements observed around jacked pre-cast shafts are presented separately in this paper.

It is also worth mentioning that deep excavation supports like diaphragm walls provide much greater restraint to ‘‘base heave’’ type mechanisms that could promote ground movement compared to a jacked segment form of construction. However, base heave movements were not an issue for the jacked pre-cast segment case study shafts because the factor of safety against base heave movements was quite high.

5.2. Excavation before support (Concurrent shaft linings)

The EBS shaft construction is comparable to tunnel excavations ahead of the tunnel lining; the ground is progressively excavated in sections, typically 1.0 m to 1.2 m height and the support (i.e. the shaft lining) is constructed after the ground has been exposed. When a ring is complete the process is repeated for the underlying ring, as shown in Figure 8. The EBS shaft construction is employed in stable ground where groundwater ingress is not a concern. Like tunnels, the concurrent shaft lining used for the EBS shaft construction category is either pre-cast segments or a sprayed concrete lining (SCL).

In London, where there is sometimes a relatively small thickness of Superficial Deposits overlying the London Clay, the top section of the shaft may be supported by pre-cast segments and the bottom section of the shaft, located in London Clay, may be supported by a sprayed concrete lining. A typical EBS circular shaft construction involving pre-cast segments in the top section and sprayed concrete in the bottom section is shown in Figure 9. This type of shaft construction was adopted for11 of the case study shafts.

It is important to differentiate between pre-cast segments that are installed concurrently (EBS shaft construction) and pre-cast segments that are jacked into the ground (SBE shaft construction). In this paper, the latter are called jacked pre-cast segments.

5.3. Combined SBE & EBS shaft construction (Dual-lined shafts)

Eight of the case study shafts were supported by two forms of shaft linings: a pre-installed shaft lining in the top section to support the Superficial Deposits (SBE shaft construction) and SCL in the bottom section through stiff, homogeneous and relatively impermeable London Clay (EBS shaft construction).

Crossrail’s auxiliary TBM launch shaft at Limmo Peninsula in east London is an example of a dual lined shaft involving steel sheet piles and SCL (Figure 10). The 14 m long steel sheet piles were embedded approximately 1 m into the London Clay before the upper part of the shaft was excavated. The shaft construction method then changed to an EBS construction involving SCL: the more stable London Clay was excavated in sections and each section was supported with sprayed concrete before excavating the next section. 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.

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6. Settlement during installation of pre-installed shaft linings

Ground movements may arise due to installation of a pre-installed shaft lining (and during subsequent excavation between the pre-installed shaft linings). Neglecting the jacked pre-cast compensation grout shafts, the pre-installed case study shaft walls comprised diaphragm walls, bored piles and steel sheet piles. Under controlled measures, bentonite slurry provides stability to an excavated diaphragm wall panel. However, the construction process inherently reduces the horizontal stress in the ground and causes movement of the adjacent ground. Secant bored piles are commonly cased through the Superficial Deposits overlying the London Clay using temporary or permanent steel casings. The process of driving steel casings or sheet piles into the ground can beexpected to generate some ground movement.

Figure 11 shows the settlements observed during installation of pre-installed shaft linings at Cambridge Heath, Farringdon and Kennington Green. Approximately 6 mm of settlement, equivalent to 0.02% of the wall excavation depth (0.02%H), occurred during installation of 1.5 m thick diaphragm wall panels for the circular case study shaft at Cambridge Heath.

Figure 11d shows relatively large movements in the region of +3 mm to –5 mm, at approximately 30 m from the Farringdon shaft. These movements are likely to have arisen from other site activities rather than installation of the piled shaft lining. Neglecting these measurements, very small displacements, 2 mm to 3 mm, were observed during installation of the 14 m and 33 m deep secant bored piles at Farringdon and Kennington Green respectively. These movements equate to a settlement of approximately 0.01%H.

In comparison, Clough and O’Rourke (1990) reported a greater maximum settlement of approximately 0.04%H due to installation of diaphragm wall panels in stiff to very hard clay.

7. Settlement during shaft excavation

Field observations of ground surface settlement adjacent to circular shafts during excavation are presented below for the different shaft construction categories:

- SBE shaft construction (pre-installed shaft linings)
- EBS shaft construction (concurrent shaft linings)
- combined SBE and EBS shaft construction (dual shaft linings)

The measurements are assembled into charts of settlement normalised by the shaft excavation depth versus distance from the shaft also normalised by the shaft excavation depth i.e. S_v/H versus x/H. The measurements do not include any contribution from dewatering activities and any settlement due to drainage towards the excavation will be negligible given the ground conditions.

7.1. SBE shaft construction

A maximum settlement of 0.03%H was observed during excavation of the SBE case study shafts at Hackney, Farringdon, Cambridge Heath and Limmo Peninsula, as shown in Figure 12. The Limmo Peninsula main shaft was supported by diaphragm walls and the other three shafts were supported by secant bored piles.

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For comparison, Clough and O'Rourke (1990) reported a much greater maximum settlement of 0.3%H behind braced or tied-back retaining walls in stiff clays, residual soils and sands. Circular pre-installed shaft linings are stiffer than a conventional planestrain wall and generate smaller settlements of the surrounding ground due to hoop compression of the circular shaft lining during excavation.

More importantly, the maximum observed settlement during SBE shaft excavation is considerably smaller than the value of 0.06%H reported by New and Bowers (1994) for an EBS shaft construction. The maximum total settlement at the Farringdon and Cambridge Heath shafts due to installation of the pre-installed walls and subsequent excavation of the shafts is 0.02%H and 0.04%H respectively. These field observations confirm that Equation 1, which is based on an EBS shaft construction, is overly conservative when applied to SBE shaft construction, in which the soil is supported by a pre-installed wall before the shaft is excavated, provided the quality of workmanship is high.

Negligible settlement is observed at a distance of approximately 1.0H to 1.5H from the pre-installed shaft lining and the influence of shaft diameter on the magnitude of settlement is evident. The smallest settlements were observed during excavation of the 12.7 m diameter diaphragm wall shaft at Hackney (0.005%H) and the greatest settlements were observed during excavation of the 28 m diameter Cambridge Heath shaft and the 30 m diameter diaphragm wall shaft at Limmo Peninsula (approximately 0.03%H). Settlements observed during excavation of the 15 m diameter secant bored pile shaft at Farringdon lie in the middle of the dataset.

7.1.1. Jacked segments

As mentioned earlier, the jacked shaft construction may cause additional ground movement if excavation is undertaken ahead of the lead cutting ring. Therefore, field observations for three 5 m diameter jacked shafts, involving pre-cast segments, built to enable compensation grout work for Crossrail, are presented separately below.

In keeping with the trend for SBE shaft construction, shown in Figure 12, smaller settlements can reasonably be expected during excavation of these 5 m diameter compensation grout shafts. However, settlements observed adjacent to relatively small jacked pre-cast segments were slightly greater than typically observed for a much larger 30 m diameter diaphragm wall shaft, as shown in Figure 13 (0.035%H compared with 0.03%H). This may possibly be due to mechanical excavation ahead of the cutting ring but details of this were not reported (see Figure 7). Negligible movement was observed at a distance of approximately 1.0H from the jacked shaft lining.

7.2. EBS shaft construction

Eleven of the case study shafts were supported by a concurrent shaft lining involving pre-cast segments and SCL, i.e. an EBS shaft construction. Field observations of settlement during excavation are presented in Figure 14. Generally, there was a small increase in shaft diameter when the shaft lining changed from pre-cast segments to SCL, as detailed in Tables 1 to 3. The shaft diameters shown on Figure 14 represent the internal diameter of the top segment.

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The field observations show a maximum settlement of 0.06%H due to EBS shaft construction and negligible movement beyond a distance of 1.5H from the shaft. Some influence of the shaft size is evident; the smallest settlements were observed during excavation of the 6 m diameter shaft at St John's Wood (SJW2). Relatively greater settlements were observed during excavation of the larger 15 m diameter shaft at Highbury (HBY). There was little discernible trend of settlements around the 10 m and 12.5 m diameter shafts.

Observations during excavation of two shafts at Kensal Green (KG1 and KG2) appear anomalous: relatively small settlements were observed. It is understood that excavation of these two shafts progressed slowly due to the presence of contaminated ground. Smaller reductions in in-situ horizontal soil stress and stiffness is likely if the depth of the excavated sections was smaller than the 1.0 m typically used for EBS shaft construction. This may have resulted in smaller settlements. However detailed field records were not available to verify the construction sequence.

Field data and the settlement prediction reported by New and Bowers (1994) for an 11 m diameter shaft constructed using similar techniques (pre-cast segments followed by SCL construction) are also shown in Figure 14. The New and Bowers (1994) relationship, given by Equation 1, is shown to be a reasonably good estimate of the maximum settlement around concurrent shaft linings (EBS shaft construction). However, some very small settlement extends to a distance of approximately 1.5H from the shaft lining rather than 1.0H as implied by Equation 1.

7.3. Combined SBE & EBS shaft construction

Eight of the case study shafts were supported by two forms of shaft linings: a pre-installed shaft lining in the top section (SBE shaft construction) and a sprayed concrete lining in the bottom section (EBS shaft construction). For four of these shafts, the pre-installed wall comprised jacked pre-cast segments. Therefore, settlements for these four shafts are interpreted separately below.

Figure 15 shows the settlements observed around four shafts that were built using a combination of pre-installed walls (not including jacked pre-cast segments) and a concurrent shaft lining. Steel sheet piles supported the top 14 m of the Limmo Peninsula auxiliary shaft and secant bored piles supported the top section of the Fisher Street, Kennington Green and Kennington Park shafts. The bottom section of all four shafts was supported by a sprayed concrete lining. The normalised settlements generally lay in a uniform band that extended to a distance of approximately 1.5H from the shaft lining. Settlements observed during excavation of the 28 m diameter Limmo Peninsula auxiliary shaft were twice as great as settlements observed during excavation of the three smaller 15 m diameter shafts (approximately 0.04%H compared with 0.082%H).

Normalised settlements observed during excavation of dual lined shafts supported by jacked pre-cast segments and sprayed concrete are shown in Figure 16. Generally a maximum settlement of 0.06%H was observed close to the shaft wall and the settlement decreased with increasing distance from the shaft. Negligible movements were observed beyond a distance of 1.5H from the shaft.

Three data points at the London Power Tunnels Wimbledon shaft (LPT WIM) show relatively large settlements, greater than 0.06%H, as highlighted on Figure 16. Site records

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reported bulging of four caisson rings. As a result,the shaft construction method for the top section was changed from jacked pre-cast segments to pre-cast segments. It is not clear whether the larger movements are associated with bulging of the jacked pre-cast segments; they are marked as anomalies on Figure 16.

The influence of shaft diameter is evident in Figure 16. Smaller settlements were observed during excavation of the 5 m diameter shaft at Hayne Street compared with the other three larger diameter shafts (12.5 m to 15 m).

8. Discussion and Conclusion

Up until now, the limited number of well-documented case study shafts in London has made it difficult to properly investigate the parameters that influence ground movements during circular shaft construction. This paper tries to address this uncertainty. Field observations of ground surface settlement were assembled from a number of circular shafts recently built for Crossrail, National Grid's London Power Tunnels Project and Transport for London's Northern Line Extension. The geometry of the case study shafts ranged from 5 m to 30 m in diameter and 15 m to 44 m in depth. Two categories of shaft construction were identified. The first category, SBE, provided support to the soil using pre-installed walls before subsequent excavation of the shaft. For the second category, EBS, the shaft was excavated in sections, typically 1 m height, before supporting the soil with the shaft lining (pre-cast segments or SCL). In some cases, the shaft was dual-lined using a combination of both shaft construction categories, SBE and EBS.

The field observations, presented in Figures 11 to 16, give a good indication of the magnitude of settlement that can be expected during circular shaft construction in typical London Basin strata. For most of the case study shafts involving SBE construction, field observations of settlement were only available for the excavation phase (limited data was available during installation of the pre-installed walls). As a result, the settlement due to installation of pre-installed walls and subsequent excavation of the shaft are presented separately in this paper. However, it is important that settlement assessments for SBE shaft construction should always consider the total settlement arising from installation of pre-installed walls and subsequent excavation of the shaft. This is particularly important for SBE shaft construction adjacent to buried pipelines which cannot tolerate much strain.

The field observations show that settlements arising from excavation of circular shafts are critically dependent on the method of shaft construction. Settlements arising from installation of pre-installed walls may be in the region of 0.02%H, provided a high quality of workmanship exists. Notwithstanding wall installation effects, there is little concern for SBE shaft construction in the cases where the pre-installed shaft lining is constructed in stiff ground; very small settlements are generated and overly conservative predictions currently used by designers are not required. Some caution should be taken for jacked pre-cast segments as relatively small excavations can generate greater movements than much larger diaphragm wall excavations. This may be due to a reduction of the in-situ horizontal soil stress and stiffness caused by excavation ahead of the lead cutting ring. Settlement due to EBS shaft construction is potentially more significant; greater settlements are generated when the ground is temporarily exposed before the concurrent shaft lining is constructed.

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The field observations also confirm that ground movements are influenced by the size of the shaft. For a given shaft construction method, smaller diameter shafts generated smaller settlements and larger diameter shafts generated greater settlements. Negligible settlements tend to occur beyond a distance of 1.0H to 1.5H from the shaft. However, the extent of the settlement profile will need to be assessed properly for shafts that are significantly different than those presented in this paper.

Acknowledgements

The authors would like to thank the Engineering and Physical Sciences Research Council (Award Reference 1220514) and Geotechnical Consulting Group for funding this research. They also express gratitude to Crossrail Limited, National Grid and Transport for London which generously provided vital shaft construction records and permission to publish the field data and site photographs. The support of Costain, Cementation Skanska, Ferrovial Agroman Laing O'Rourke Joint Venture (FLO) and Geocisa UK is also gratefully acknowledged. In addition, special thanks are given to David Harris, John Davis, John Roseler, Professor Kenichi Soga, Dr Mehdi Alhaddad, Mike Black, Mohamad Alsedare, Neil Moss, Paul Braddish, Dr Phil Smith, Pietro Bologna, Dr. Seda Torisu and Thomas Smith for assistance with installing monitoring instruments and obtaining field measurements. The associated research data is available at https://doi.org/10.17863/CAM.22617.

Notation

α	Empirical constant from New & Bowers (1994)
bgl	Below ground level
CK	Chalk
CRL	Crossrail
D	Diameter
EBS	Excavation before support (shaft construction category)
H	Excavation depth
LC	London Clay
LG	Lambeth Group
LPT	London Power Tunnels
NLE	Northern Line Extension
S_v	Settlement
SBE	Support before excavation (shaft construction category)
SCL	Sprayed concrete lining
TBM	Tunnel boring machine
TS	Thanet Sand
x	Distance from shaft wall

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10.1680/jgeen.17.00166

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Table 1. Overview of the Northern Line Extension case study shafts

Shaft location	Construction method	External diameter	Excavation depth	Lining thickness	Encountered strata
		(m)	(m)	(m)	
Kennington Green	Secant bored piles SCL	15.9	13.6 12.5 (26.1)	0.6 -	Made Ground (2.2m) River Terrace Deposits (5.3m) London Clay (21m)
Kennington Park	Secant bored piles SCL	15.9	16.1 10.1 (26.2)	0.6 -	Made Ground (2m) River Terrace Deposits (5.8m) London Clay (18.5m) Lambeth Group

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Table 2. Overview of the London Power Tunnels case study shafts

Shaft location	Construction method	Internal diameter	Excavation depth	Lining thickness	Encountered strata
		(m)	(m)	(mm)	
Channel Gate Road	Pre-cast segments	12.5	22.2	325	Made Ground (2.2m)
	SCL	12.5	10.7 (32.9)	312	London Clay (75m)
Eade Road	Pre-cast segments	12.5	26.7	325	Made Ground (1.4m)
	SCL	13.5	12.6 (39.3)	338	London Clay (37m)
					Lambeth Group
Earl’s Court	Pre-cast segments	10.5	29.9	300	Made Ground (1.9m)
	SCL	11.4	9.6 (39.5)	250	Superficial Deposits (0.8m)
					London Clay (49.2m)
Hackney	Diaphragm walls	12.7	27.2	1300	Made Ground (2.2m)
					Superficial Deposits (3.2m)
					Lambeth Group (6.3m)
					Thanet Sand (17m)
					Chalk
Highbury	Pre-cast segments	15	25.4	350	Made Ground (2.5m)
	SCL	16.1	9.8 (35.2)	320	London Clay (25.8m)
					Lambeth Group
Islington	Pre-cast segments	10.5	27.7	300	Made Ground (3.2m)
	SCL	11.4	9.9 (37.6)	240	London Clay (28.3m)
					Lambeth Group
Kensal Green No 1	Pre-cast segments	15	17.7	350	Made Ground (1.8m)
	SCL	15.9	8.8 (26.5)	240	London Clay (76.3m)
Kensal Green No 2	Pre-cast segments	12.5	30.2	350	Made Ground (1.9m)
	SCL	13.4	12.5 (42.7)	275	London Clay (76.3m)
St Johns Wood No 1	Pre-cast segments	12.5	33.1	350	Made Ground (2.9m)
	SCL	13.8	12.5 (45.6)	315	Superficial Deposits (1.2m)
					London Clay (61.4m)
St Johns Wood No 2	Pre-cast segments	6.0	34.5	225	Made Ground (4.6m)
	SCL	10	12.5 (47)	300	Superficial Deposits (1.2m)
					London Clay (61.4m)
St Pancras	Pre-cast segments	10.5	35.7	300	Made Ground (2.0m)
	SCL	11.4	9.1 (44.8)	305	London Clay (43.6m)
					Lambeth Group
Wandsworth	Jacked ‘‘wet’’ caissons	15	22.7	350	Made Ground (2.5m)
	SCL	16	12.5 (35.2)	285	Superficial Deposits (4.5m)
					London Clay (41.9m)
Willesden	Pre-cast segments	12.5	20.3	350	Made Ground (1.7m)
	SCL	13.4	8.7 (29)	225	London Clay (74.4m)
Wimbledon	Jacked ‘‘wet’’ caissons	15	10.5	350	Made Ground (2.3m)
	Pre-cast segments	15	16 (26.5)	350	Superficial Deposits (2.0m)
	SCL	16	10.7 (37.2)	310	London Clay (45.4m)

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Table 3. Overview of the Crossrail case study shafts

Shaft location	Construction method	Internal diameter (m)	Excavation depth (m)	Lining thickness (mm)	Encountered strata
Farringdon Western ticket hall	Secant bored piles	15	24.7	1200	Made Ground (3m)
					London Clay (6m)
					Lambeth Group (17m)
					Thanet Sand
Farringdon Hayne St	Jacked pre-cast segments	5	14.6	200	Made Ground (1m)
	SCL	6.2	10.9 (25.5)	300	London Clay (22m)
					Lambeth Group
Fisher Street main shaft	Secant bored piles	15	11.85	620	Made Ground (3m)
	SCL		19.13 (30.98)		Superficial Deposits (4m)
					London Clay (17.5m)
					Lambeth Group
Fisher Street grout shaft	Pre-cast segments	5	9.0	300	Made Ground (4.5m)
					River Terrace Deposits (3.3m)
					London Clay (18.5m)
					Lambeth Group
Limmo Peninsula main shaft	Diaphragm wall	30	44	1200	Superficial Deposits (17m)
					London Clay (31m)
					Lambeth Group (18m)
					Thanet Sand
Limmo Peninsula auxiliary shaft	Steel sheet piles	28	14	450	Superficial Deposits (16.7m)
	SCL		25 (39)	800	London Clay (75m)
					Lambeth Group (6.3m)
					Thanet Sand (17m)
					Chalk
Whitechapel Cambridge Heath	Diaphragm wall	28	32	1500	Made Ground (4.5m)
					Superficial Deposits (3m)
					London Clay (25.5m)
					Lambeth Group
Whitechapel No. 2	Jacked pre-cast segments	12.5	10.6	325	Made Ground (8.5m)
	SCL		18 (28.6)	800	London Clay (24.5m)
					Lambeth Group
Soho Sq. Southeast	Jacked pre-cast segments	5.0	15	not reported	Made Ground (2m)
Soho Sq. West	Jacked pre-cast segments	5.0	14		Superficial Deposits (3m)
Sheraton	Jacked pre-cast segments	5.0	14		London Clay
					Lambeth Group

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Figure 1. Comparison of published settlements during excavation of circular shafts
Figure 2. Comparison of the 11 m diameter Heathrow Express and 30 m diameter Limmo Peninsula auxiliary shaft
Figure 3. Location plan for the Northern Line Extension shafts. Base map source: Google Earth (2017)
Figure 4. Location plan for the London Power Tunnels shafts. Base map source: Google Earth (2015)
Figure 5. Plan view of Crossrail's 21 km twin-bore running tunnels in central London showing the case study shaft locations (Basemap reproduced with kind permission from Crossrail Limited)
Figure 6. Excavation in front of 1.2 m thick pre-installed diaphragm walls for Crossrail's 30 m diameter and 44 m deep TBM launch shaft at Limmo Peninsula (SBE construction)
Figure 7. Jacked pre-cast segments for Crossrail's construction access shaft at Whitechapel: excavation ahead of the lead cutting ring which may cause a reduction of in-situ horizontal soil stress and stiffness
Figure 8. Erection of pre-cast segments for National Grid's London Power Tunnels project (Ref. National Grid (2015)). The ground is exposed prior to erecting the shaft lining (EBS construction).
Figure 9. EBS shaft construction for National Grid's London Power Tunnels project (Ref. National Grid (2015))
Figure 10. A 28m diameter and 39m deep TBM launch shaft at Limmo Peninsula comprising pre-installed sheet piles (SBE construction) and a sprayed concrete lining (EBS construction)
Figure 11. Settlements arising from installation of pre-installed shaft linings in London
Figure 12. Field observations of settlement around pre-installed circular shafts (SBE shaft construction)
Figure 13. Field observations of settlement around jacked pre-cast segments (SBE shaft construction)
Figure 14. Field observations of settlement around concurrent shaft linings involving pre-cast segments and SCL (EBS shaft construction)
Figure 15. Field observations of settlement during excavation of dual lined shafts involving pre-installed walls and SCL (combined SBE & EBS shaft construction)
Figure 16. Field observations of settlement during excavation of dual lined shafts involving jacked pre-cast segments and SCL (combined SBE & EBS shaft construction)

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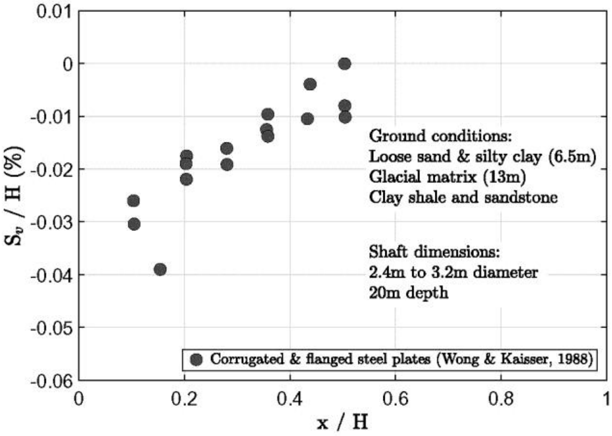
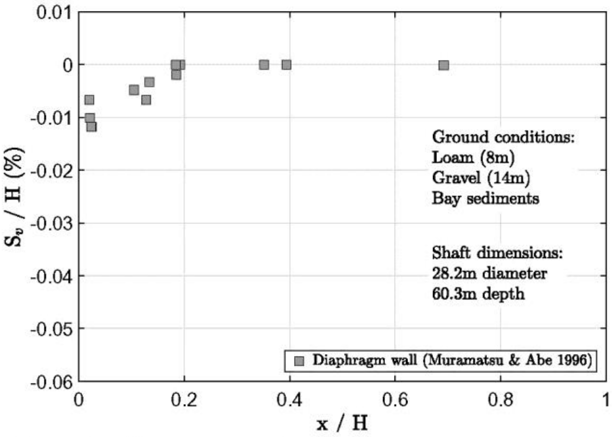
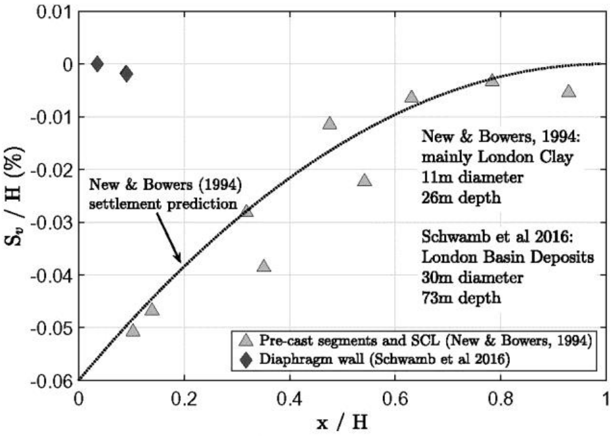


(a) Ground conditions: Sand and Edmonton Till



(b) Ground conditions: Loam and Gravel



(c) Ground conditions: London Basin deposits

Figure 1

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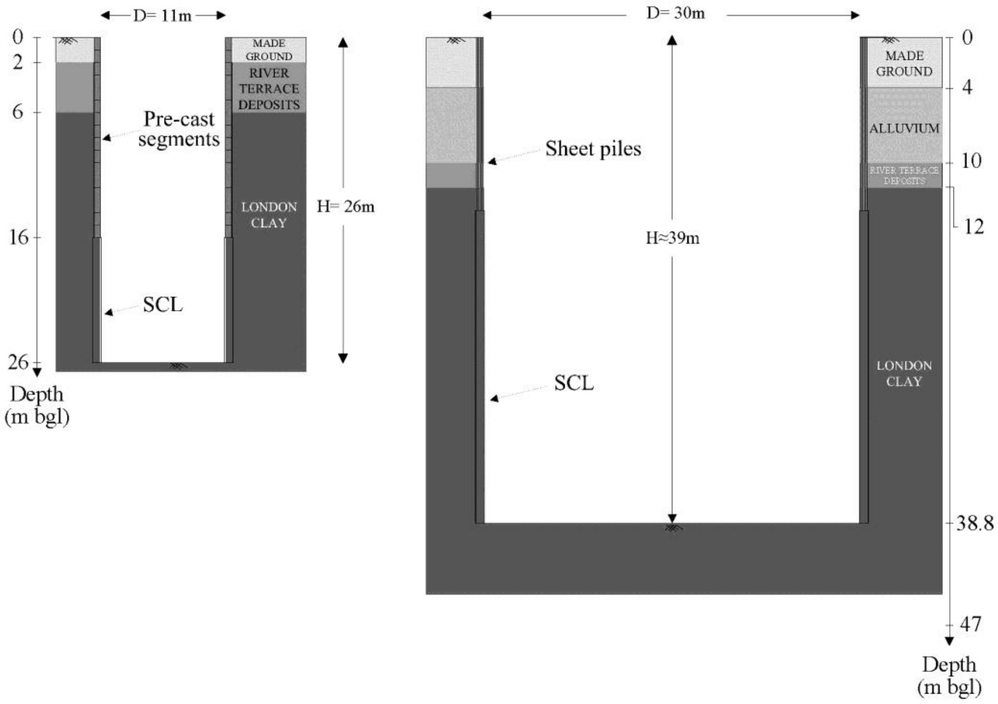

a. Heathrow Express trial tunnel shaft (New & Bowers 1994)

b. Crossrail TBM launch shaft at Limmo Peninsula, east London

Figure 2

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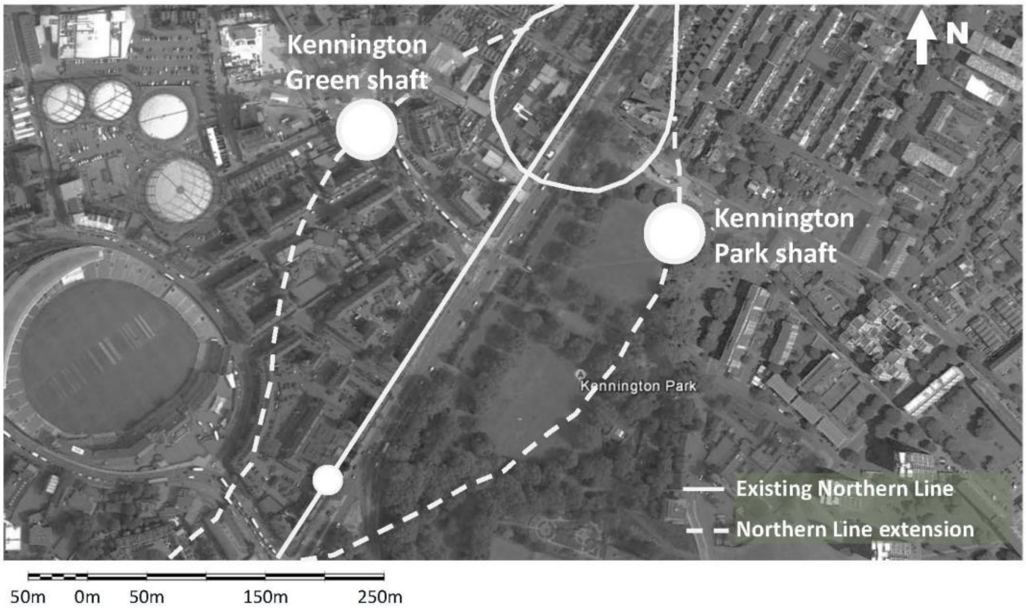

Figure 3.

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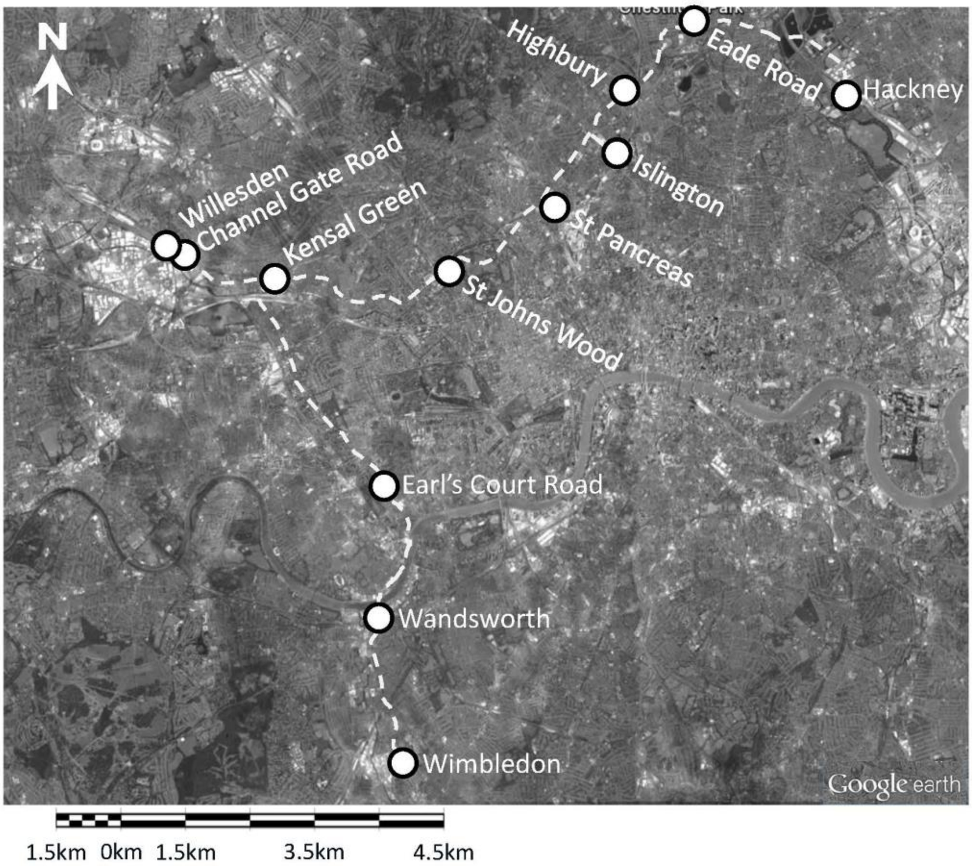

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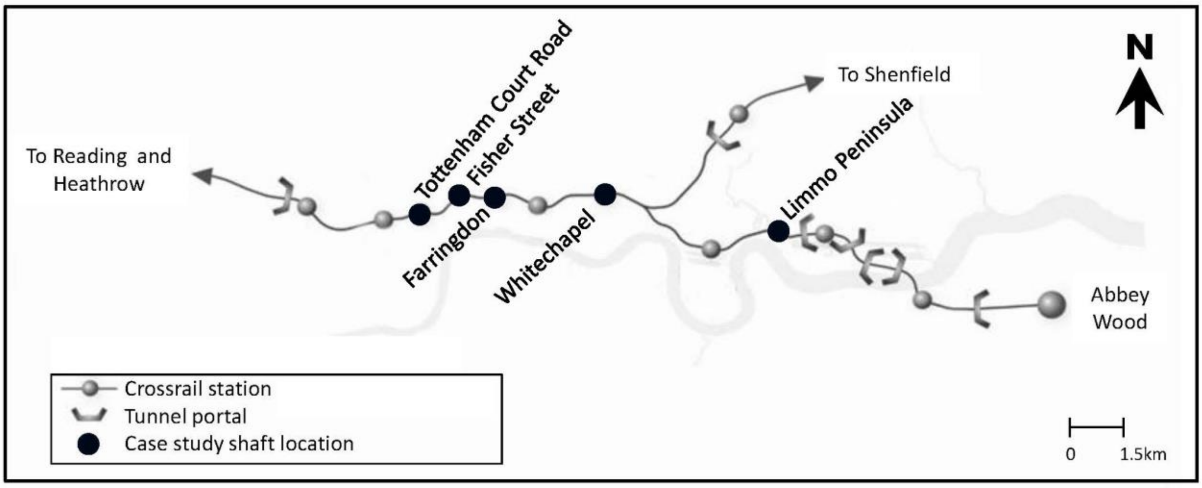

Figure 5.

Figure 6.

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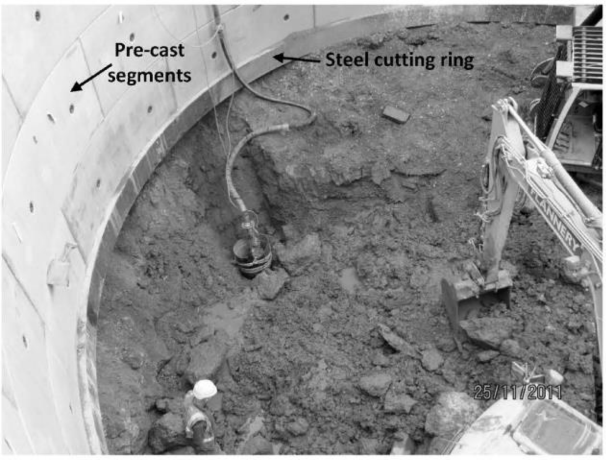

Figure 7.

Figure 8.

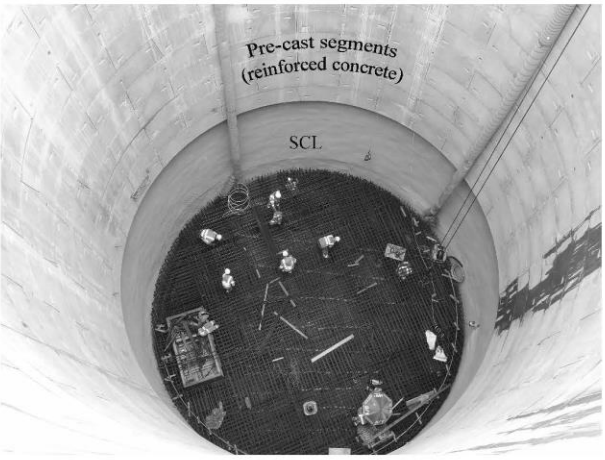

Figure 9.

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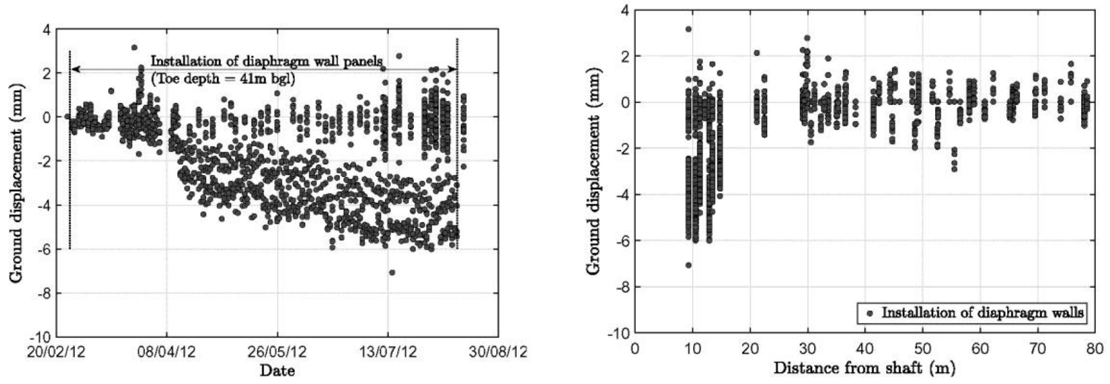
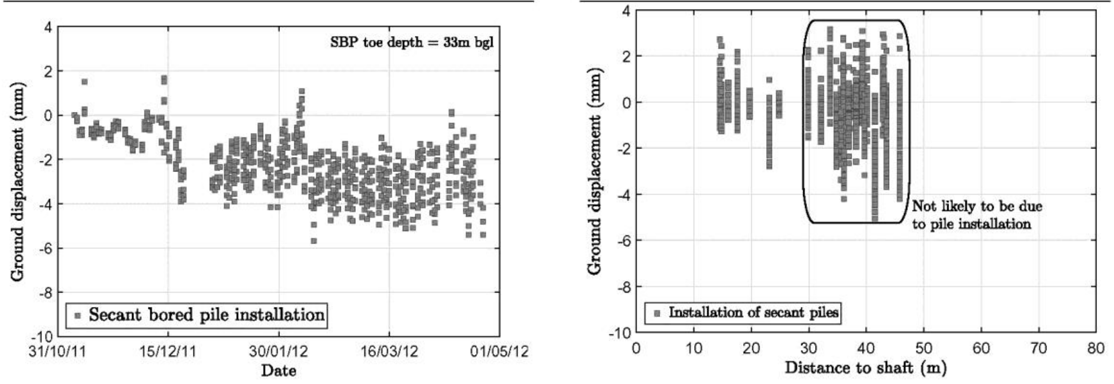


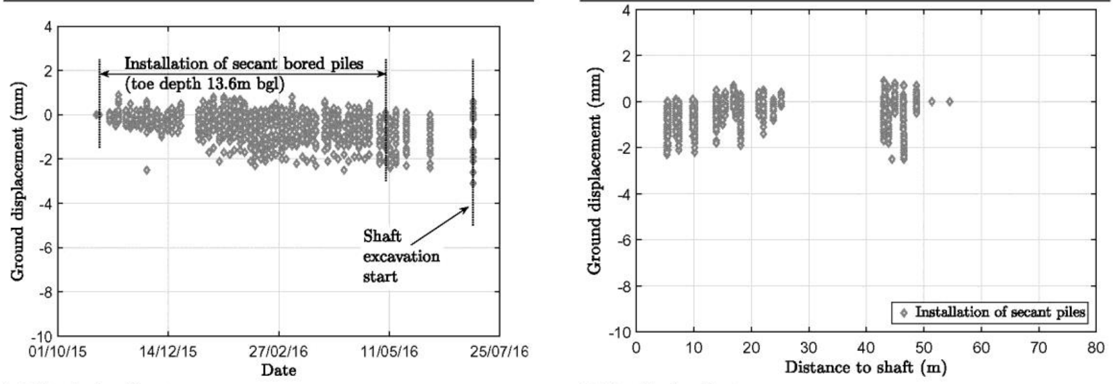
(a) Cambridge Heath

(b) Cambridge Heath



(c) Farringdon

(d) Farringdon



(e) Kennington Green

(f) Kennington Green

Figure 11.

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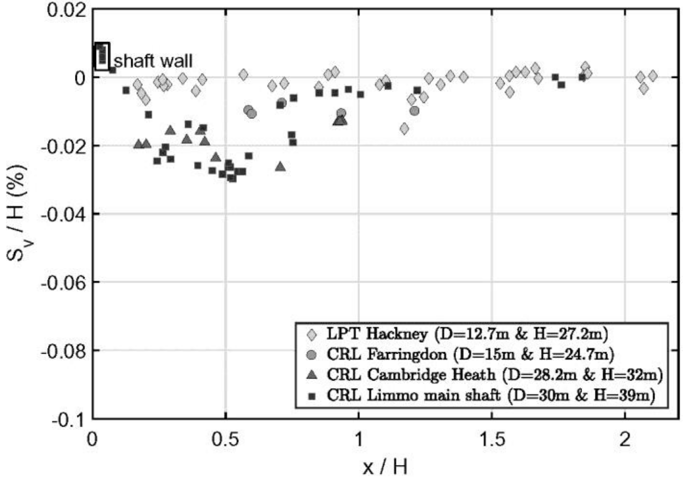

Figure 12.

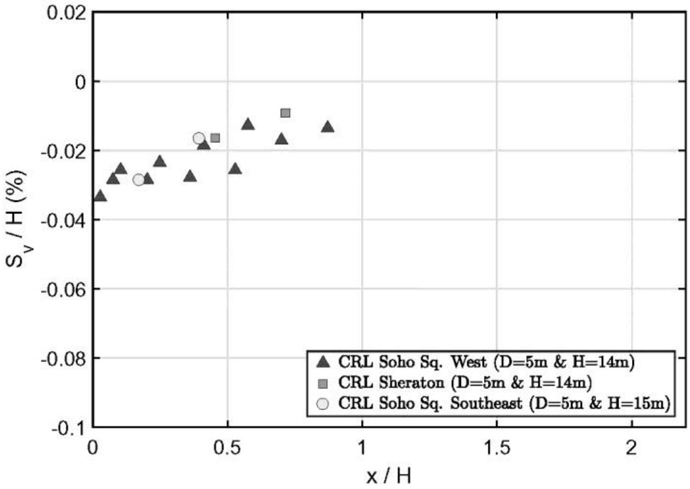

Figure 13.

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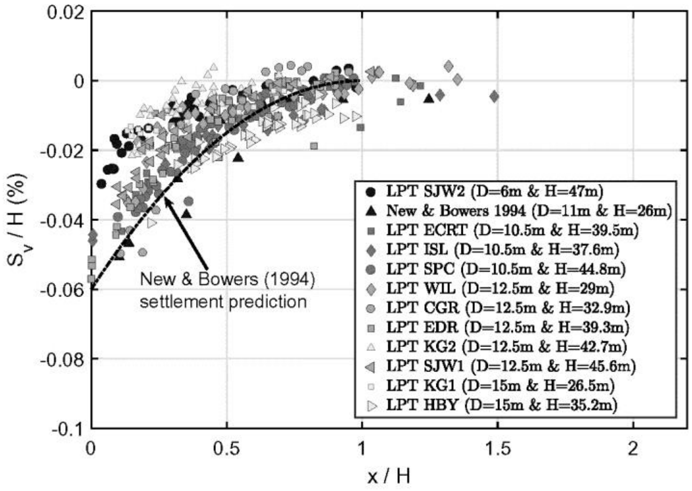

Figure 14

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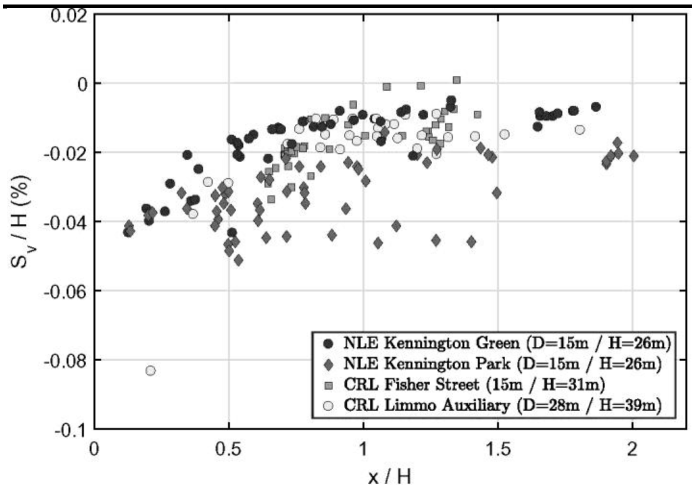

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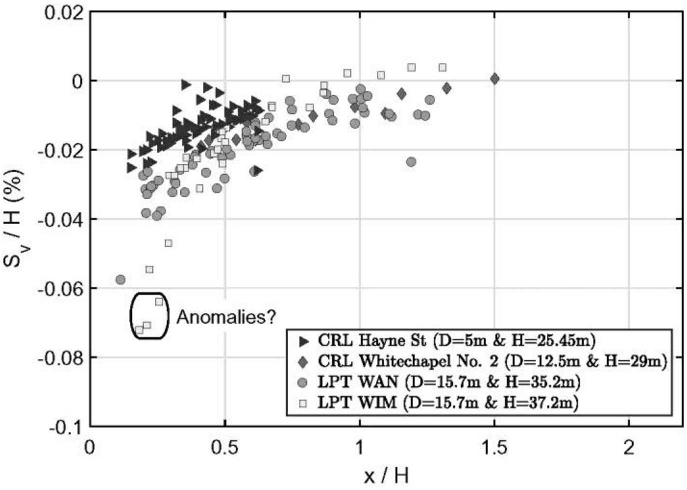

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