Ground Movement Caused by the Effects of the Installation of Embedded Retaining Walls

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Introduction

Ground movement induced by the installation of embedded retaining walls is often a major contributor to the total movement induced on third party assets surrounding retained excavation. It is therefore critical that this potential movement is estimated and the corresponding precautions made when planning an excavation.

CIRIA C580 is a book that provides design guidelines on embedded retaining walls. The aim of the book is to allow its users to be able to achieve an economic design for the retaining structure and its support system while maintaining simplicity. It covers the design of temporary and permanent cantilever, anchored, single and multi-propped retaining walls in different types of soil[4].

In CIRIA C580, there is a proposed method of predicting ground movement induced by the installation of retaining walls which involves an empirical relationship between the geometry of the wall and the anticipated ground movement. However, this method is based upon dated and limited case history data, which may not be applicable and suitable for modern large infrastructural projects like the London Crossrail.

As the Crossrail project proceeds, new data is available for more relevant analysis as the data is much more recent. The results of analysis will be able to reinforce or challenge the existing data and methods.

Objectives

In light of the current situation, it is the aim of this project to:

1. Assemble the relevant available case histories data into a database to analyse for new interpretation
2. Understand the significance of wall installation effects on ground movement with comparison to ground movements caused by deep excavations
3. Cross reference the data retrieved from the London Crossrail project to the guidelines in CIRIA C580 to investigate on the similarities/differences, determining the suitability of CIRIA C580 as a guideline to current construction works

Literature Review

Causes of ground movement

In a site where the presence of adjacent structures and facilities is negligible, the effects of ground movement are of little consequence. However, in most urban locations ground settlement that is unaccounted for can prove to be devastating. Therefore it is always safer and more economical to try and predict ground movements and set limits for settlement prior to deep excavation works. A number of different sources contribute to the total ground movement in deep excavations such as:

- Installation of walls and other construction elements
- Excavation and deformation of construction components
- Flow of water causing loss of ground and consolidation caused by changes in water pressures due to seepage through and/or around the wall

For the purposes of this report, only the effects of the installation of walls along with a brief overview of excavation effects will be covered.

Wall installation

The construction of retaining walls in excavation works often contribute to the total ground movement in the area. These movements depend upon the conditions of the ground, the methods of construction and also the quality of the workmanship in construction. However the movements that prove to be the most harmful to the construction process tend to be localised and caused by construction problems. For example, the removal of obstructing objects and the excavation of guide trenches before the installation of the wall often causes significant movement when compared to the actual effects of wall installation itself. Although it is impossible to try and predict or model such disturbances that may happen during construction, the magnitudes of influence of such occurrences should be noted.

Drilling and driving piles into the ground for these walls cause vibrations and the excavation of panels into the ground involves loss of ground support. However, not every

method of wall construction will involve the aforementioned elements. It is therefore important to have a brief understanding of the sort of wall installation techniques available and the type and magnitude of ground movements they are prone to cause.

Wall Types

Contiguous Pile Walls

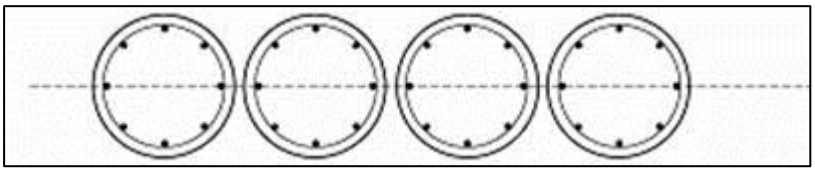

Figure 1 Contiguous pile wall[11]

Figure 1 shows a plan view of a contiguous pile wall. Contiguous pile walls are constructed by separate piles bored into the ground with a small gap in between (typically around 100mm). This will mean that there is exposed soil at the surface but self-support will often suffice due to arching. This method is suitable in a variety of soils given that the ground water table lies below the maximum excavation depth.

The ground movements due to contiguous pile walls are similar to those of secant pile walls, but the localised area is smaller as the surface area is smaller.

Diaphragm Wall (Slurry Wall)

Figure 2 shows the construction sequence of a diaphragm wall. To construct a diaphragm wall, a guide trench will be excavated in the ground and supported by a support fluid until the fluid is fully replaced by the permanent material. Typically diaphragm walls are constructed with reinforced concrete, but unreinforced walls are also used. Diaphragms are often used in top down construction methods and are suitable in congested areas or where the excavation depth is deep.

The ground movements induced in the installation of diaphragm walls will depend on the margin of safety against trench instability, which depends on the material used as the supporting fluid (usually bentonite mud). The level of the supportive fluid relative to the groundwater level will also be an influential factor to the ground movements caused.

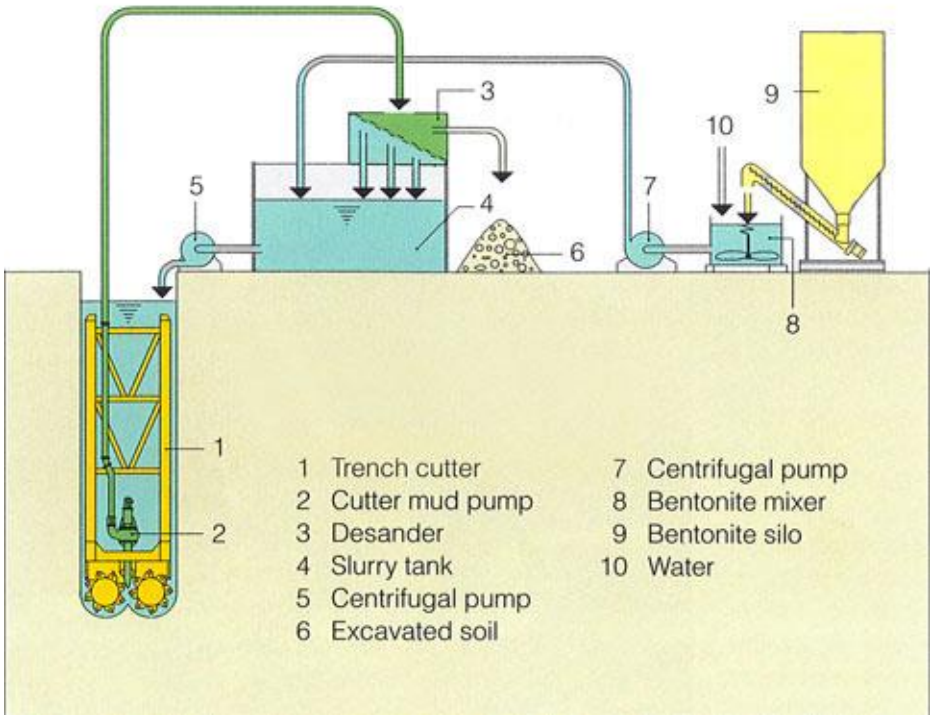

Figure 2 Construction of a diaphragm wall[17]

Secant Pile Walls

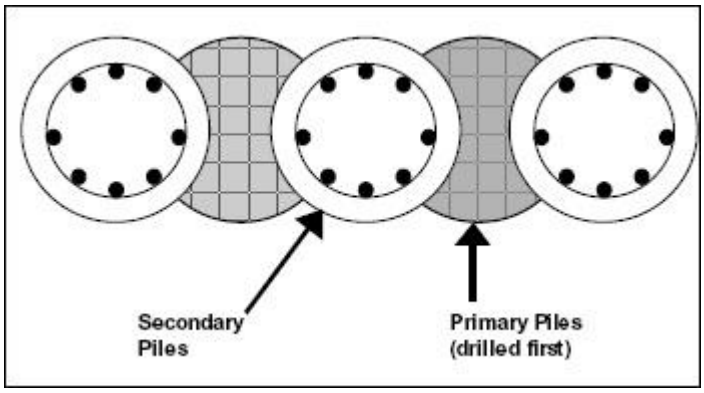

Figure 3 Secant pile wall[20]

Figure 3 shows the plan view of a secant pile wall. Primary piles are drilled in first to form a guide wall that ensures that the secondary piles will be installed accurately to achieve a secant cut into the adjacent primary piles. A secant pile wall is the retaining structure created by the interlocking of these male and female piles. The primary piles are usually unreinforced for the reinforced secondary piles to cut into. Special equipment like high torque drill rigs and specially designed cutting tools are required.

Ground movements are usually confined to the local areas around the piles, except when the soil flows towards the piling area as it is bored. This may happen where the pile boring is under the water table or when boring in sandy deposits or soft clay. Extra caution must be taken during construction of secant pile walls, ensuring that the temporary casing is kept ahead of spoil removal and that a high water level is maintained within the bore.

Sheet piled Walls

Figure 4 shows a unit of a sheet pile and the sheet pile wall, where these units are joined together. This method involves driving individual sheet piles into the ground to the desired depth and ensuring the adjacent piles interlock to form a wall. This method has the advantage of being light weight and is also flexible in pile length as welding and bolting can extend the pile. However the installation of sheet piles in areas with lots of cobbles may be difficult.

The ground movements induced by the installation of sheet piling is generated by the vibrations created during the piling of the sheet piles. However, the influenced areas are usually localized around the areas of piling so extensive damage is seldom seen.

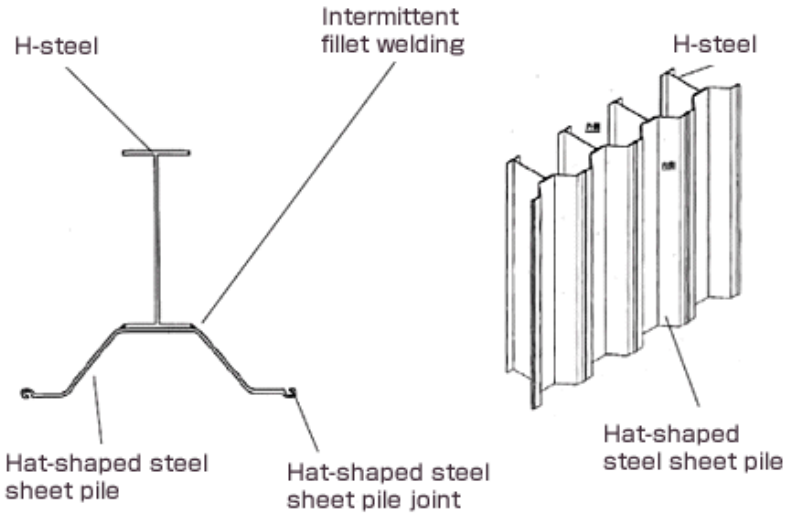

Figure 4 Sheet pile wall[98]

Soldier Pile Wall (King Post Wall)

Figure 5 shows a diagram of a typical soldier pile wall. Soldier pile walls are usually used for temporary works due to its low cost and quick completion. It is installed at a wide spacing of 5-8 pile diameters, but may differ in different ground conditions. The soil in between the

piles are often retained using wood lagging and is therefore unsuitable where high water pressures or flow is present in the retained soil.

The fact that piles are installed every few metres will mean that the ground movement induced by pile installation is small. However, the installation of the infill panels can lead to larger soil movements, depending on the installation method and the workmanship of the installation.

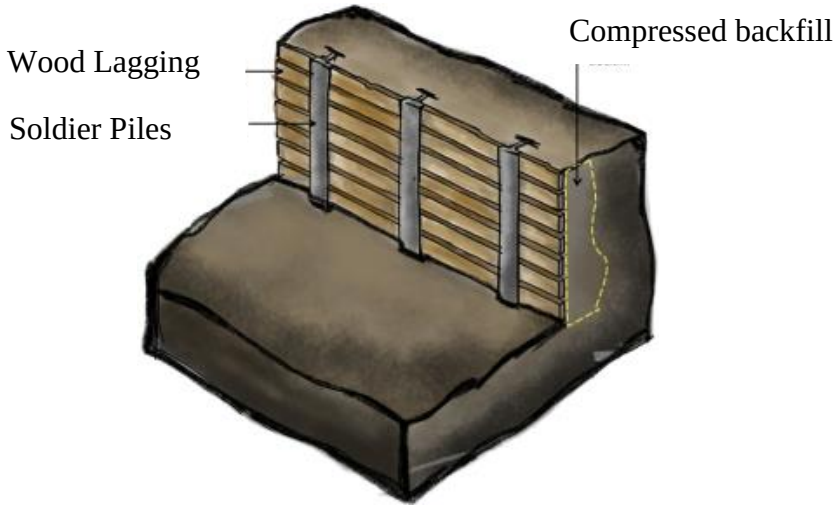

Figure 5 Soldier pile wall[76]

Support Configurations

Apart from different wall types available for excavation, different support configurations are available. Temporary or permanent works are often an economic solution when excavating to avoid having to install more than one wall. It is important in design to understand the advantages and disadvantages of each method. Some understanding of the different techniques used in current construction will also aid the analysis of the ground movements seen in different cases as different techniques adopted will affect the movement of the ground as well.

Cantilever Wall

The cantilever wall is a simple construction sequence with no temporary propping the wall, therefore it is a very popular supporting method. This will allow the permanent works to be constructed in a free space where no temporary props will be in the way. However, this method maybe uneconomic for deeper excavations as the strength of the wall needed to support the deep soil may be substantial. Large soil movements may also be seen with such a

technique as shown by the bending mechanism shown in Stage 2 in Figure 6. The large wall deflection may not be suitable in certain sites and must be a consideration during design.

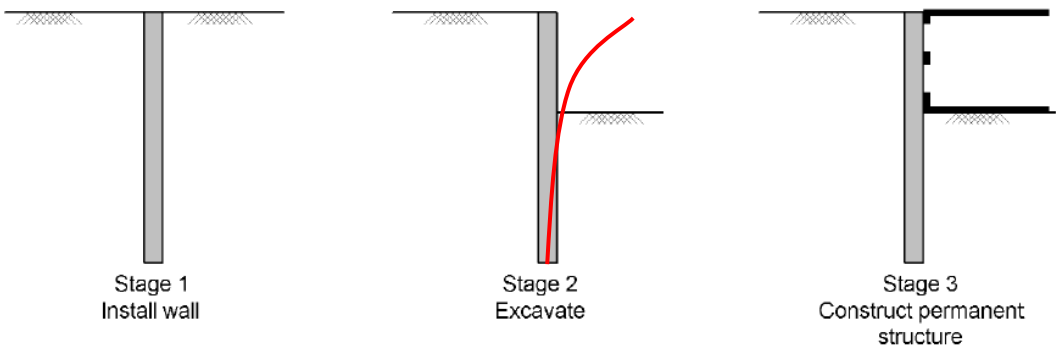

Figure 6 Construction of a cantilever wall[4]

Propped Wall – Top-Down Sequence

Figure 7 Single propped wall and multi-propped wall[4]

Figure 7 shows a single propped wall and a multi-propped wall. Propped walls can be constructed via a top down sequence or a bottom-up sequence. In a top down sequence, horizontal slabs are installed from the higher levels to provide lateral support to the soil. In a bottom up sequence, the permanent works are constructed from the lowest level upwards, with the foundation slab casted before any of the internal walls and slabs. Temporary props will be installed for the permanent slabs to be constructed, and are removed after the structure is built.

This method allows the superstructure to be constructed at the same time as the substructure, thus saving construction time. It also manages to lower the deflections of the wall and thus ground movement significantly. It should be noted that the deflections of the wall are reduced with the increasing number of props supporting the wall as demonstrated in Figure 7.

However, this method is generally costlier and slower to complete, and the size of the area available for construction of the permanent works is substantially smaller than that of a cantilever wall. Furthermore, the horizontal slabs will require vertical support temporarily during the installation of the props.

Anchored Wall

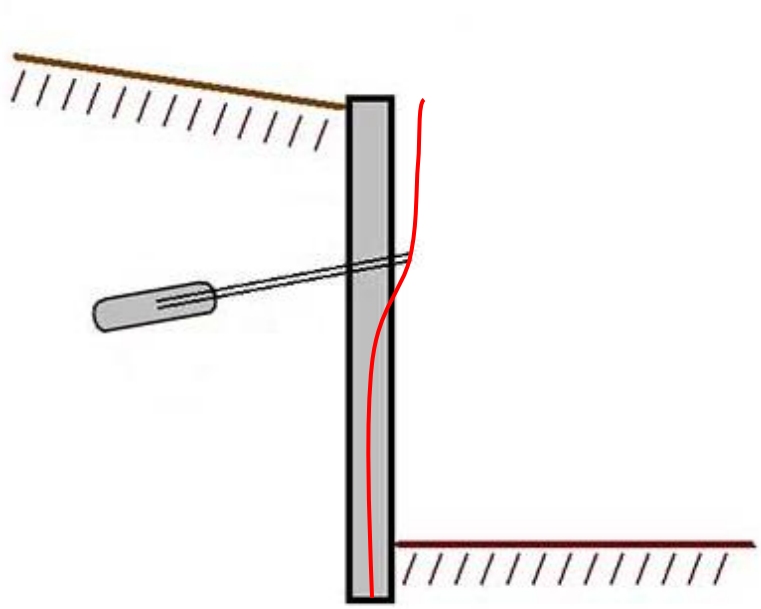

Figure 8 Anchored wall[21]

Figure 8 displays the basic concept of an anchored wall. An anchor provides a cantilever wall with additional strength by connecting the wall to the soil behind it. After the anchor is bored into the soil, the end is usually expanded by injecting pressurized concrete through the anchor or by mechanical methods. This method has the advantage of allowing free spaces to be used for construction of the permanent works without the obstruction of props while enhancing the strength and reducing the deflections of the wall. However, this

method is technically complex and potentially expensive. Also, the boring of the anchor may cause damage to nearby structures by inducing excess ground movement.

Excavation in front of wall

[4]Excavations in front of the wall affect the ground movement by:

- Stress changes due to excavation
- Soil strength and stiffness
- Changes in groundwater conditions
- Stiffness of the wall and its support system
- Shape and dimensions of the excavation
- Quality of workmanship
- Other effects such as site preparation works, installations of deep foundations e.t.c.

Predictions of ground movement

There are numerous methods that attempt to predict these ground movements available. Some model the ground movement as a combined effect from all the sources listed above, while recent studies have leaned towards analysis of the contributing factors separately. In this report, the emphasis will lie on the effects brought by embedded retaining wall installation.

The Observational Method that was first described by Peck in 1969 involved obtaining immediate feedback from monitoring the construction works to alter the designs and construction sequences for more economical projects in the future. It is essential for the method to be successful that predictions from numerical analysis or case studies are available. Movements of the ground are a function of many factors such as soil and groundwater conditions, changes in groundwater level, depth and shape of installation, type and stiffness of the wall, supports, construction methods of the wall and adjacent facilities, and workmanship. Furthermore, different types of construction of these walls are available and will depend on the exact conditions of the situation and the cost will vary with the method chosen. To accurately estimate the magnitude of horizontal and vertical settlement of the soil, one will require an in-depth knowledge of all the possible factors. Due to the difficulty of performing reliable numerical analysis, attempts on predicting ground movement

have often been based on case history data where similar techniques have been used in similar ground conditions.

CIRIA C580

CIRIA C580 provides engineers with guidelines for economic design of embedded retaining walls. Predictions on ground movement acts as a major function of the document by using case history data where the effects of wall installation have been recorded. Previous case histories that have contributed to the current methods of prediction have been summarized in the following publications and documents[4]:

- Clough and O'Rourke (1990)
- Thompson (1991)
- Carder (1995)
- Carder *et al* (1997)

Wall type	Horizontal movements		Vertical movements	
	Surface movement at wall (per cent of wall depth)	**Distance behind wall to negligible movement** (multiple of wall depth)	**Surface movement at wall** (per cent of wall depth)	**Distance behind wall to negligible movement** (multiple of wall depth)
Bored piles				
Contiguous	0.04	1.5	0.04	2
Secant	0.08	1.5	0.05	2
Diaphragm walls				
Planar	0.05	1.5	0.05	1.5
Counterfort	0.1	1.5	0.05	1.5

Table1 Ground surface movement due to wall installation[4]

The data relevant to wall installation effects from these documents have been collated together to produce Figure 9. The horizontal and vertical ground movements of caused by the installations of bored pile walls and diaphragm walls are plotted separately, and it is seen that the two type of walls in fact have rather similar trends. However, this is a rough speculation due to the limited data available. Trend lines that cover the maximum values of movement and distances to negligible movement are added to the figures for each type of wall.

The table shown above is produced by taking the displacements at the wall and also the required distance for negligible movement of the trend lines of each wall type. Table 1 summarises the magnitude of the monitored movement as a normalized percentage of wall depth. As seen from the plots, the settlement is also presented as a percentage of wall depth. This implication that the settlement is correlated to the depth of the installation of the wall originated from Peck's work, where a vague trend could be seen in the plots that support this assumption.

It is stated in the C580 document that these plots and Table 1 should only be treated as indicative only because of the evidently limited data that they were based upon. It can be seen from the figures that apart from the vertical movements of bored pile walls, there is a lack of data points to produce a reliable trend line. As the current methods of ground movement prediction are based on past case histories, it is particularly problematic that there is a lack of variety of available data. This is because a case history with similar stratigraphy and construction methods will be able to provide a much better estimation for the project that is being worked on.

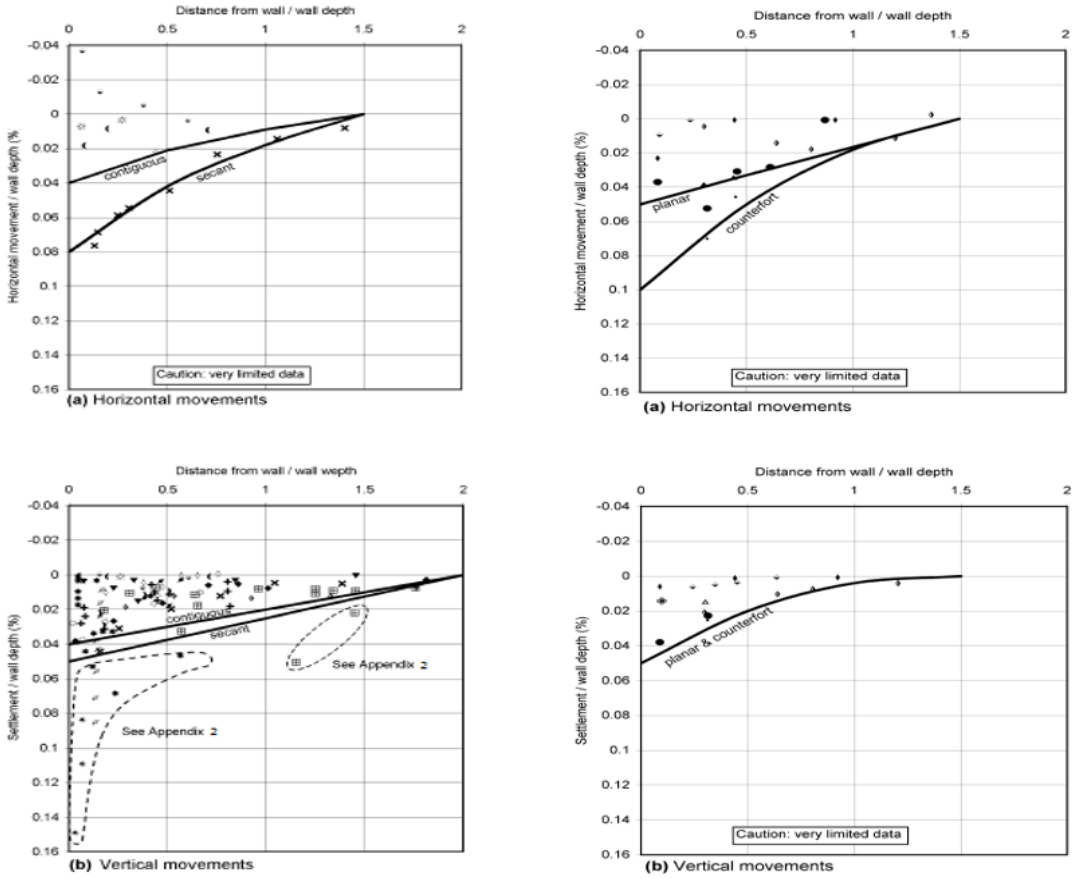

Figure 9 Ground movements due to bored pile wall installation (left) and diaphragm wall installation (right)[4]

Consulting with leading civil engineering firm ARUP has led to a general consensus that the predictions of ground movement in C580 has not been realised in practice. The documents in which the predictions are based upon show that the most recent reference is dated to 1997, which means that technology has advanced by 17 years since then. It is believed that due to the increase in technological and engineering capabilities, the ground movements observed in recent works are no longer accurately predicted by C580. In fact, it has been considered so uneconomical and inaccurate that there are cases where the C580 guidelines are ignored and other forms of prediction are used instead.

A recent case involves part of the Crossrail project in the Farringdon Station's East Ticket Hall (Figure 10) where there were two different predictions made for piling works. Using a method derived from Thompson (1991)[12] that had similar traits with the CIRIA C580 method (both methods involved normalizing settlements with wall depth), the maximum settlement was calculated to be 10mm. Another method which involved the Crossrail project's own assessments (C122)[14] gave a maximum settlement of 5mm. The decision was made for the team to go with the criterion of 5mm because of two reasons:

- Thompson data not fully representative of deep shafts in central London
- The Thompson data is 20 years old, and not fully representative of modern piling techniques

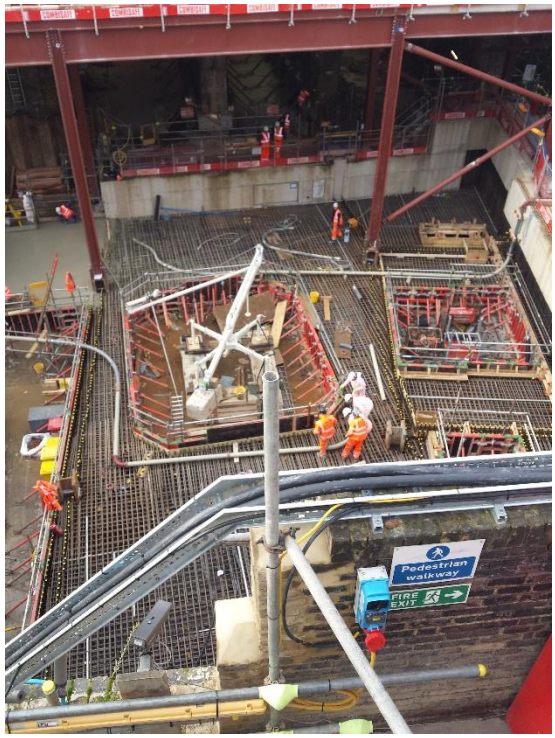

Figure 10 Farringdon station East Ticket Hall construction site[22]

In reality, the maximum settlement observed during the construction was 11mm, over 100% more than what was estimated. A joint review of different Crossrail reports suggested a variety of possible factors that contribute to the settlement observed. These can be broadly classified into pile construction problems, groundwater issues and other concurrent construction works in the area[14]. This incident exactly highlights the unpredictable ground movements and the lack of a reliable method to predict ground settlement during construction. Although no further damage was inflicted on the project, it is clear that a good method of prediction is very much needed. The Crossrail project has been able to provide

recent data for effects of wall installation on ground movement. It is therefore possible now to examine and compare the data from Crossrail with the dated case histories to observe if the trends are still seen in current construction works.

Results and Discussion

Case Studies: Deep Excavation Effects

In the past, some have attempted to model the total ground movement of a deep excavation without separating the sources of such movement. Long (2001)[11] provides a database with case studies worldwide of total ground movements during excavation. To investigate on the different effects of soil type and wall type on ground movement, the data has been organised for analysis.

London Clay

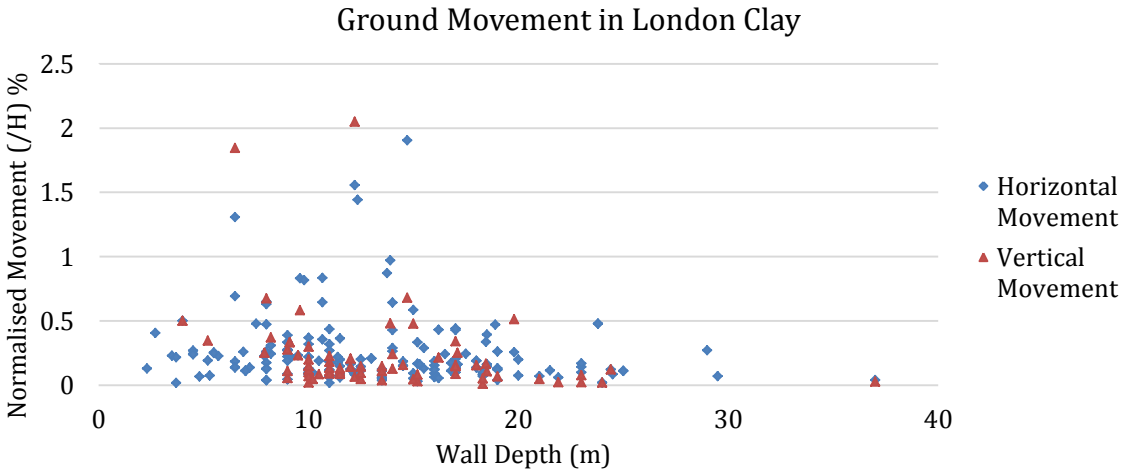

Figure 11 Ground Movements in London Clay

Figure 11 shows the ground movements recorded in London Clay. The large spread of the results makes the analysis of the finer trends difficult, and therefore the plot is further broken down to different wall types constructed and different support configurations.

Contiguous Pile Walls

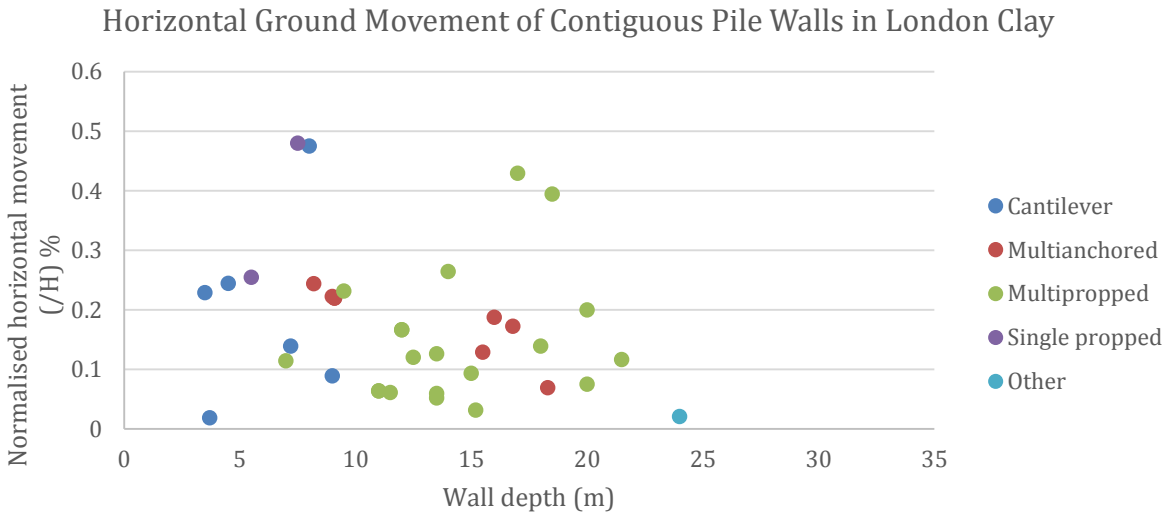

Figure 12 Horizontal ground movement of contiguous pile walls in London Clay

The horizontal and vertical movements are shown in Figure 12, as a percentage of the corresponding wall depth, with respect to the depth of the retaining wall. The normalised horizontal movements all remain within 0.5% of the wall depth and apart from four cases they remain below 0.3%. Amongst the four, the larger deflections from a cantilever wall and a single propped wall are expected but the multi-propped walls should not experience deflections of the same magnitude. However it can be seen that the wall depths of those cases are large and large deflections can be seen if fewer props are used. In general the horizontal movements seen are consistent and small as expected from a contiguous pile wall.

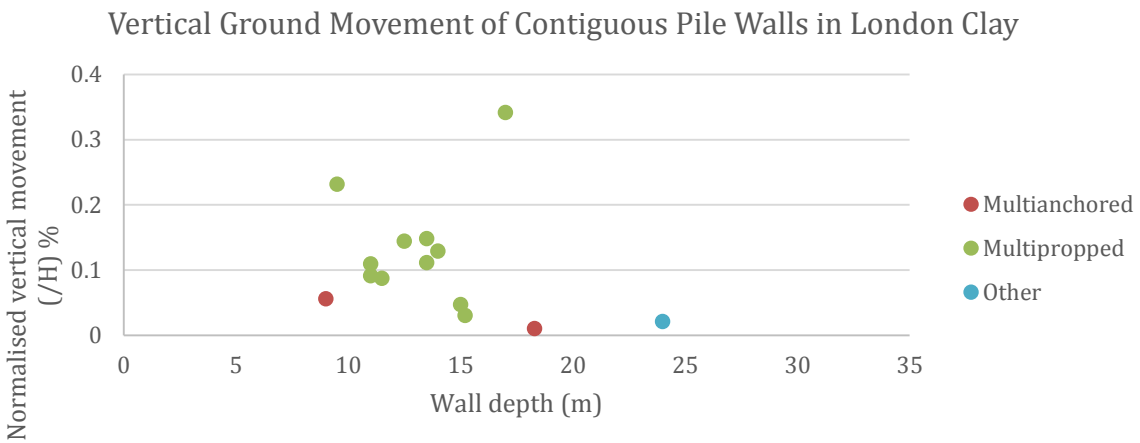

Figure 13 Vertical ground movement of contiguous pile walls in London Clay

The vertical movements of contiguous pile walls in London clay are small as well. Most settlements seen in Figure 13 are around 0.2% of wall depth and below except from a single multi-propped case. Again it is evident that the larger deflection when compared to the rest is related to the deeper wall in the case.

Diaphragm Walls

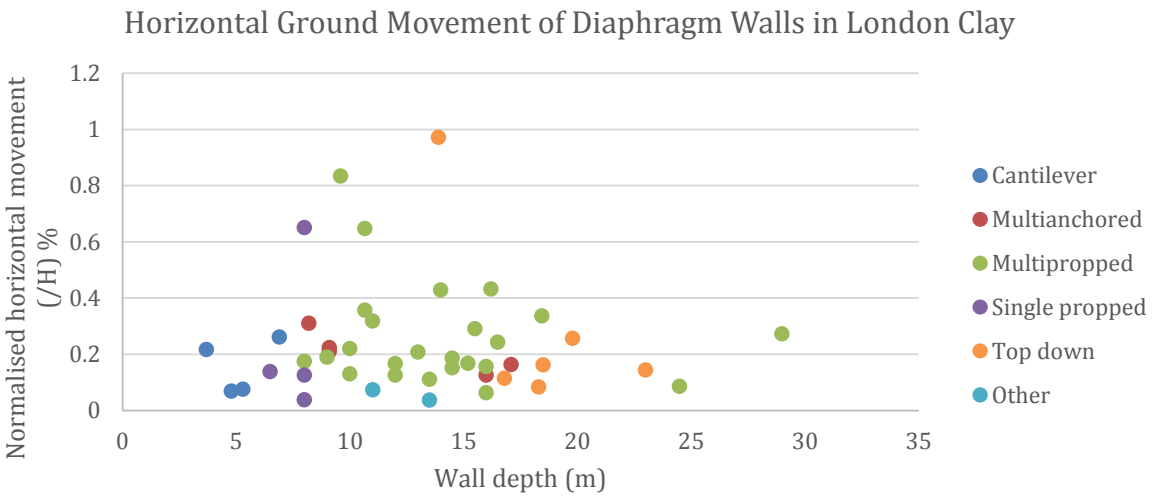

Figure 14 Horizontal ground movement of diaphragm walls in London Clay

The horizontal deflections of a diaphragm wall in London Clay are shown in Figure 14. As expected, the observed deflections of a diaphragm wall are large than those of a contiguous piled wall. Most settlements lie below 0.5% of wall depth, with only three multi-propped walls and one single propped walls exceeding the 0.5% mark. The single propped wall's larger deflections are understandable but what should be noted are the three multi-propped walls' large deflections. These walls have a relatively shallow depth compared to the other data points and are not expected to have such large deformations. This suggests that there might have been construction obstructions or problems during those cases. There is also another possibility that the props installed to support the wall were situated at lower levels of the wall. This could be due to the need of space for the construction of permanent works.

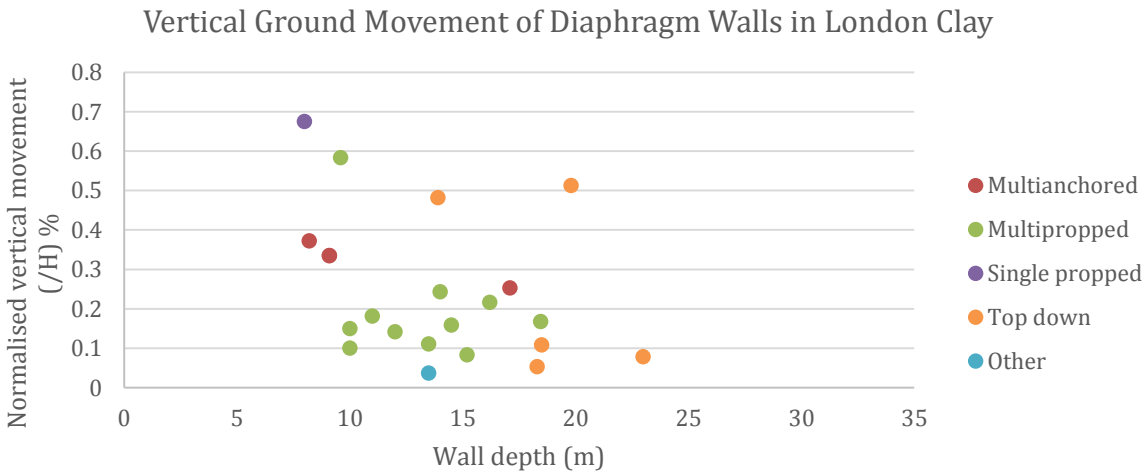

Figure 15 Vertical ground movement of diaphragm walls in London Clay

The settlements of diaphragm walls in London Clay as shown in Figure 15 show similar results. Most data points lie below 0.4% of wall depth with an exception of a single propped wall and three multi-propped wall. Again the single propped wall shows a large settlement as expected, and the same speculations are made that some construction obstruction were present during the construction of the multi-propped walls.

Secant Piled Walls

Secant pile walls are one of the strongest retaining wall types and the data from Figure 16 proves this. Apart from the cantilever wall showing a 0.5% wall depth movement, all other data points lie below 0.3%. The cantilever wall is expected to give a larger wall deflection due to the nature of the support configuration.

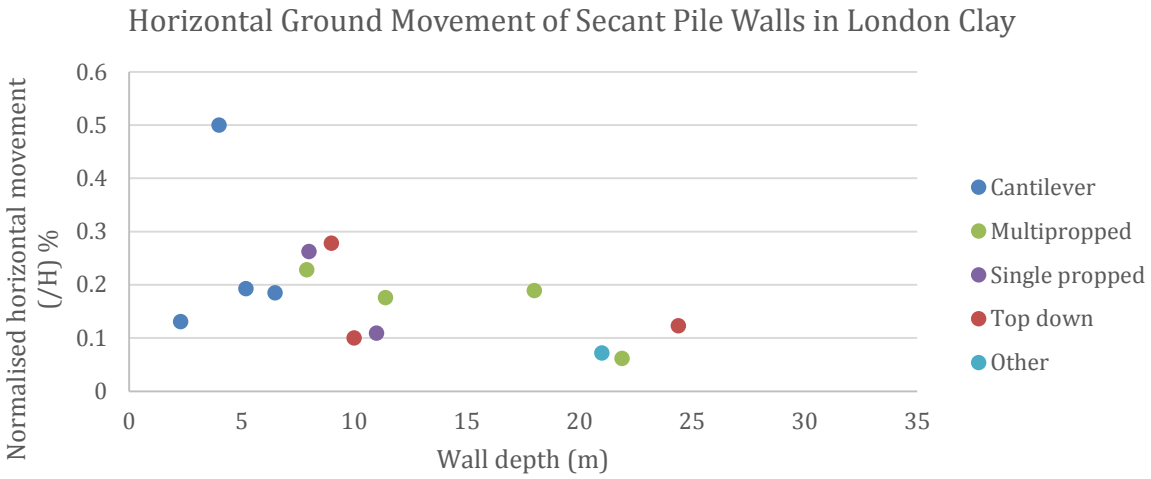

Figure 16 Horizontal ground movement of secant pile walls in London clay

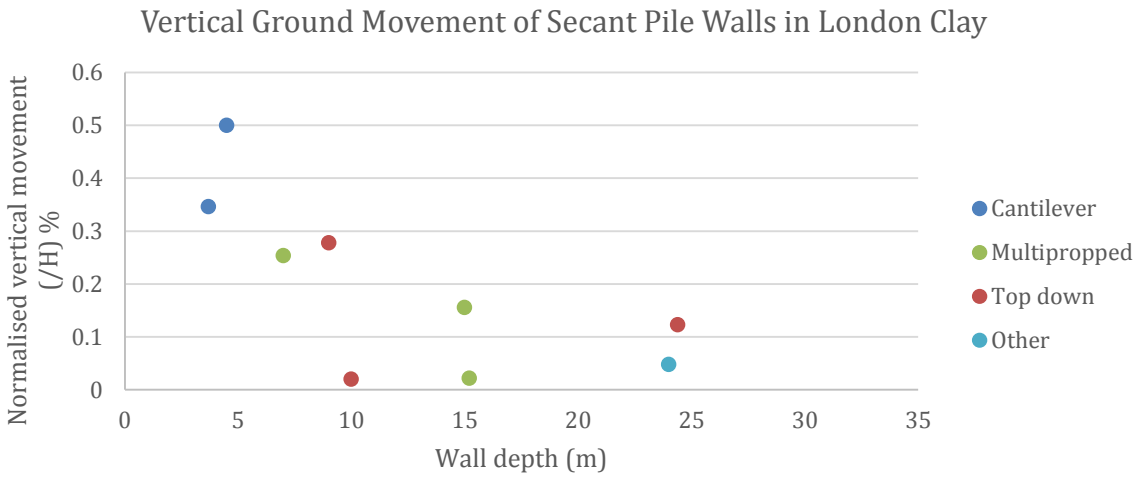

Figure 17 Vertical ground movement of secant pile walls in London Clay

Figure 17 shows the settlement of Secant Piled Walls in London Clay. Again it is seen that the settlements observed are small compared to other wall installation methods as the secant piles are able to provide the wall with high strength and smaller deflection. The two cantilever wall data points show a higher ground settlement due to the large deflections from the support configuration.

Sheet Piled Walls

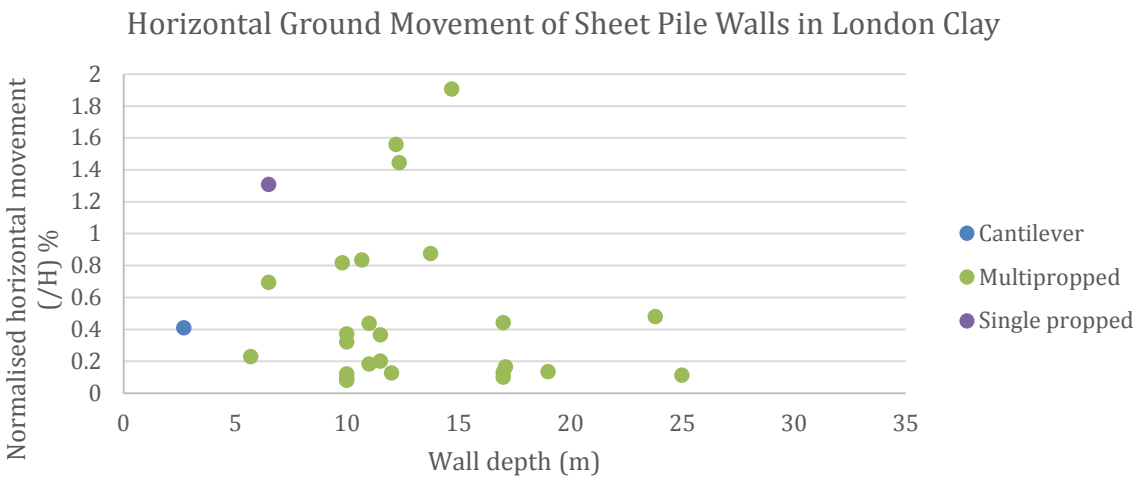

Figure 18 Horizontal ground movement of sheet pile walls in London Clay

Figure 18 displays the lateral movement of sheet piled walls in London clay from the compiled database. As shown, the movements of sheet piled walls are the largest amongst all wall types, suggesting the inferiority in strength of sheet pile walls when compared to the rest. Most data points lie below the 1% wall depth mark, but there are four cases in which the lateral movement exceeds it. It should be noted that the maximum settlement takes a value of 1.9% which is extremely high compared to the rest of the data suggesting that the measurements in that case were affected greatly by local works.

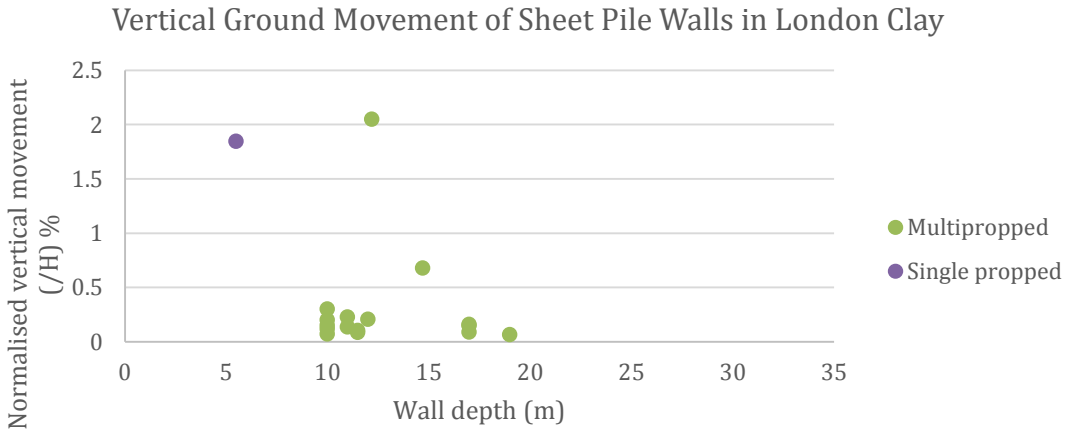

Figure 19 Vertical ground movement of sheet pile walls in London Clay

Again it is shown in the plot above that there is a large movement seen on the same case as the outlier in Figure 19. This confirms the speculation that the conditions of the site in

the case had produced such large soil movements and it does not correctly reflect the effect of multi-propped sheet piled walls in London Clay. The other large settlement in this plot is a single propped wall which also had a large lateral movement. However the nature of the support configuration makes the large deformations more feasible. It is clear that the sheet pile wall is significantly weaker at limiting soil settlements than the other wall types.

Soldier Piled Walls

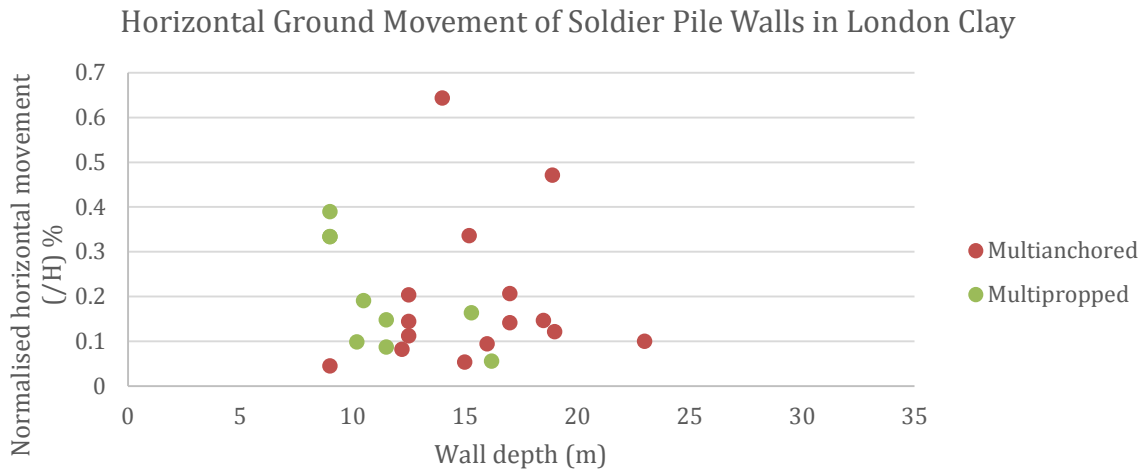

Figure 20 Horizontal ground movement of soldier pile walls in London Clay

Figure 20 shows the recorded case history horizontal movements of soldier piled walls in London Clay. It can be seen that apart from two cases of multi-anchored walls, all measurement points lie below 0.4% wall depth. This is because all the recorded data are either multi-anchored or multi-propped, which are both support configurations which are effective in limiting deflections. However, the anchored approach may allow for a larger deflection if the tip of the wall is not an anchored point.

Interestingly, all the data in the vertical ground movements of soldier piled walls in London clay lie relatively close to each other. The data points all lie within 0.15% wall depth which is remarkable considering all the other movements seen in the rest of the plots. The fact that all data points in Figure 21 are of the reliable multi-anchored and multi-propped is a major reason for the consistent and small settlement. It should also be noted that the vertical deflections of the multi-anchored walls are no longer larger than the ones for multi-propped walls as it was when the lateral movements were considered.

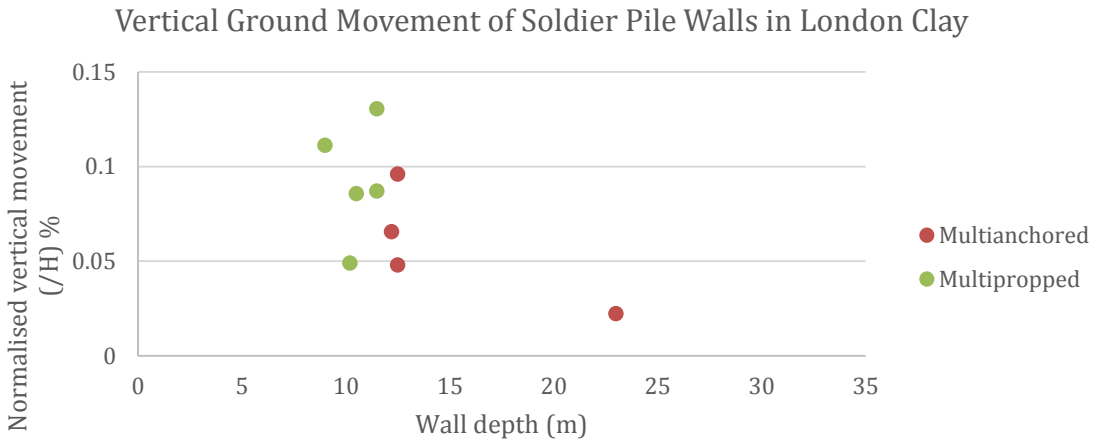

Figure 21 Vertical ground movement of soldier pile walls in London Clay

Other Wall Types

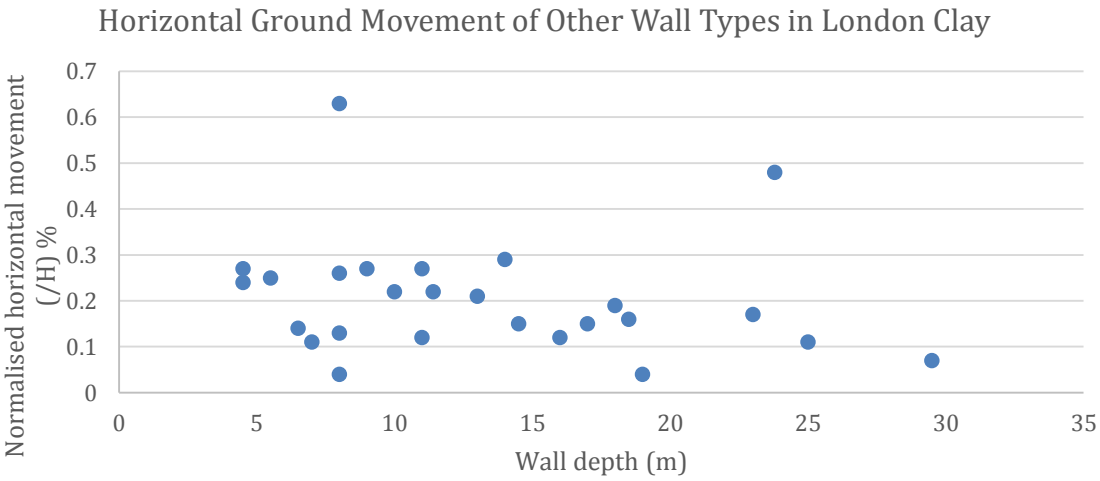

Figure 22 Horizontal ground movement of other wall types in London Clay

Some of the data collected from the literature review did not include vertical movements, nor did they include information about the type of wall used and the support configuration that was used to construct it. These data points are displayed in Figure 22. Most of the data displayed show small lateral movements with the exception of two which lie between 0.45 – 0.65% of wall depth. From previous trends, it can be estimated that these two data points could be cantilever walls unless their large movements were due to construction obstructions.

Sand/Gravel

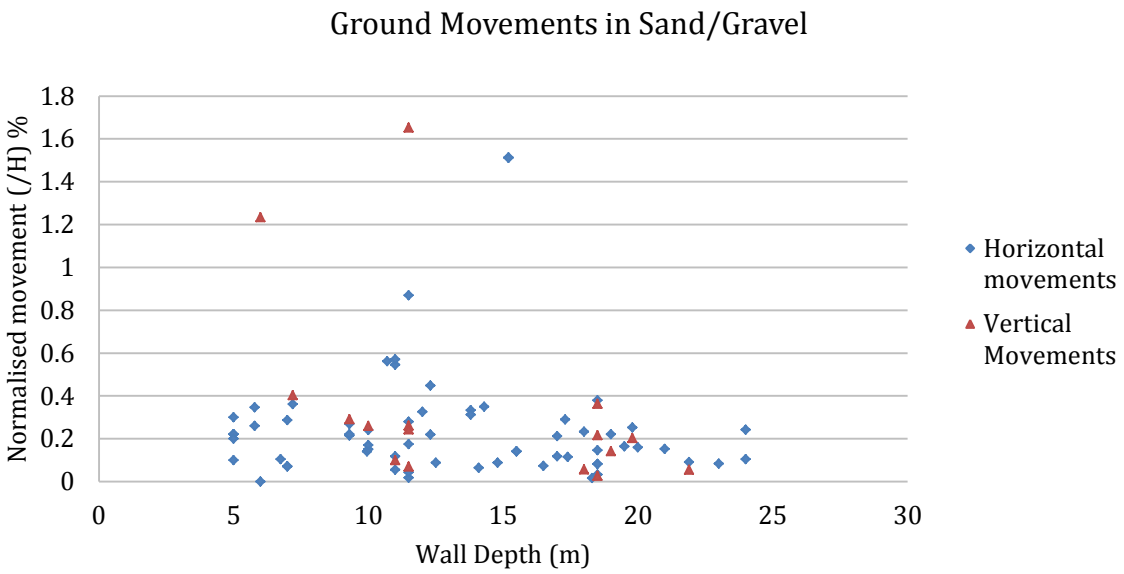

Figure 23 Ground movements in sand/gravel

Figure 23 displays the data relevant to the ground movements observed in sand/gravel. Similarly, it is clear that more detailed analysis can only be performed with a further classification of the results. The data is presented in similar fashion to the data concerned with London Clay.

Contiguous Pile Walls

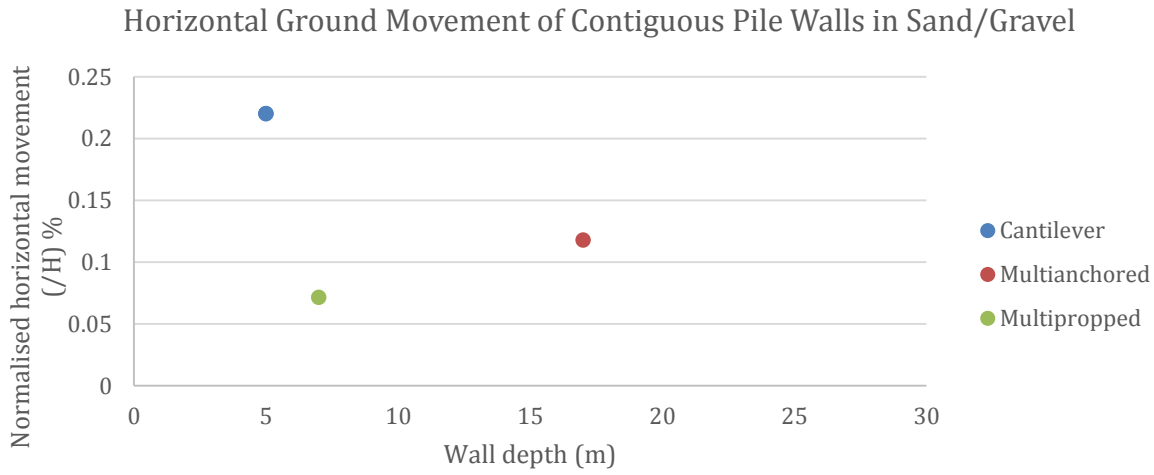

Figure 24 Horizontal ground movement of contiguous pile walls in sand/gravel

There is limited data on the horizontal movements of contiguous walls in sand and gravel and what is available is displayed in Figure 24. Although there are only 3 data points, it is evident that the cantilever wall has the largest lateral deflections followed by the multi-anchored walls which is in turn followed by the multi-propped walls. However, the deflections of the wall are ultimately governed by the conditions of the site and also the placement and number of props and anchors on the multi-propped and multi-anchored walls. It should also be noted that the movements recorded are small, with all data points below 0.25% of wall depth

No relevant case history data on the settlements of contiguous piled walls in sand/gravel are found and therefore the plot will be omitted.

Diaphragm Walls

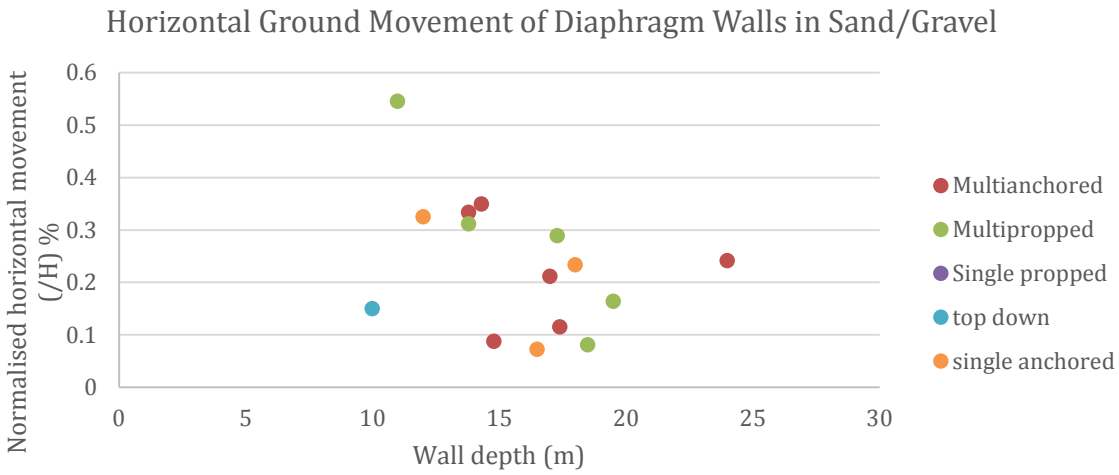

Figure 25 Horizontal ground movement of diaphragm walls in sand/gravel

The horizontal movements of diaphragm walls are shown in Figure 25. The data points are consistent, with only a multi-propped case at 0.55% wall depth. Although this value is not extremely high, it is almost twice as high as the bulk of the data. This multi-propped has a shallow depth, which suggests that the reason of the large horizontal deflection of the wall is due to the placement and number of props. If this is not the case then the large movement could possibly be traced back to construction obstructions in the site.

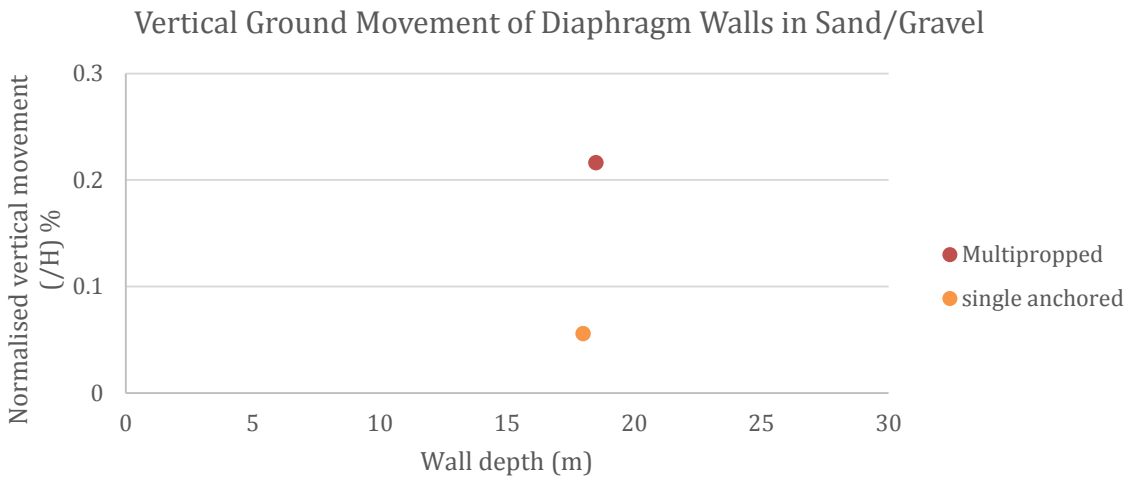

Figure 26 Vertical ground movement of diaphragm walls in sand/gravel

There is limited data available for the ground settlement for diaphragm wall sin sand and gravel. Only two relevant case histories were compiled into the database and are now displayed in Figure 26. Not much can be deduced from the lack of data points, but it is noted that the unexpected magnitude of the multi-propped wall when compared to the single anchored could be due to the placement and number of props or construction obstructions at the site.

Secant Piled Walls

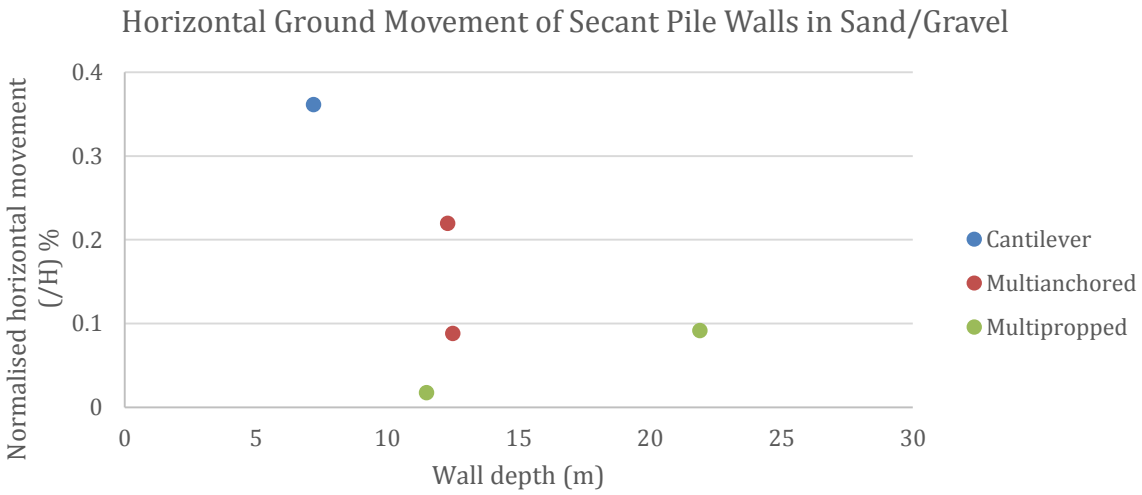

Figure 27 Horizontal ground movement of secant pile walls in sand/gravel

Again secant piled walls show good resistance against deflections and therefore the observed movements are small when compared to the other wall types with all data points below 0.4% of wall depth. Despite the lack of data as shown in Figure 27, it is still obvious that the cantilever wall is able to produce the largest lateral movement due to the nature of the support configuration.

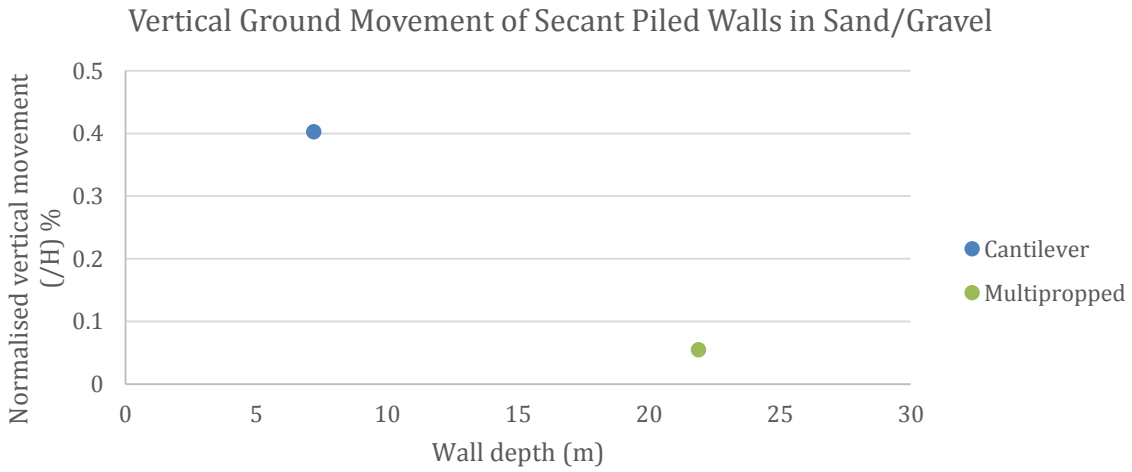

Figure 28 Vertical ground movement of secant pile walls in sand/gravel

There were only 2 relevant case histories available for the settlement of secant piled walls in sand/gravel, and they are shown in Figure 28. The settlement magnitude remains low due to the strength of secant pile walls

Sheet Piled Walls

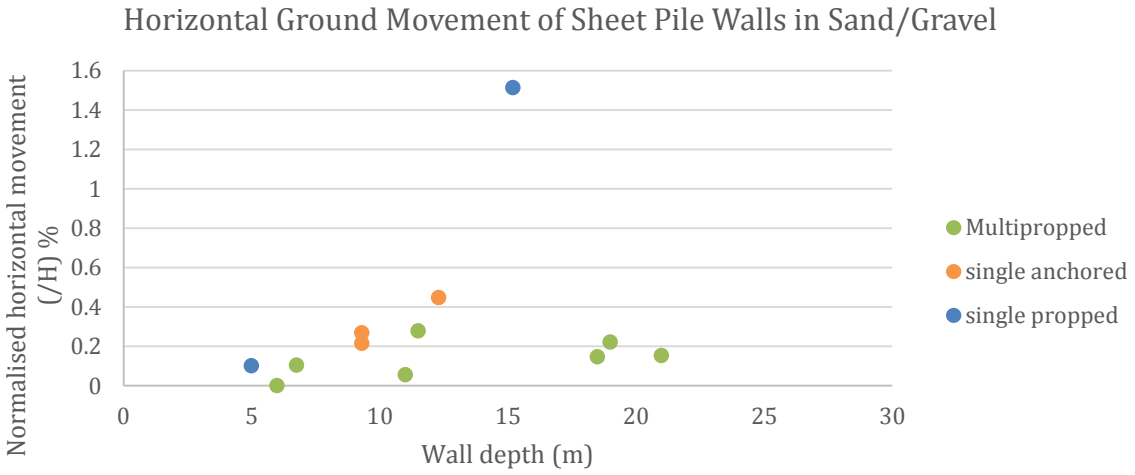

Figure 29 Horizontal ground movement of sheet pile walls in sand/gravel

Figure 29 shows the horizontal movement of the sheet piled walls in sand and gravel, and it is seen that the general lateral movement is around 0.3% of wall depth. However, an outlier lies at 1.5% of wall depth which is extremely high considering the positions of the rest of the data. This large difference is most probably due to a construction problem or condition that has led to large deformations of the soil, as the wall depth of that case is not particularly deep and there are no other obvious reasons for the lateral movements to be so high.

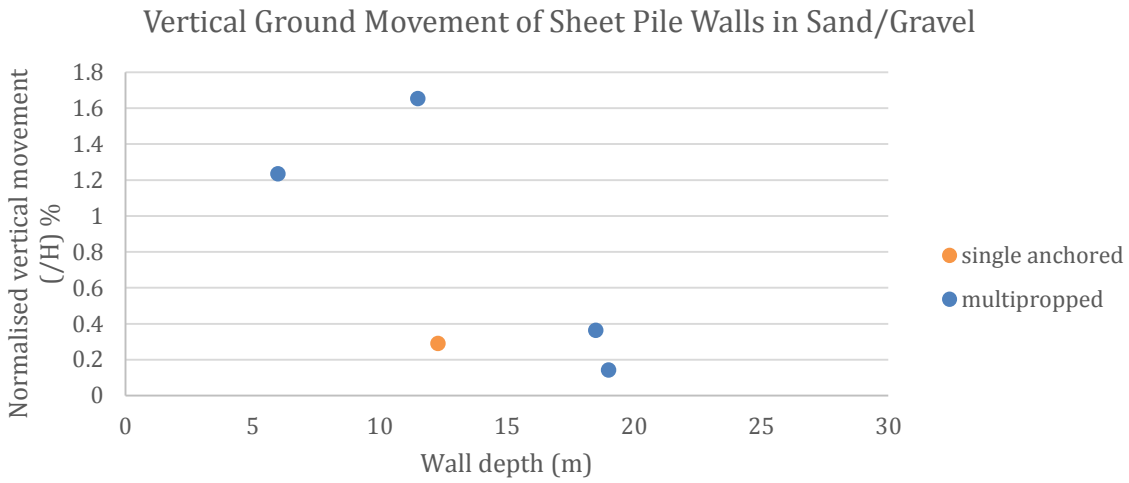

Figure 30 Vertical movement of sheet pile walls in sand/gravel

Once again, it is apparent that sheet pile walls are weak at limiting vertical ground movements. Two out of five data points shown in Figure 30 are over 1.2% of wall depth, which is a significant movement that should not be ignored. This magnitude of movement has not been observed in sand/gravel other wall types which highlights the inadequacy of sheet piled walls where large movements are expected.

Soldier Piled Walls

Figure 31 shows the lateral movements of soldier piled walls in sand and gravel. It is clear that most of the data points are fairly consistent at the lower regions of the plot with a maximum settlement of 0.33% of wall depth. However, as stated previously, cantilever walls can produce large lateral deformations due to the lack of props and therefore lack of restraint to wall deflections. Therefore, it can be observed that a case involving a cantilever has become an outlier in the plot with a movement of almost 0.9% of wall depth.

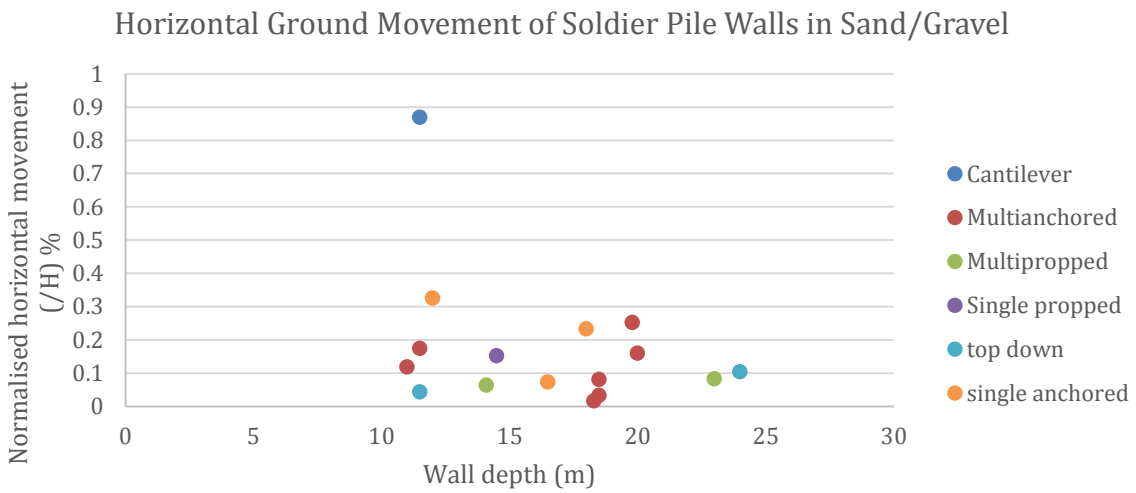

Figure 31 Horizontal ground movement of soldier pile walls in sand/gravel

As shown in Figure 32, the settlements of the soldier piled walls are in fact much more consistent and much smaller than the lateral movements. This implies that the large horizontal movements seen could be simply due to the influence of other construction problems instead of the effects of the wall type and support configuration.

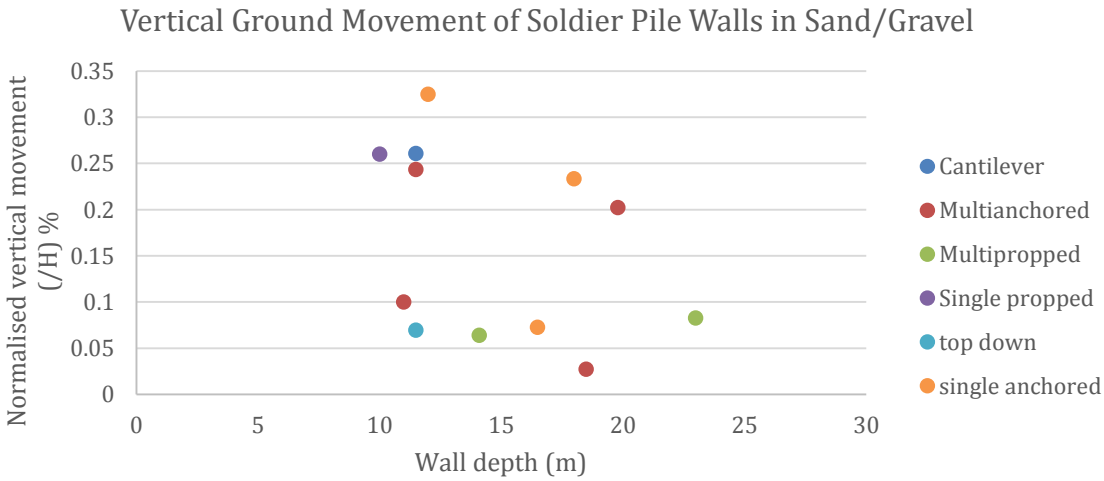

Figure 32 Vertical ground movements of soldier pile walls in sand/gravel

Other Wall Types

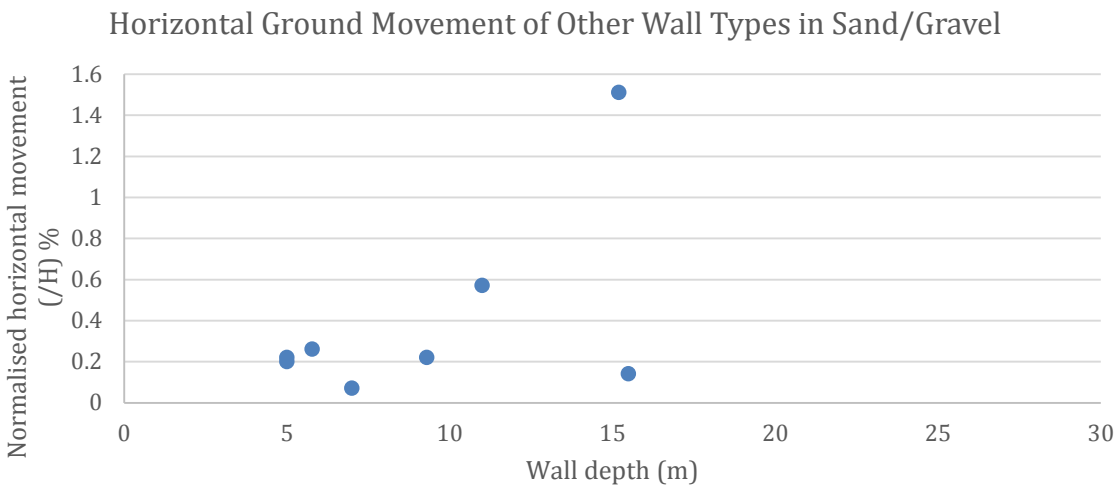

Figure 33 Horizontal ground movement of other wall types in sand/gravel

The data that did not include vertical movements, wall types and support configurations are displayed in Figure 33. From observing, it is clear that an outlier is present as the other data are fairly consistently below 0.6% of wall depth. The high lateral movements could be due to a variety of reasons ranging from a deep cantilever wall to construction obstructions.

Soft Clays

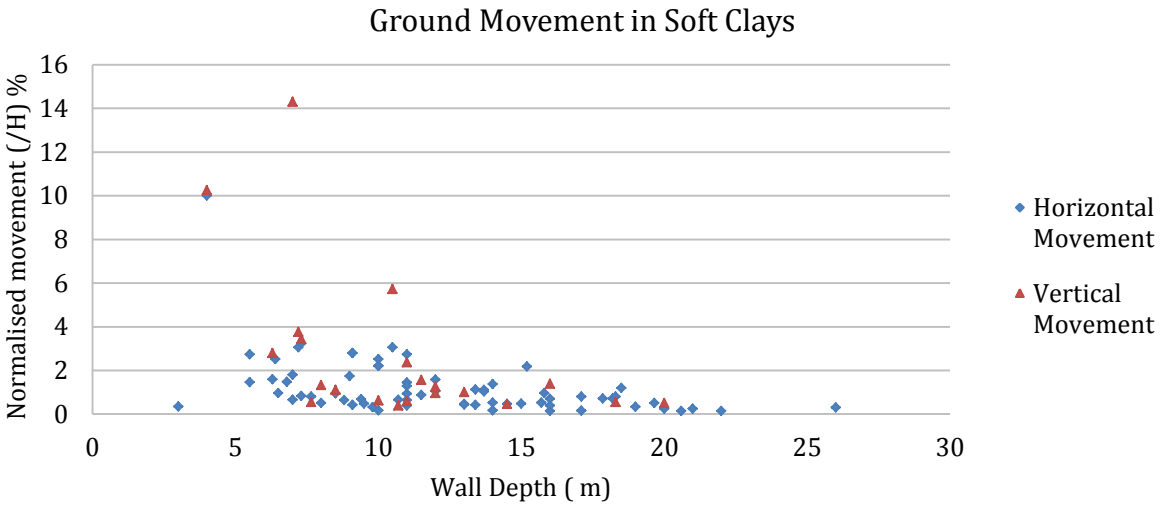

Figure 34 Ground movements in soft clays

Figure 34 shows the ground movements in soft clays. The results are yet again categorized into wall types and support configurations to be able to see trends clearly and aid analysis.

Diaphragm Walls

Figure 35 displays the horizontal movement of diaphragm walls in soft clay. Immediately the difference of the general magnitudes of the movements when compared to other soils are noticeable. However, this is expected as soft clays will inevitably have a lower resistance to soil movements. Large movements are seen in a multi-propped wall, possibly due to inadequate positioning of props. The number of props will also affect the magnitude of deflection observed.

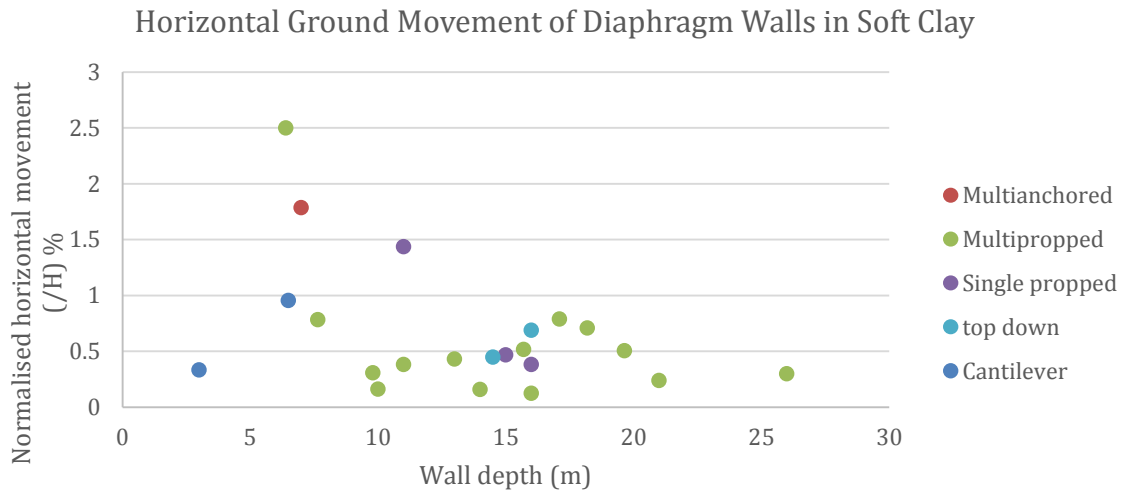

Figure 35 Horizontal ground movement of diaphragm walls in soft clay

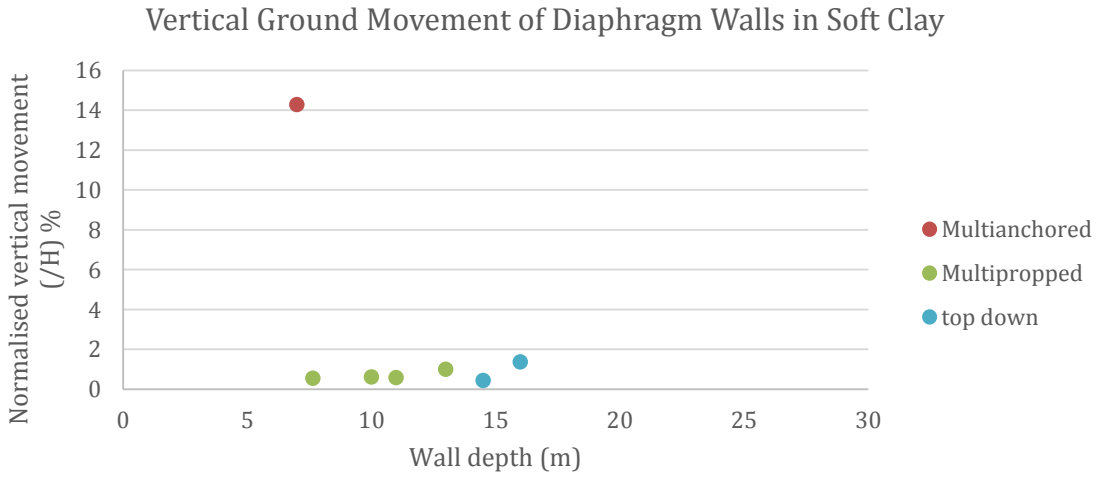

Figure 36 Vertical ground movement of secant pile walls in soft clay

An outlier is seen in Figure 36, and its magnitude exceeds the rest of the data points by over ten times. This is almost certainly due to a construction obstruction where the instrumentation

experiences excess settlement as the other data points behave otherwise. Inadequate positioning of anchors is unlikely to cause a settlement ten times larger than other cases.

Sheet Piled Walls

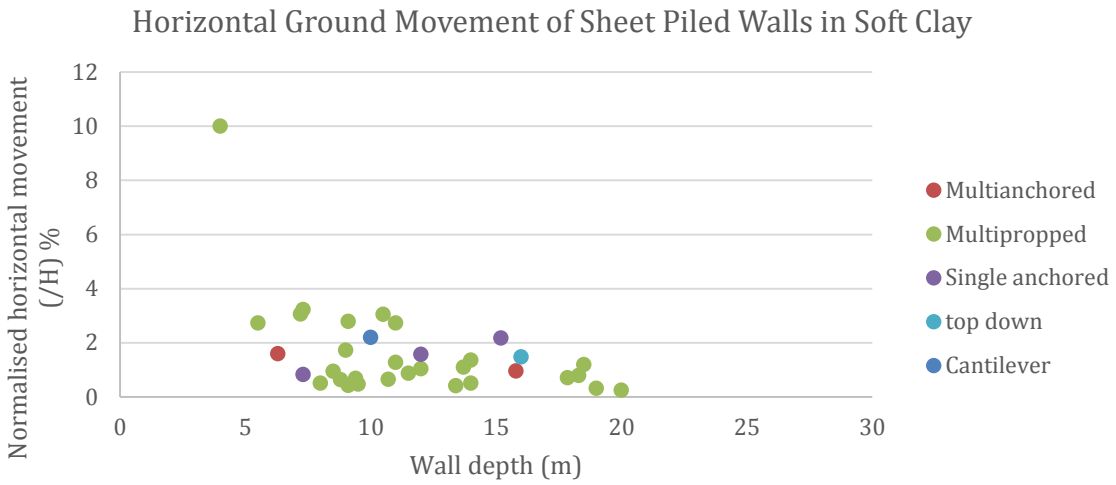

Figure 37 Horizontal ground movement of sheet pile walls in soft clay

Figure 37 shows the lateral soil movements when deep excavations are made using sheet piled walls in soft clay. As expected, the ground movements are large compared to other soil types. The data points are consistent once again except from an outlier at 10% of wall depth. This again is most likely to be due to construction obstructions as the consistency of the other data suggest that the large deflections are abnormal for sheet pile walls in soft clay.

Figure 38 shows the settlement of the sheet piled walls in soft clay. The data is less consistent, with a larger spread towards higher values of vertical movement. Only two cases have settlements of over 5% of wall depth, suggesting that the workmanship and the design of the props in those two multi-propped wall cases have a significant influence on the settlements observed.

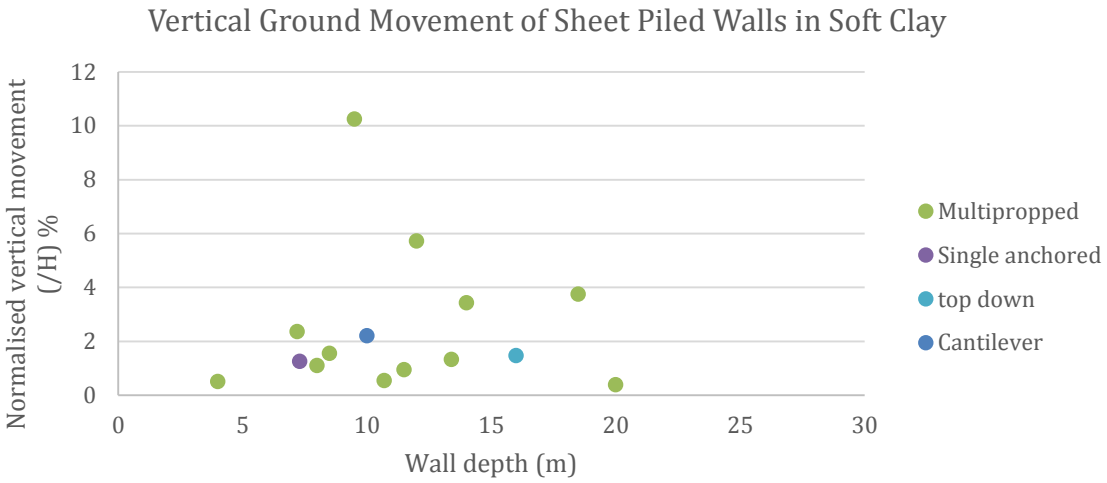

Figure 38 Vertical ground movement of sheet pile walls in soft clay

Other Wall Types

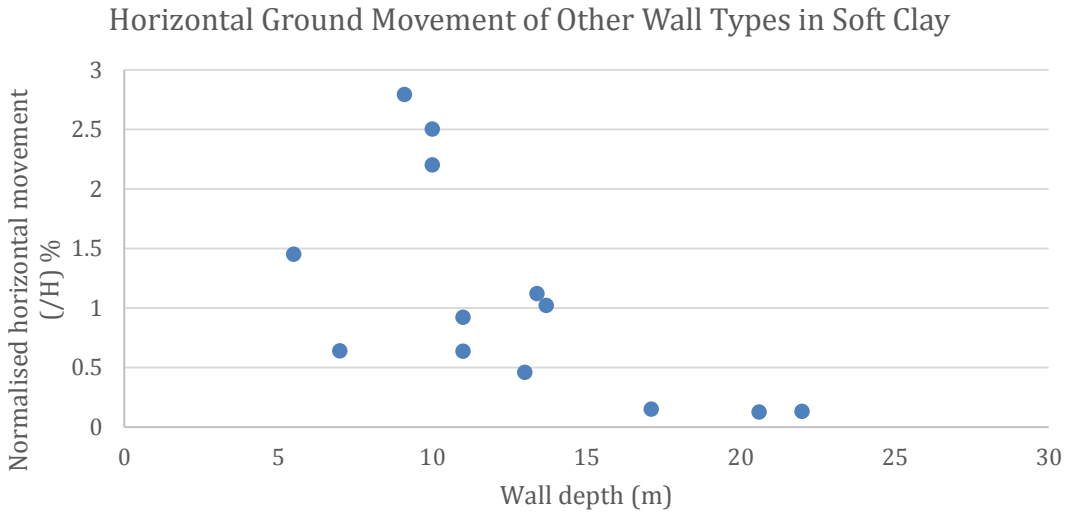

Figure 39 Horizontal ground movement of other wall types in soft clay

The data that did not include vertical soil movements, wall types and support configurations are displayed in Figure 39. The trends and magnitudes that are seen are similar to the results from the diaphragm wall, with a lack of large horizontal movements as seen from the sheet piled walls. The data is fairly consistent however not much analysis could be made due to the lack of information.

Case Studies: Wall Installation Effects

In the past, there have been many case history data for deep excavation effects as presented in the previous section, but there has been a low abundance of data concerning the effects of wall installation. Some relevant data has been collected so that a brief comparison could be made to the effects from deep excavations.

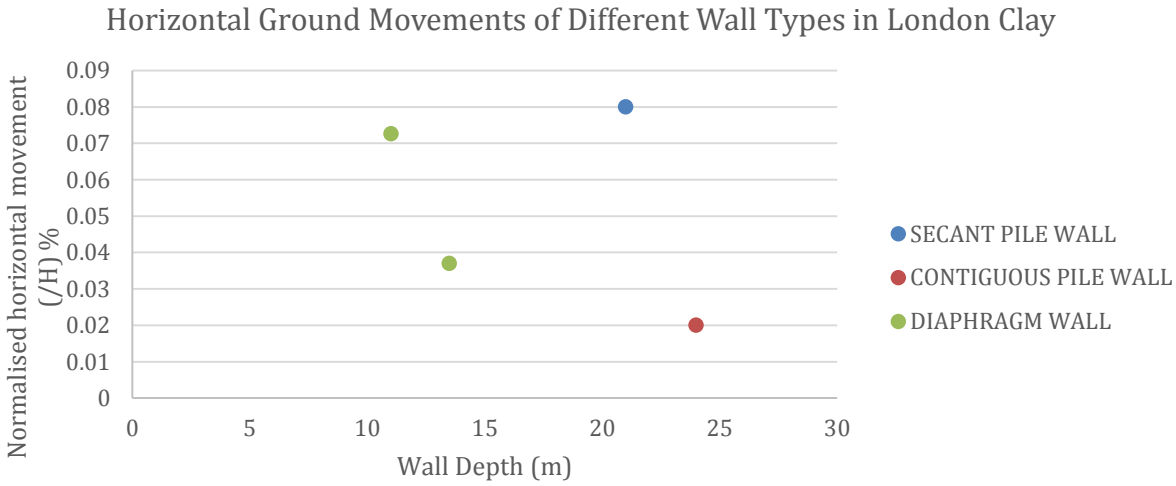

Figure 40 Horizontal movements of different wall types in London Clay

Figure 40 shows the relevant case history data on the effects of installation of embedded retaining walls from Carder (1997). However, there is limited data in this field, highlighting the importance and benefits the recent data from Crossrail will bring towards understanding this sector of ground movement sources. It can be seen that the maximum recorded lateral movement lies within 0.1% of the wall depth, which is 45% of the average horizontal movement seen in the effects of deep excavation.

To obtain a more unbiased grasp of the significance of wall installation effects, the diaphragm wall and contiguous wall movements are also analysed. An average of the two diaphragm wall cases gives a horizontal movement of 0.055%, which is 23.1% of the average value of horizontal movements seen in an excavation using a diaphragm wall (0.239% of wall depth) as shown in Figure 14. The effects of wall installation in a contiguous piled wall case only takes up 11.6% of the effects seen by a deep excavation (referring to Figure 12).

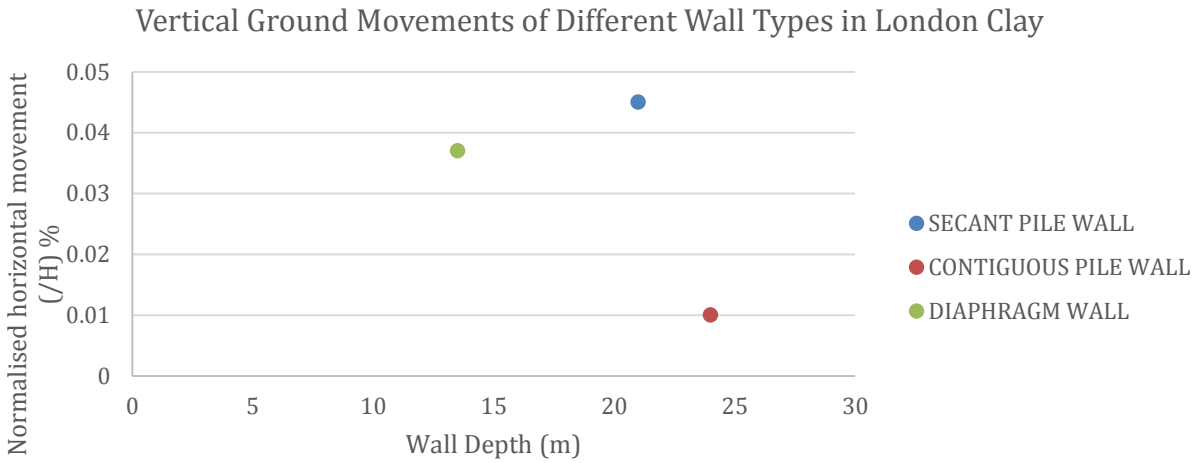

Figure 41 Vertical ground movements of different wall types in London Clay

Similarly the results of vertical movements are shown in Figure 41. For the secant pile wall, the settlement seen in wall installation is 0.045% of wall depth, which is 25.4% of the settlements caused by the entire excavation. The installation of contiguous pile wall takes up merely 9% of the total settlement caused by excavation. The settlements caused by the installation effects of a diaphragm wall take up 15.3% of the averaged total settlement caused by the entire excavation that is displayed in Figure 15.

It can be seen from the mean of the two values that as an average the effects of wall installation take up around 20% of the total ground settlement from an excavation. However, it should be noted that the data for wall installation effects is limited and focused on London Clay, and so the influence of wall installations in other soil types could not be analysed.

Farringdon Data Analysis

The construction at Farringdon stems from the project where CROSSRAIL LTD is responsible of promoting and completing a new railway through central London from Maidenhead and Heathrow via Paddington, Liverpool Street and Stratford to Shenfield, and via Canary Wharf to Woolwich ending at Abbey Wood[15]. Farringdon station is split into two regions- the East Ticket Hall (ETH) and the West Ticket Hall (WTH) as displayed in Figure 42. In this report only data from the ETH will be considered. The ETH of Farringdon station is located in the block between Charterhouse Street, Lindsey Street, Long Lane and Haynes Street. The construction site includes a shaft that extends to the platform level of the station

and another to the level of the existing London Underground line. Both these shafts will be constructed with the use of secant pile walls as shown in Figure 43, and it is the focus of this project to investigate the effects that the installation of these piles imposes on soil settlement in the region.

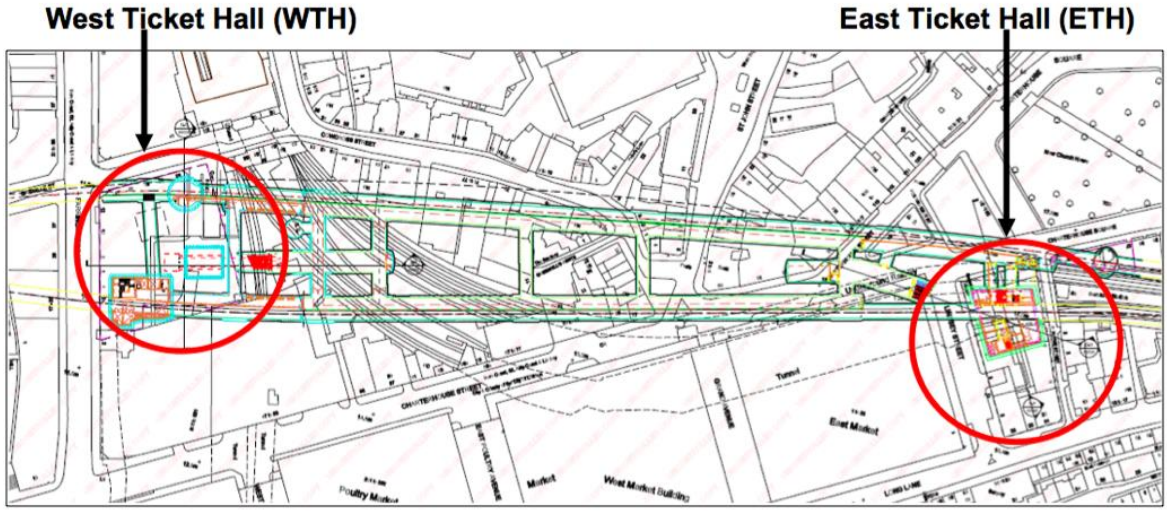

Figure 42 Farringdon Station WTH and ETH

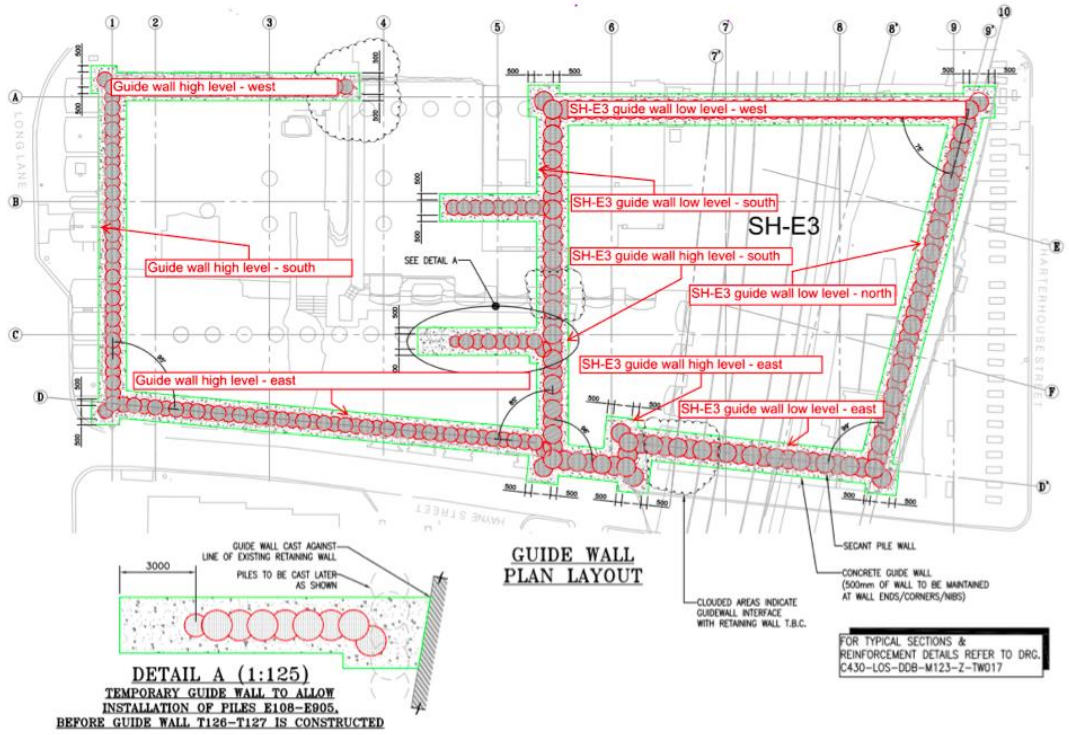

Figure 43 Plan view of the ETH

The data for settlement at the ETH was with the use of brass levelling studs located at numerous locations on both sides of the pavement of the streets that surround the ETH. Crossrail control was used as a reference datum and highly accurate barcode staffs were used

to measure the settlement of the brass leveling studs daily to produce a logbook of results[15]. However, it should be noted that only the settlements of the ETH have been recorded without information on the lateral movements. Therefore the analysis made in this report will focus on the effects on the vertical movement by the installation of secant pile walls.

The ground settlement measuring points are located on certain areas on both sides of the streets that surround the Farringdon Station, with the exception of Charterhouse Street where no measuring has been done. However, it is not relevant to analyse all of the data points available due to positional problems. The majority of measuring points are either too far away from the piling works at the station or under the influence of too many different sources that affect the ground settlement readings. Another major consideration when selecting data points for analysis is the availability of another that can align with a pile linearly for linear interpolation. Considering these factors, four areas with a sum of 24 measuring points in total have been selected as points of concern for this part of the analysis. The selected pairs of measuring points are shown in their corresponding areas in Figure 44.

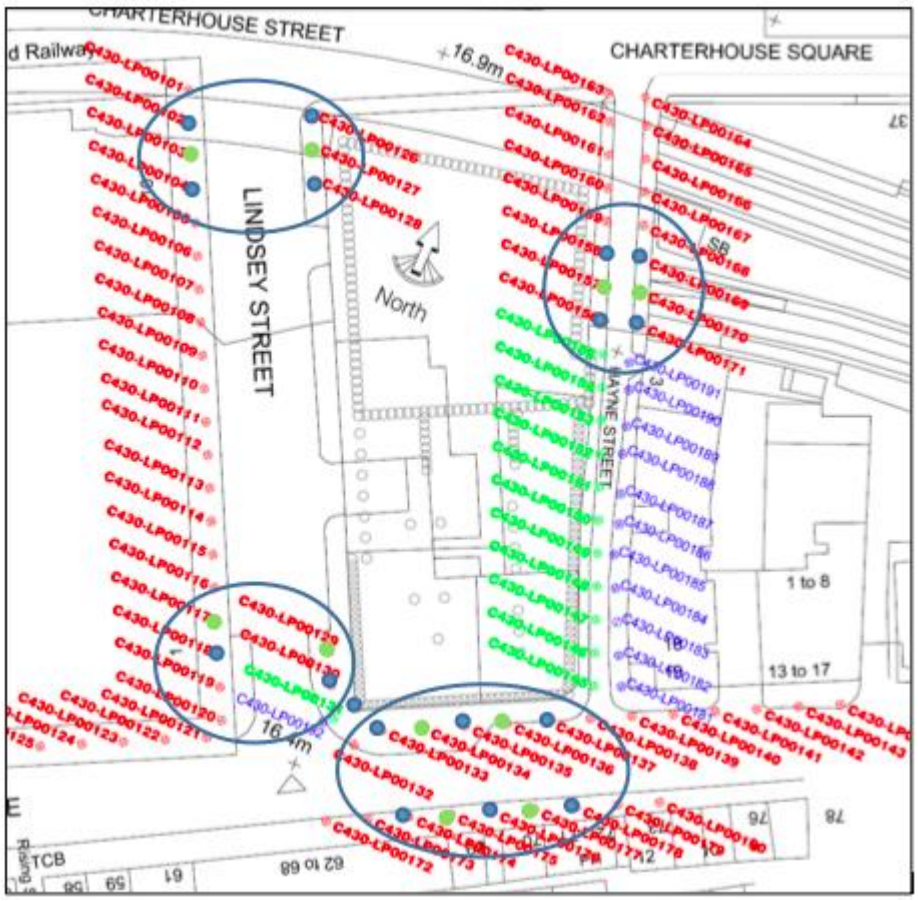

Figure 44 Location of selected measuring points around construction site

Settlement of measuring point locations

The plots of the ground settlement of these measurement points with respect to time is then produced for analysis by comparing to the piling schedules of the site. For better comparison, the plots of the measured settlements from each side of the streets in their respective areas are displayed together.

North Haynes Street

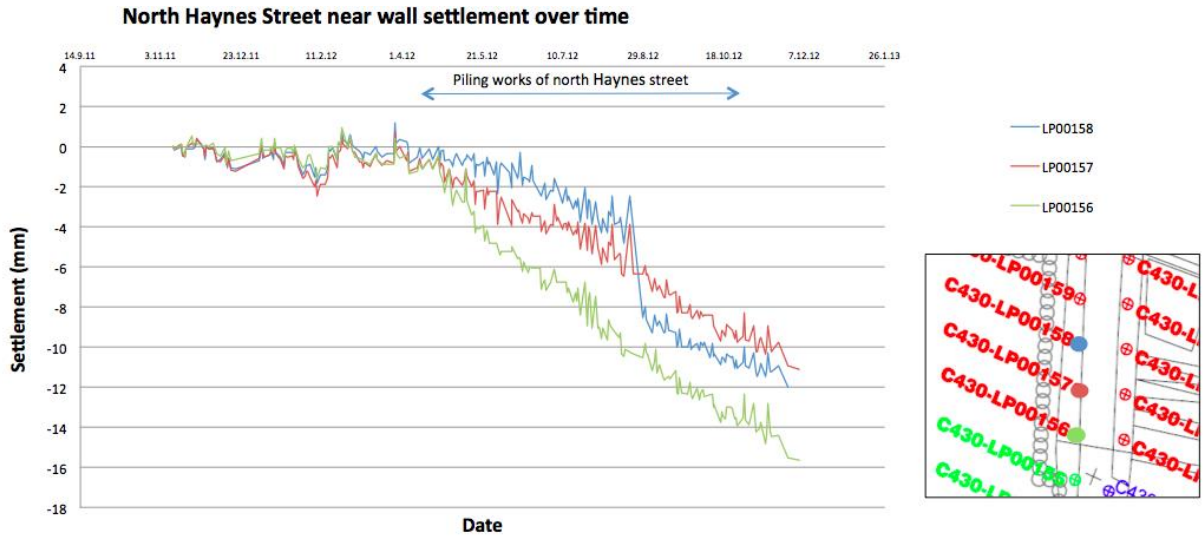

Figure 45 North Haynes Street near wall settlement over time

The piling works that correspond to the ground movements shown in the Northern region of Haynes Street lasted from April through to mid-October 2012 as shown in Figure 45. Unsurprisingly we are able to see that the ground settlements in the three measuring points react accordingly as the soil starts to settle as soon as the pile installation initiates in April. The trend is linear throughout the time the construction works take place, however the gradients of the ground settlements at the three measuring locations differ slightly.

As shown from Figure 45, there is an unusually large drop in the settlement of LP00158 at around August. It can be seen that the gradient of the settlement before and after the drop is constant and that this appearance of a drop of this magnitude is only seen on that one instance, suggesting that the observed offset of the curve is unique. This drop could be

due to an instrumental/human error in the reading, or a separate affect that is not felt by the two adjacent measuring points. The possibility of the drop being an instrumental/reading error is ruled out by the method of instrumentation and the characteristics of the drop. The technique used for leveling involved brass leveling studs and Barcode staffs where it would be unlikely that a reading error could produce the characteristics of the graph. The readings after the drop should return to normal if the drop was simply an anomalous reading produced by instrumental/human error. The current graph shows that the offset of the drop remains throughout the rest of the duration of the construction, suggesting the soil at that point has in fact settled by 6mm.

In light of this effect, the offset of the latter part of LP00158 will be ignored for ease of data interpretation. The trend of the difference in gradients amongst the three measuring points results in measurement point LP00156 having the largest settlement (14mm) followed by LP00157 (10mm), which is in turn followed by CP00158 (5mm). This increase in settlement gradient as the distance to the centre of the site suggests that another source of ground movement is present and that the measuring points closer to the centre of the site are more influenced.

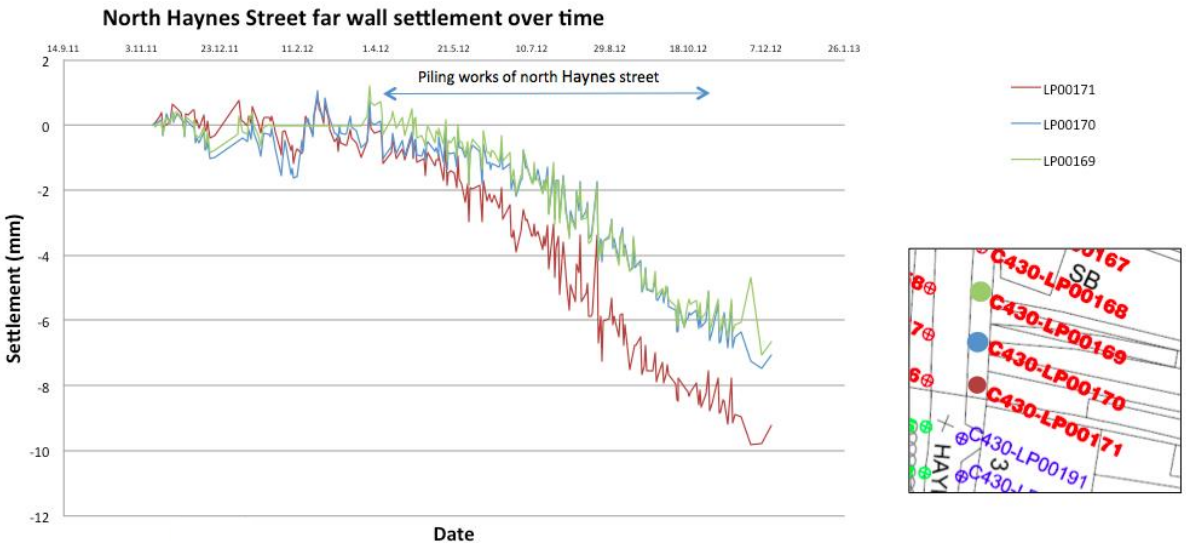

Figure 46 North Haynes Street far wall settlement over time

Displayed in Figure 46, the data set of the measuring points across Haynes Street show that the settlement with time is largely linear. Again it is apparent that the gradient of the settlement of the southmost measuring point is significantly steeper than the rest. This difference is due to the influence of other construction works near the site that is sourced

closer to LP00171 than the other points. It is also interesting that the measured settlement of LP00169 and LP00170 are so similar in the measured time period. This differs from the near wall measurements as there is no offset between the two measuring points, suggesting that the zone of influence of the alternate source does not reach the location of LP00169 and LP00170. The maximum settlements of the measuring points are 6mm for LP00169 and LP00170, and 9mm for LP00171.

North Lindsey Street

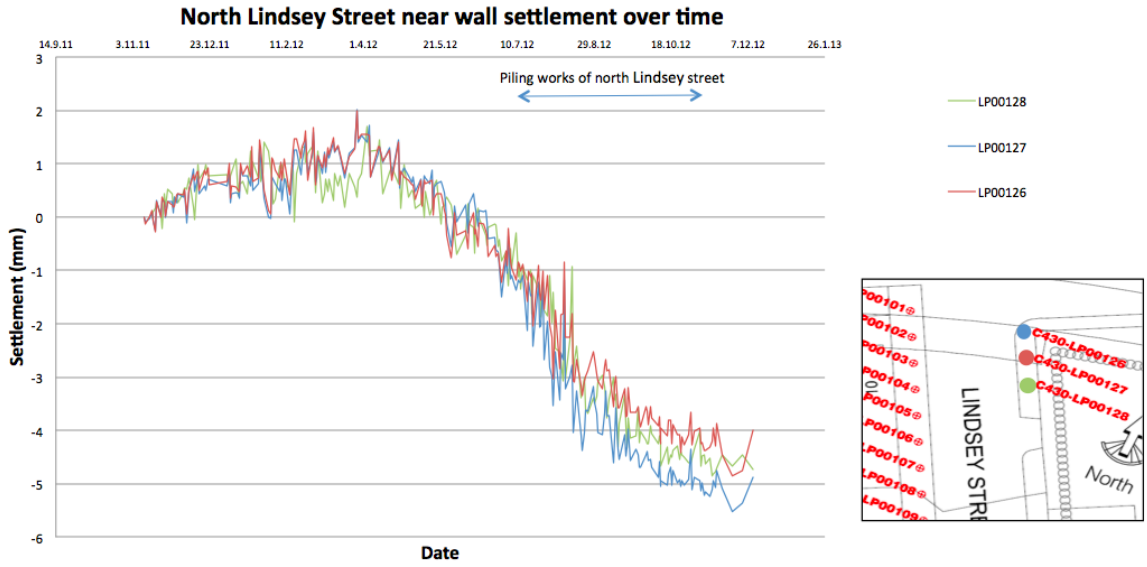

Figure 47 North Lindsey Street near wall settlement over time

The settlements of the near wall measuring points on North Lindsey Street are displayed in Figure 47. It can be seen that the settlements at these three points are in fact very similar, with all three data lines overlapping each other until the end of August where the settlements begin to diverge. It can also be seen that the settlement gradient of all three measuring points have a sudden increase in steepness during July. This fits in well with the data from the piling schedule as this sudden increase in gradient occurs during the installation of the piles closest to the measuring points. The small difference in gradient and magnitude of this set of data suggests that the influence of other construction works is minimal, implying a good representation of the ground settlement effects due to pile installation only. The maximum settlements of the three measuring points are very similar and take the value of around 5mm, which is a rather small settlement when compared to the settlements seen in North Haynes Street. Again this suggests that the effect of other construction works that influenced the

settlement in Haynes Street is not present or of only a small influence, which is beneficial for the purposes of analysing the effects of pile installation.

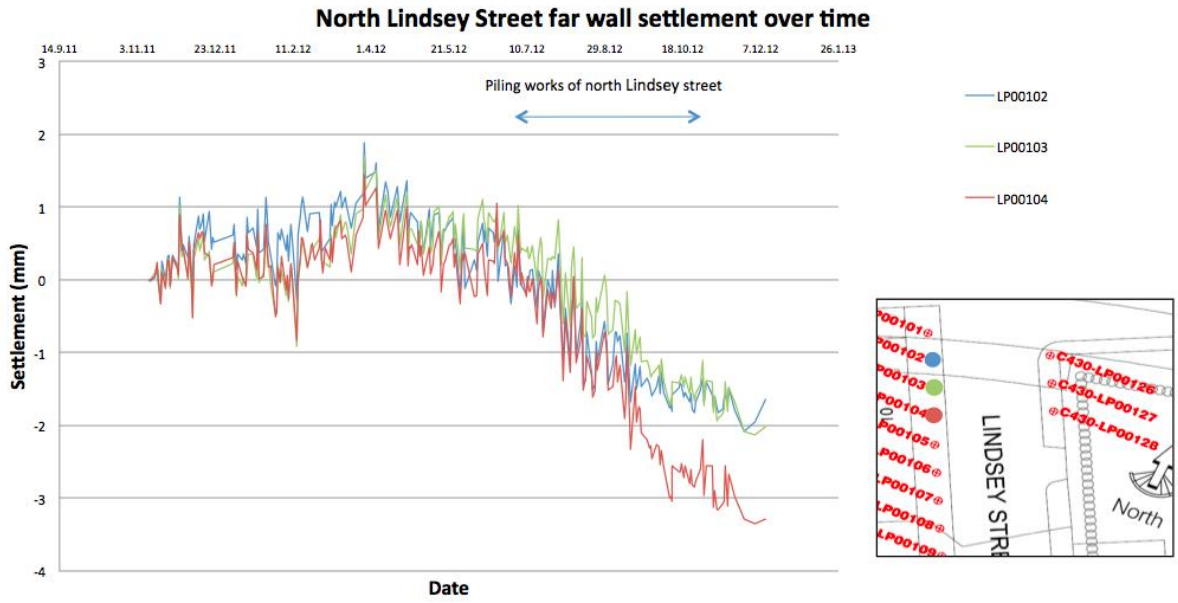

Figure 48 North Lindsey Street far wall settlement over time

Figure 48 displays the settlement of the three measuring points across the street from the piles at North Lindsey Street. Again it can be seen that the settlements of the three points are very similar with lots of overlaps until the end of August where LP00104 has a much steeper settlement gradient than the others. The consistency of the settlements diverging at the end of August on both sides of the street suggest that there may be some other works at that period of time that contributed to ground settlement at these points and that they affect the measuring points closer to the centre of the site. The maximum settlement of LP00102-104 are 1.5mm, 1.5mm and 3mm respectively, which are very small settlements compared to the results from Haynes Street. It should also be noted that the magnitude of these settlements greatly reduce the credibility of the results, as a small deviation of ground settlement readings will create a large change in the trend of the data.

South Lindsey Street

Figure 49 shows the settlement of the near wall brass leveling studs in the southern area of Lindsey Street. The period in which the piles adjacent to these points were constructed lasted for only a few months from November 2011 to March 2012, which only takes up a small portion of the time span of the monitoring. It can be seen that both

measuring points follow similar trends until July when the two data sets start to diverge, suggesting the presence of other construction works that affect ground settlement. From the trends of the two measuring points, it can be seen that the settlement is linear with time until the end of the construction of the piles near the measuring points, and the settlement remains constant for a month before continuing to grow linearly again in late May. This characteristic of the trend suggests the start of other construction works during late May that has caused the measuring points to sink again. However, effects from the initial piling may still be contributing to the ground settlement in the latter period of monitoring so the final settlement should still be considered when analysing the effects of wall installation.

The maximum settlement during the piling was 3mm for both LP00129 and LP00130, and the final settlement was 8mm and 7mm respectively. Again it is seen in Figure 49 that the measuring point closer to the centre of the site is more affected than the one further away, implying that the settlement is due to other construction works that took place in the time period of monitoring.

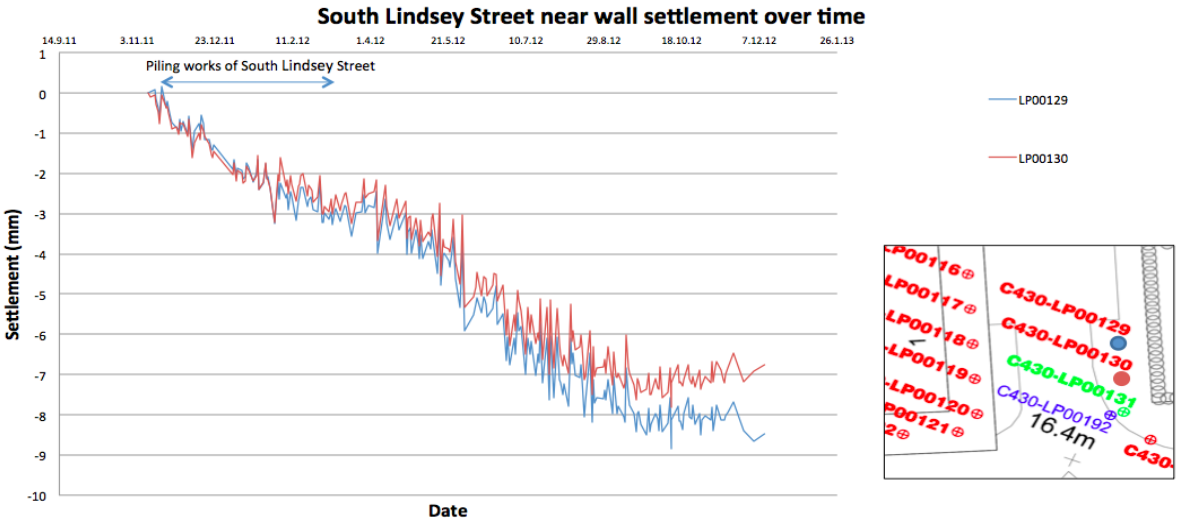

Figure 49 South Lindsey Street near wall settlement over time

The settlement of the two far wall measuring points are shown in Figure 50. It is apparent that the piling works during November to March did not cause any significant effect on the ground settlement at the monitored points. However, during late May the start of some ground settlement can be observed from the two points, suggesting that the influence of the other construction works at that time period had caused the ground settlements. This also gives an idea of the magnitude of influence in pile installation when compared with other construction works. It should also be noted that the end settlement remains very small, and that the credibility of the trends displayed in the data sets will proportionately decrease.

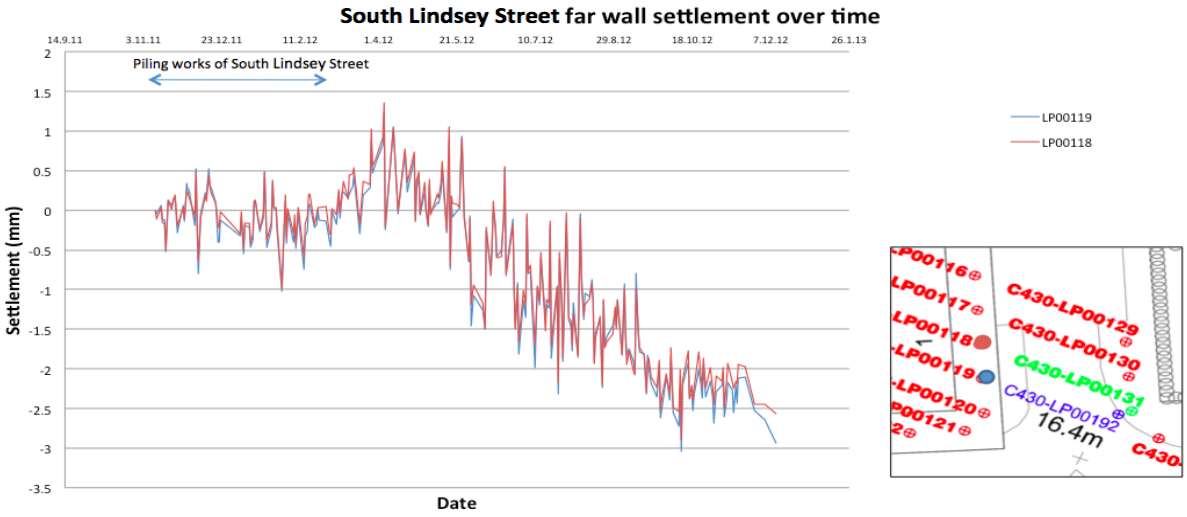

Figure 50 South Lindsey Street far wall settlement over time

Long Lane

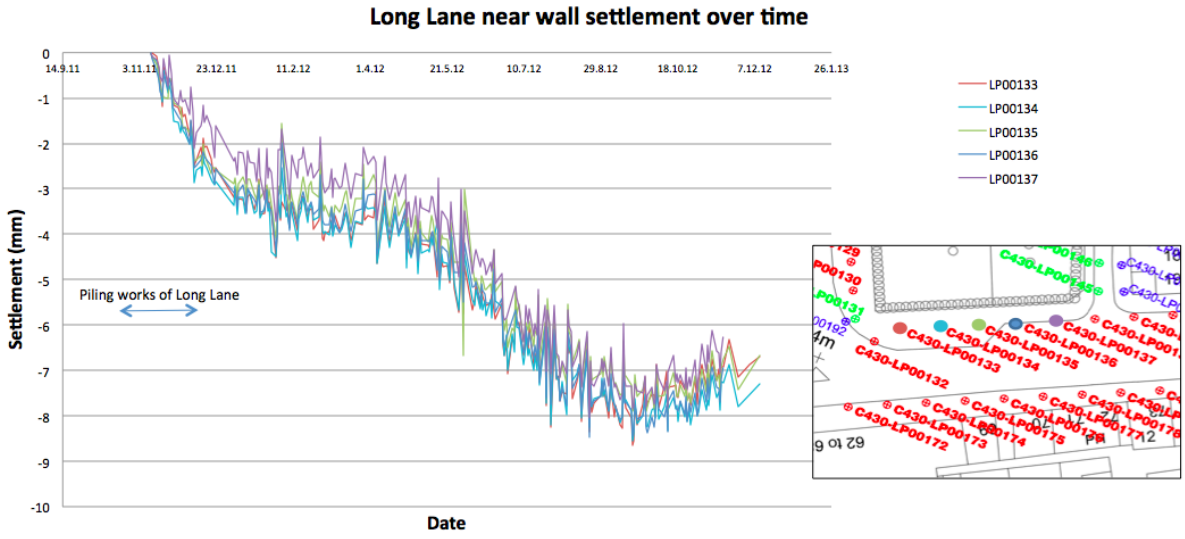

Figure 51 Long Lane near wall settlement over time

Figure 51 displays the readings from the near wall measurement points from Long Lane. The piling schedule shows that the period of pile construction is November to December of 2011. During this period of time, it can be seen that there is a settlement gradient in all 5 measuring points. However, the settlement remains constant for a period of time before the ground settles again late May. This again suggests that the latter part of the settlement shown in Figure 51 is influenced by construction works apart from the initial pile installation. All the measuring points show similar settlements with only LP00137 showing slightly less settlement at all times, possibly due to its further distance away from the construction

activities. Again it can be seen that the effects of pile installation on ground movement is small compared to other construction works.

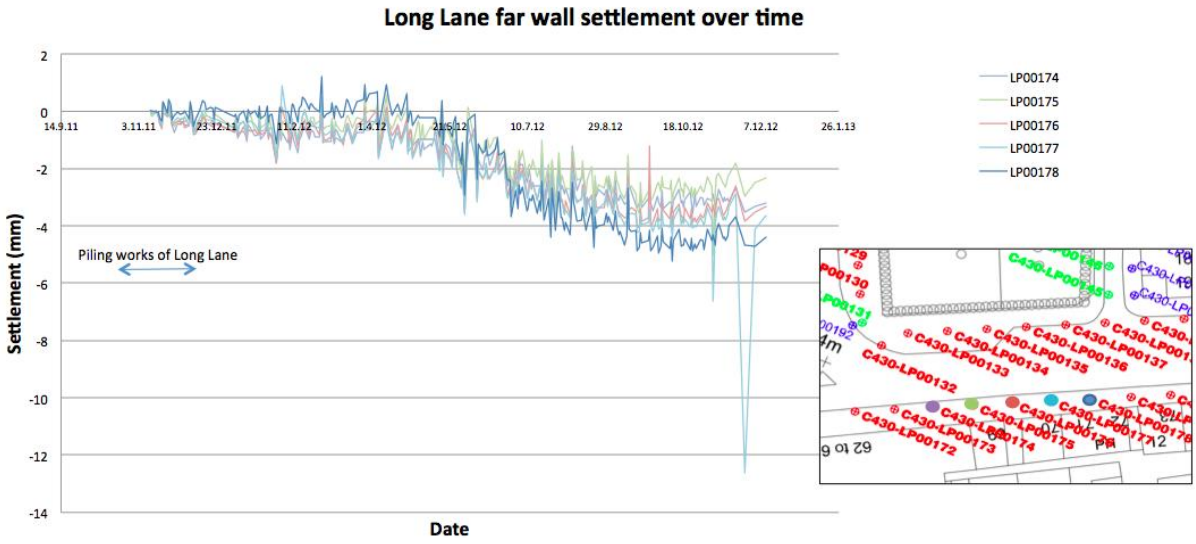

Figure 52 Long lane far wall settlement over time

The plot shown in Figure 52 displays the ground settlement of the far wall measuring points at Long Lane. The general settlements are much smaller than the ones near wall as expected. However LP00178, which corresponds as a pair to LP00137, exhibits the largest settlement amongst its group while LP00137 had the least settlement amongst its group. This could simply be due to the minor differences in the soil at different points that makes each point's susceptibility to settlement different. During the time of the piling works the settlement is negligible and yet again the ground settlement commences during late May. The sudden drop in reading in the start of December is considered to be an anomaly considering the magnitude and the single occurrence of the rogue reading. This may be due to human error during the measurement of the point or during the input of the data.

Surface Settlements at the Wall and Distances to negligible settlement

Apart from the magnitude and trends of settlements, it is also critical to understand the zone of influence of the ground movements. Good understanding of the distance away from the piling until there is negligible settlement will allow appropriate measures to be taken, thus protecting structures, construction equipment and staff. Using the data obtained

from the Farringdon Station construction site, simple linear interpolation could be performed to find out the distance to negligible movement and the ground movement at the wall surface. As data concerning the settlements of both sides of the streets surrounding the Farringdon station are available, it is possible to estimate the distance to negligible movement by measuring the distances between the piling works and the two measuring points when aligned to an axis. The fact that the data is largely linear and that the maximum settlements of the measured points mostly lie within October also implies that using the maximum settlements for both sides of the road for the calculations in linear interpolation is legitimate.

North Haynes Street

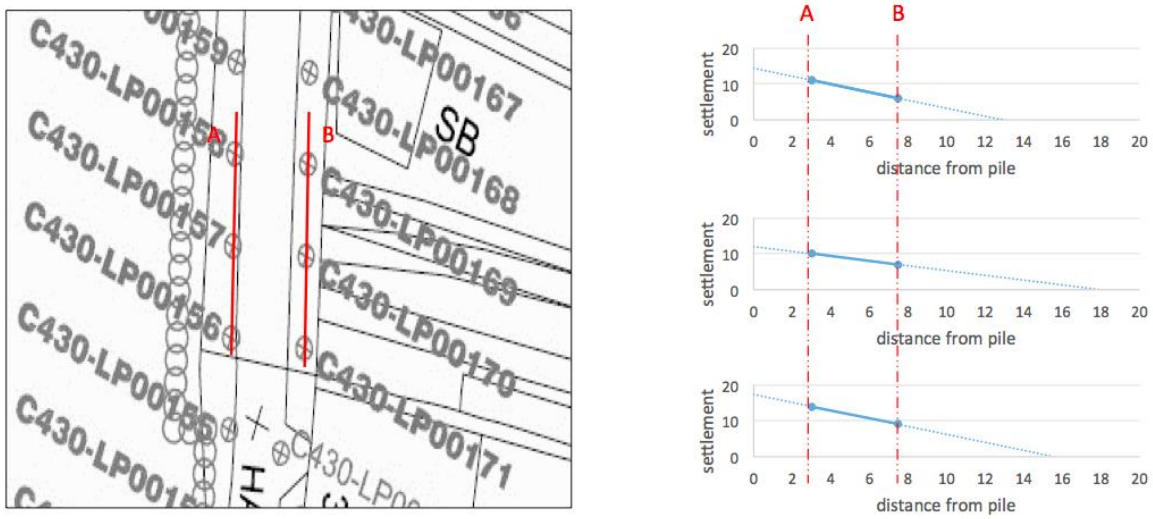

Figure 53 Linear interpolation for North Haynes Street

Figure 53 shows the results of the linear interpolation using the maximum settlements from the three pairs of measuring points in North Haynes Street. As displayed, the pair of measurements which is located in between the other pairs gave the furthest distance to negligible settlement. This suggests that the effects of the other construction works located in the centre of the site do not have a significant effect on the zone of influence. Although LP00156 - LP00171, have higher settlements on both measured points, the gradient of the settlement with distance is steeper than LP00157-LP00169 and therefore results with a shorter distance. The interpolated distance for the three pairs are 13mm, 18mm and 16mm, respectively from north to south, averaging to give a distance to negligible settlement of 15.7mm. The predictions in C580 suggest that the distance to negligible movement is 2 times

the wall depth, which equates to 66m. This estimate exceeds the actual distance by an alarming 50m, with implications that the empirical formula in C580 is inappropriate for recent works.

At a distance of 0, the settlement corresponds to the movement of the piles. It is seen that the vertical wall movement of LP00158-LP00169 is 14mm, 12mm for LP00157-LP00170 and 18mm for LP00156-LP00171. The average of the three pairs comes to 14.7mm, which agrees with the C580 predictions of the vertical surface movement at the wall being 0.05% of wall depth, i.e.. 16.5mm. Although being 11% larger than the actual settlement, CIRIA C580 is a guideline and therefore the empirical formula in C580 is expected to produce a conservative prediction.

North Lindsey Street

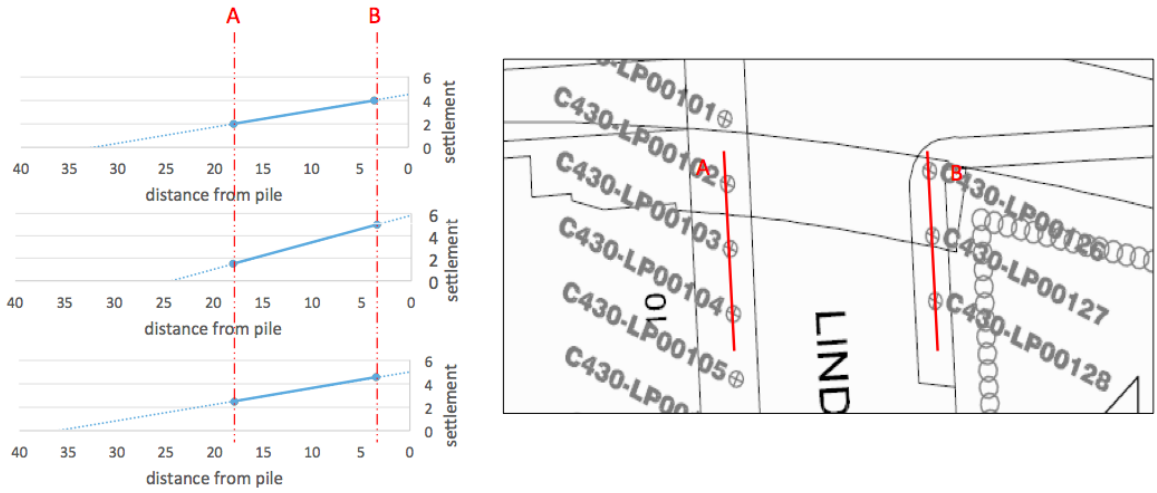

Figure 54 Linear interpolation for North Lindsey Street

The results of linear interpolation using the data of settlements at the 6 measuring points at North Lindsey Street are displayed in Figure 54. It can be seen that the LP00104-LP00128 pair has the largest distance to negligible settlement, followed by LP00102-LP00126, which is in turn followed by LP00103-LP00127. The large differences in distances to negligible settlement and the inconsistency of the trend with the trend of settlements from Figures # and # also suggest these results are not very accurate. The fact that the settlements on both sides of the street are small compared to other regions of measurement also means that the results of linear interpolation tend to lead to large distances to negligible settlement. This is because the fluctuations in readings that may not necessarily portray the concerned effects on settlement of the soil will take up a large percentage of the maximum settlement

and alter the result of the interpolation. This can be demonstrated from the difference between the furthest and shortest distances to negligible movement which exceeds 25%. CIRIA C580 predicts a zone of influence that extends 66m from the piles which is still an overestimate for this region, which highlights the over-conservative nature of C580 in distances to negligible settlement.

The surface movements at the wall are 4.5mm, 6mm and 5mm respectively, north to south, averaging to a value of 5.2mm. Once again the predictions of C580 give a much larger estimate of 16.5mm. It should be noted that the small settlements in the region that caused the large distances to negligible movement will give smaller predictions of wall surface movement as the settlement gradient with distance is lowered. However even in light of the effects of this factor, the actual settlement should be below 16.5mm from simple observation and logical thinking.

South Lindsey Street

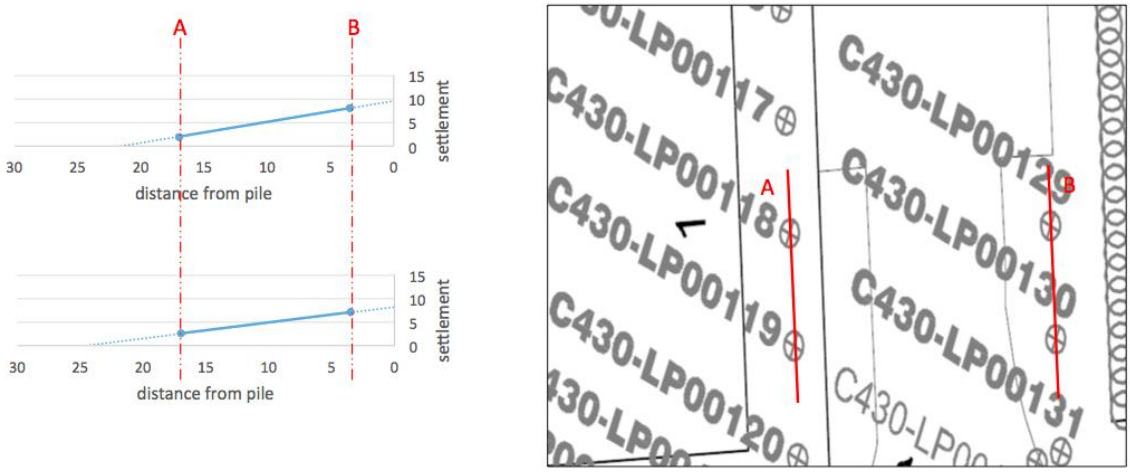

Figure 55 Linear interpolation for South Lindsey Street

Figure 55 displays the results of linear interpolation of the 4 measuring points in South Lindsey Street. As shown in the plots, the distance to negligible settlement for both pairs of measuring points are fairly consistent with values of 22m and 24m, with an average value of 23m. This is merely a third of the predicted distance to negligible settlement from the CIRIA C580 prediction tables. However, it should still be noted that the far wall measurements are of small magnitudes, and a different interpretation of the readings can lead to large differences in linear interpolation results.

The vertical surface movements at the wall are 10mm and 8mm respectively from north to south, and this is 36% away from the predicted wall movements from the CIRIA C580 predictions. It should be noted the small measurements in the far wall measuring points will give a lower value for the vertical surface movements at the wall. Again it is apparent that the CIRIA C580 produces an estimation that is too conservative, and the results highlight the importance of the understanding of ground movements for more accurate guidelines.

Long Lane

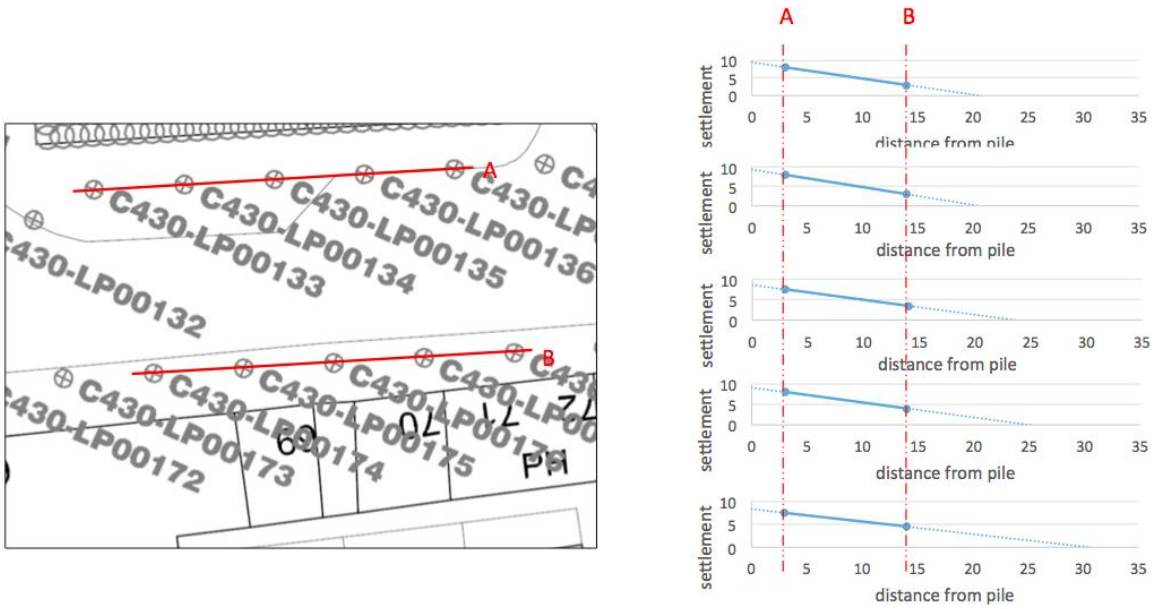

Figure 56 Linear interpolation for Long Lane

Figure 56 shows the interpolated settlements of the ten measuring points in Long Lane with respect to distance away from the pile. The results show that the distance to negligible settlement for the pairs of measuring points in Long Lane seem to increase gently from LP00137-LP00178 to LP00134-LP00173, with LP00133-LP00174 having a sudden jump in distance to negligible settlement. This trend is created from the consistent settlements near wall on Long Lane and the change in far wall where LP00178 shows the most settlement amongst the far wall measuring points. The maximum distance to negligible settlement shown in Figure 56 is 31m which is approximately half of the predictions given by CIRIA C580.

The average vertical surface movement at the wall produced by the linear interpolation from the ten measuring points in Long Lane is 9.4mm. This is 7mm less than

the predicted value from CIRIA C580. This set of results show consistent values for the surface movement at the wall while even considering the effects of the change in trend in the ground settlement measurements shown in Figure 51 and Figure 52.

Comparison to previous case histories

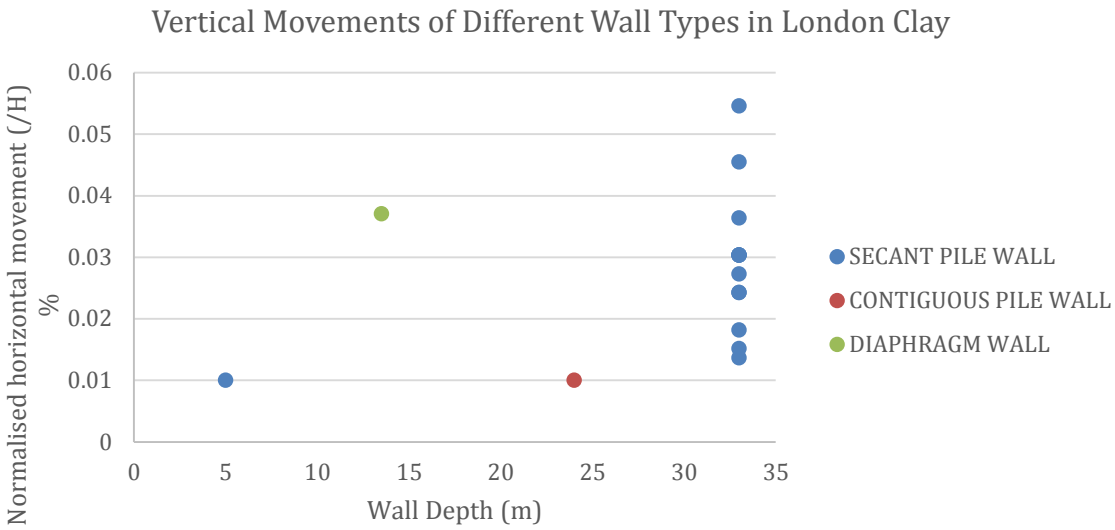

Figure 57 Vertical movement caused by wall installation in London Clay

Figure 57 shows the ground movements observed at Farringdon station incorporated into the database of ground movements caused by wall installation. It is seen that the maximum seen settlement in Farringdon exceeds the maximum value shown in the data. This suggests that the improvement in quality of workmanship and technological advances in the recent years have not been able to reduce the effects of wall installation on ground movements. However, it should be noted that the values for surface movements at the wall are achieved from linear interpolation and are prone to large errors due to the nature of the method and the small readings from far wall measurements. The fact that the majority of the data in the plot now belongs to a single construction project also introduces bias due to the lack of variety of construction conditions.

Conclusion

The analysis of the data obtained has provided information with regards to the aims of the project. By the collating the relevant case histories from previous years, plots showing the effects and trends of different wall types constructed with different support in different soil

types are generated. Some trends could be seen as in the analysis of these plots. It is clear that cantilever walls tend to generate a much larger lateral movement of soil due to its flexibility, giving a rough insight into the sacrifices in ground movement restraint when retaining more free space for constructing permanent works. It is also seen from the plots that multi-propped and multi-anchored walls are capable of achieving high values of horizontal and vertical movement, as the positioning and number of props and anchors supporting the walls influence the resulting ground movement greatly. However construction obstructions in the construction site can cause large unpredictable deformations in the soil, so the reliability of the analysis of the data is reduced with this underlying uncertainty. It is also apparent that secant piled walls have the largest resistance against soil movements and sheet piled walls have the least. This is expected from the understanding of the natures of the wall types as the sheet piles are much more flexible than the piles used in secant piled walls. The results are also classified into three soil types (London Clay, Sand/Gravel and Soft Clay), giving a brief idea of how much settlement is expected in each type of soil.

The limited data of soil movement under the effects of wall installation solely are then presented. Although trends are not spotted due to the sparse data, the effects are compared with the total ground movement caused in a deep excavation. It is seen that secant piled walls, contiguous piled walls and diaphragm walls contribute 45%, 11.6% and 23.1% to the total lateral movement from an entire excavation, and 25.4%, 9%and 15.3% of the total settlement. These values add up to an average of 20%, which gives a good idea on the importance and significance of the effects of wall installation.

Finally, the data from Crossrail was analysed. Data points from the streets surrounding the East Ticket Hall of Farringdon station provided important data on the settlements observed during the period of piling of secant piled walls. The settlements of the measuring points are analysed and compared with their adjacent measuring points, and trends suggesting other construction works or obstructions were spotted. The plots of settlement with time gave a good grasp on the settlement gradient and the way the ground reacted with piling. It was evident that different zones reacted very differently to piling, possibly owing to the differences in soil composition and the quality of the piling at each zone.

Linear interpolation was performed on the measuring point surrounding the ETH, obtaining surface ground movements at the wall and also distances to negligible settlement. It was seen that the CIRIA C580 predictions gave over-conservative results, predicting surface movements of 16.5mm and 66m as a distance to negligible settlement. None of the interpolated results exceeded the predictions, but it was clear that the predictions for

distances to negligible movement needed to be reconsidered as the predictions exceeded the interpolated results drastically. However, the interpolation of each area was only performed with two measuring points, so there is a large room for improvement for the accuracy of the analysis. Furthermore, the measurements at each point were small, suggesting that a small error in the readings will deviate the results of the analysis substantially.

Further works

- Obtain more data on ground movements on wall installation effects in other recent construction works to enlarge variety and size of database
- Achieve a better understanding on the other concurrent works in the site at the ETH of Farringdon station. The ground movements caused by these effects can then be deduced and the plots calibrated to show the settlements of the area due to the sole effect of pile installation.
- Investigate on possibility of devising accurate numerical analysis methods on predicting wall movement due to wall installation
- Look into the ground movements caused by other sources

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