Monitoring the response of a piled building to tunnelling using different techniques

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Abstract

Swanlea School is a piled structure that was affected by the construction of tunnels (pilots, enlargements and cross-passages) for the nearby new Crossrail station at Whitechapel, London. The settlement of various school buildings was monitored using four systems: precise levelling using (i) roadstuds and (ii) BRE sockets; (iii) automatic total stations (ATS); and (iv) water-level cells. Along some sections more than one system was applied, providing: redundancy; confidence in measurements; and the opportunity to compare the data in terms of factors such as accuracy, frequency, reliability, and ease of measurement. The four systems and their installation and operation are described. Brief details about the underground construction works and the relevant timeline are given, with a focus on specific activities for which the incremental monitoring data have been isolated for detailed analysis. The response of a selected number of sections of the buildings, where more than one system was used, are presented and discussed in the context of the instrumentation and the construction works. Incremental and total settlements of up to 27 mm and almost 70 mm respectively were recorded. Issues relating to the comparison of the data sets in terms of base readings, spatial and time differences and datum points are explained and discussed.

1. Introduction

This paper focuses on the construction works that were undertaken at Whitechapel Crossrail Station, mostly during 2012 and 2013, that affected Swanlea School. Extensive real-time surface monitoring data exist concerning these works adjacent to and below Swanlea School. Swanlea School is a 3-storey building, built in 1993. The school has no basement and is founded on 1-m deep reinforced concrete ground beams which are supported on 600-mm and 750-mm diameter piled foundations ranging in length from 16 m to 29 m. The school's canteen extension is founded on a 300-mm thick reinforced concrete raft and is continuous with the main building's ground floor slab. The City Learning Centre is also founded on a 300-mm thick reinforced concrete raft but is separated from the main building by soft jointing. The school has been affected by two primary phases of tunnelling; these include construction of 6-m diameter pilot tunnels followed by enlargements to form 10-m diameter sprayed concrete platform eastbound and westbound tunnels (PTE and PTW), approximately 20 m below ground level in the London Clay stratum. Construction of Cross Passage 1a (CP1a) and Launch Chamber Eastbound (LCE) of the Eastbound Running Tunnel (EBRT) to the west of Durward Street Shaft (DSS) also contributed to measured settlements. The location of Swanlea School with respect to these Crossrail works is shown in Fig. 1.

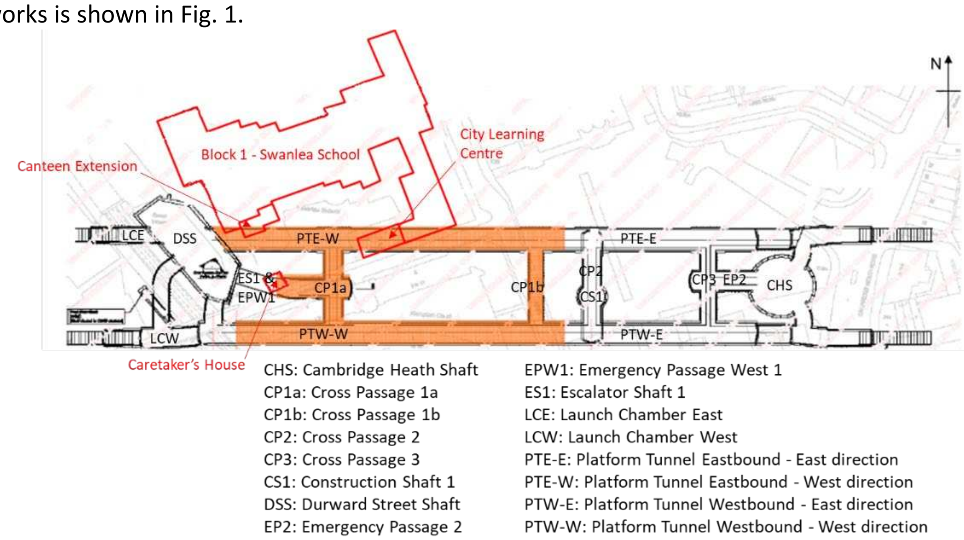

Figure 1: Plan of Whitechapel Station Crossrail works in relation to Swanlea School.

The Crossrail works close to the school, and therefore likely to impact it, are highlighted in orange in Fig. 1. The Durward Street Shaft (DSS) that provides the main access route to the Crossrail platforms, although directly adjacent to the school, was constructed after the platform tunnels and cross-passages were complete and its influence on the school is not covered in this paper. Platform Tunnel Eastbound West direction (PTE-W) passed directly below the school at both the south-eastern and south-western corners. To allow for its passage below these corners of the school, a total of 5 piles were cut by up to about 6 m. Fig. 2 shows a cross-section of the Crossrail works with respect to the school. The Crossrail team predicted ground movements due to the shaft and tunnel excavations; these included settlements of approximately 100 mm at the south-eastern and south-western corners of the school, and differential settlements of approximately 22 mm between the piled main school building and ground bearing canteen extension, and 45 mm between the piled main school building and the City Learning Centre. Mitigation measures were incorporated which included new mini piles and pile caps, as well as a jacking system.

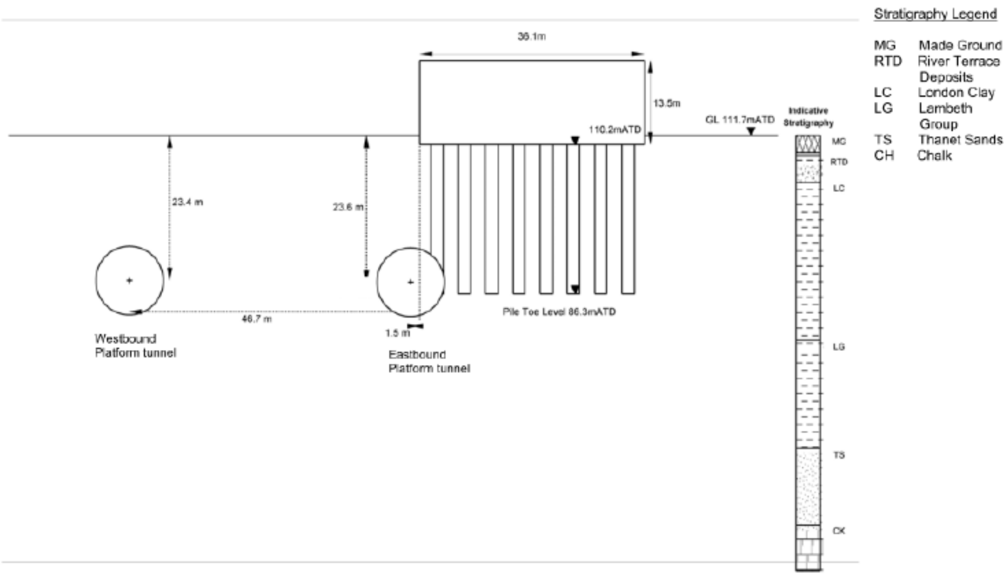

Figure 2: Cross-section of Crossrail works in relation to Swanlea School including ground stratigraphy.

2. Surface level monitoring at Swanlea School

Fig. 3 shows the location of the four monitoring systems (i.e., roadstuds, BRE sockets, water-level cells, and total station monitoring or 3D prisms) that were used at Swanlea School. Most of these instruments were installed prior to the Whitechapel Station construction activities, which are recorded as starting on 1 June 2012. However, there were some instruments that were installed after construction works had begun. These instruments measure vertical ground movement as they record the ground surface level by outputting a vertical (z) coordinate from which the level differences can then be calculated. However, measurements from 3D prisms also allow horizontal displacements to be determined through changes in horizontal orthogonal x and y coordinates. Water-level cells and total station monitoring readings are taken automatically while precise levelling readings (i.e., roadstuds and BRE sockets) are taken manually. As highlighted in Fig. 3, there were some BRE, 3D prism and water-level cell monitoring points which recorded data showing large fluctuations, and therefore these data were unable to be used further. This unfortunately included the south-western corner of the school where two piles were cut to allow for the passage of PTE-W.

2.1 Roadstuds

Nine Block 1 roadstuds were located near to Swanlea School along Durward Street while twenty-five Block 25 roadstuds were located along the other side of Durward Street, as shown in Fig. 3. Installation involved drilling holes into the pavement and fixing the domed metal studs using Hilti Hit adhesive. The Block 1 roadstuds were installed on 24 November 2011 with monitoring beginning two days later. The Block 25 roadstuds were installed on 12 July 2012, i.e., after construction works started, with monitoring beginning the same day. Readings were mostly taken every few days rather than daily, and not at the same time each day. Sometimes, on particular days, readings were not possible due to obstructions.

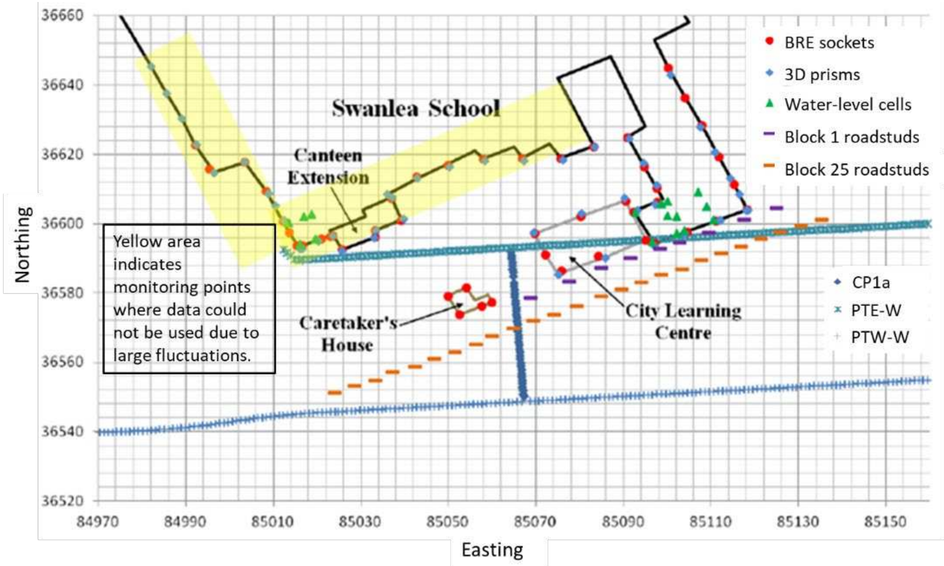

Figure 3: Location of monitoring points at Swanlea School with respect to Whitechapel Station Crossrail works.

2.2 BRE sockets

Forty-eight BRE sockets were installed along the southern external walls of Swanlea School, and along the external walls of the City Learning Centre and the Caretaker's House (Fig. 3). These were installed by drilling holes in the external walls and fixing the BRE sockets with Hilti Hit adhesive. When taking readings, BRE levelling plugs were screwed into the BRE sockets which allowed for radial positioning within a 0.1 mm tolerance. The first set of BRE sockets were installed between 2 April 2011 and 19 April 2013 (in the main body of the school and the City Learning Centre), i.e., both prior to and after construction activities had started. The second set (at the Caretaker's House) was installed between 15 August 2013 and 18 August 2013. Prior to the start of construction activities, readings were taken every few days. However, once construction works began, readings were taken daily, but not necessarily at the same time each day. The outside conditions when the readings were taken were also recorded as this could affect the accuracy of the readings.

2.3 Water-level cells

Sixteen water-level cell sensors were installed to monitor the vertical movement of the internal structures of the school (Fig. 3). The sensors and water tanks were installed at a height of between 2-3 m to ensure that there was no risk of disturbance. A cable connected the sensors together which was connected to a datalogger. These systems were also connected to the 3D prisms located nearby in order to calculate absolute movements. The sensors were installed on 1 September 2011. Readings were taken almost daily from 24 February 2012 at 00:00 hours.

2.4 3D prisms

Fifty 3D prism targets and five ATS instruments and control boxes were installed along six southern external facades of the school, which included the City Learning Centre, to carry out optical surface levelling (Fig. 3). Holes were drilled into the external walls to fix the prisms which were orientated to face the ATS installations which were also fixed to the walls. The control boxes were installed on the façades 3.5m above ground level with a signal cable running from the ATS to the control boxes. The prisms were installed between 18 April 2011 to 19 April 2011. Prior to construction activities starting, readings were taken almost daily. Daily measurements were recorded automatically in both the horizontal and vertical directions once construction activities began.

3. Whitechapel station construction works

Referring to Fig. 1, the key tunnelling construction activities included: i) CS1 followed by CP2 pilot and enlargement; ii) PTE-E and PTE-W pilots; iii) PTW-E and PTW-W pilots; iv) CHS followed by PTE-E and PTW-E enlargements; vi) PTW-W and PTE-W enlargements; and vii) CP1a pilot and enlargement. To relate significant changes in settlement to the Crossrail construction activities, a construction time-line was produced which showed the dates that each tunnel advance was constructed. Settlement-time graphs were produced from the monitoring data which was base-lined and then replotted to determine periods of significant settlement. The construction phases that caused these significant changes in settlement were then established. It was found that the PTE-W pilot and enlargement construction phases caused significant settlement across all monitoring points and were the nearest construction elements to the school, see Table 1 and Fig. 1. There were two construction phases for PTE-W pilot (shown in Fig. 4). The water-level cells and Block 1 and Block 25 roadstuds recorded noticeable increases in settlement for both these phases, however measurements to the BRE sockets and 3D prisms only indicated a noticeable increase in settlement for the second phase (Fig. 4). Construction of CP1a also caused noticeable settlement across the BRE sockets and roadstuds and was another construction element located close to the school (Table 1 and Fig. 1).

Monitoring instrument	From	To	Cause of settlement / heave
BRE sockets	25/01/2013	14/02/2013	PTE-W pilot
	17/06/2013	22/07/2013	PTE-W enlargement
	19/08/2013	22/08/2013	CP1a pilot
	10/09/2013	16/09/2013	CP1a enlargement
	24/01/2014	28/01/2014	LCE pilot
3D prisms	29/11/2012	08/12/2012	Unknown
	13/12/2012	20/12/2012	Unknown
	25/01/2013	14/02/2013	PTE-W pilot
	24/06/2013	22/07/2013	PTE-W enlargement
Water-level cells	31/05/2012	05/06/2012	Unknown
	14/11/2012	10/11/2012	PTE-W pilot
	06/12/2012	09/12/2012	Unknown
	26/01/2013	10/02/2013	PTE-W pilot
	21/06/2012	14/07/2013	PTE-W enlargement
Block 1 roadstuds	06/11/2012	19/11/2012	PTE-W pilot
	26/01/2013	12/02/2013	PTE-W pilot
	22/06/2013	22/07/2013	PTE-W enlargement
	16/08/2013	24/08/2013	CP1a pilot
	08/09/2013	15/09/2013	CP1a enlargement
	23/09/2013	07/10/2013	CP1a enlargement
Block 25 roadstuds	06/11/2012	18/11/2012	PTE-W and PTW-W pilots
	26/01/2013	26/02/2013	PTE-W and PTW-W pilots
	19/06/2013	15/07/2013	PTE-W and PTW-W enlargements
	17/08/2013	26/08/2013	CP1a pilot
	08/09/2013	17/09/2013	CP1a enlargement
	26/09/2013	08/10/2013	CP1a enlargement

Table 1: Time periods during which significant settlements occurred and the associated construction phase.

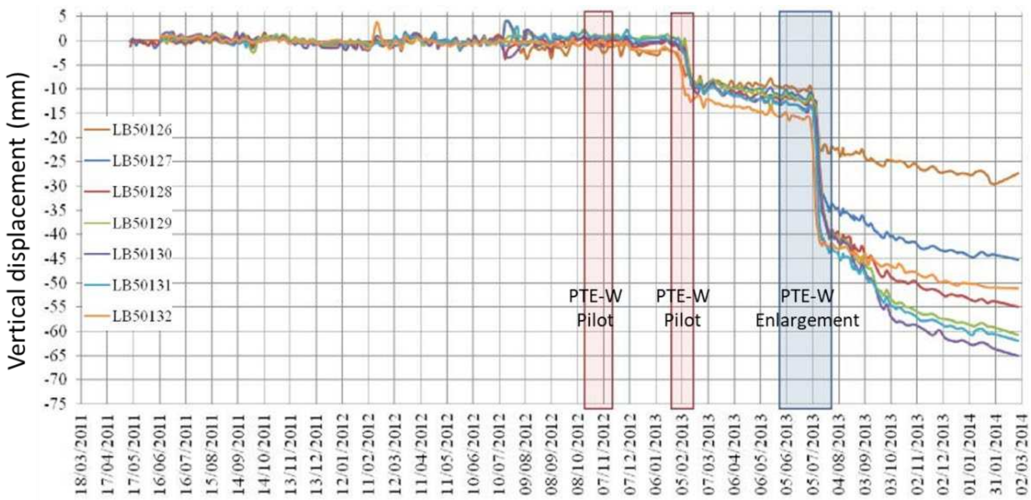

Figure 4: Settlement-time graph for BRE sockets located at the City Learning Centre.

There is some ambiguity as to which construction phase caused noticeable heave and settlement to be recorded by the 3D prisms and water-level cells, as the construction activities occurring at these times were located far from the school and would therefore have had negligible impact. The cause of this settlement / heave is therefore recorded as unknown over these time periods in Table 1. The base-lined settlement-time graph for the BRE sockets located around the City Learning Centre is shown in Fig. 4. The data indicate that the enlargement of PTE-W caused the greatest increase in settlement. During the early monitoring period, until about July 2012, before any construction influenced the school buildings, the scatter in the data suggest an accuracy of about ± 1 to 2 mm. Shortly after this and prior to the PTE-W pilot, the accuracy seems to reduce. The reason for this is unknown, it could be caused by reasons such as change of survey team or instrument or climatic conditions. The accuracy seems to improve again during the works and is also evident towards the end of the monitoring period. Observations such as this highlight the need to keep careful and accurate records of any events that might influence the monitoring records. They also reflect the potential obstacles encountered when compiling case histories such as this where the authors were not directly involved in the project.

4. Overall changes in settlement

Overall changes in settlement have been plotted against perpendicular distance from the centre-line of PTE-W, as it was the construction element that had the greatest impact on the school in terms of settlement. Linear slices are taken for each type of monitoring data and the settlement plotted with perpendicular distance from PTE-W. Fig. 5a and b show the linear slices taken both externally and internally along and near to the south-eastern corner of the school (referred to as Zone 1) and the associated settlement curves. Fig. 5c and d show the linear slices taken from the south-eastern corner of the school to the City Learning Centre and Caretaker's House, and along Durward Street near to the school (referred to as Zone 2) and the associated settlement curves.

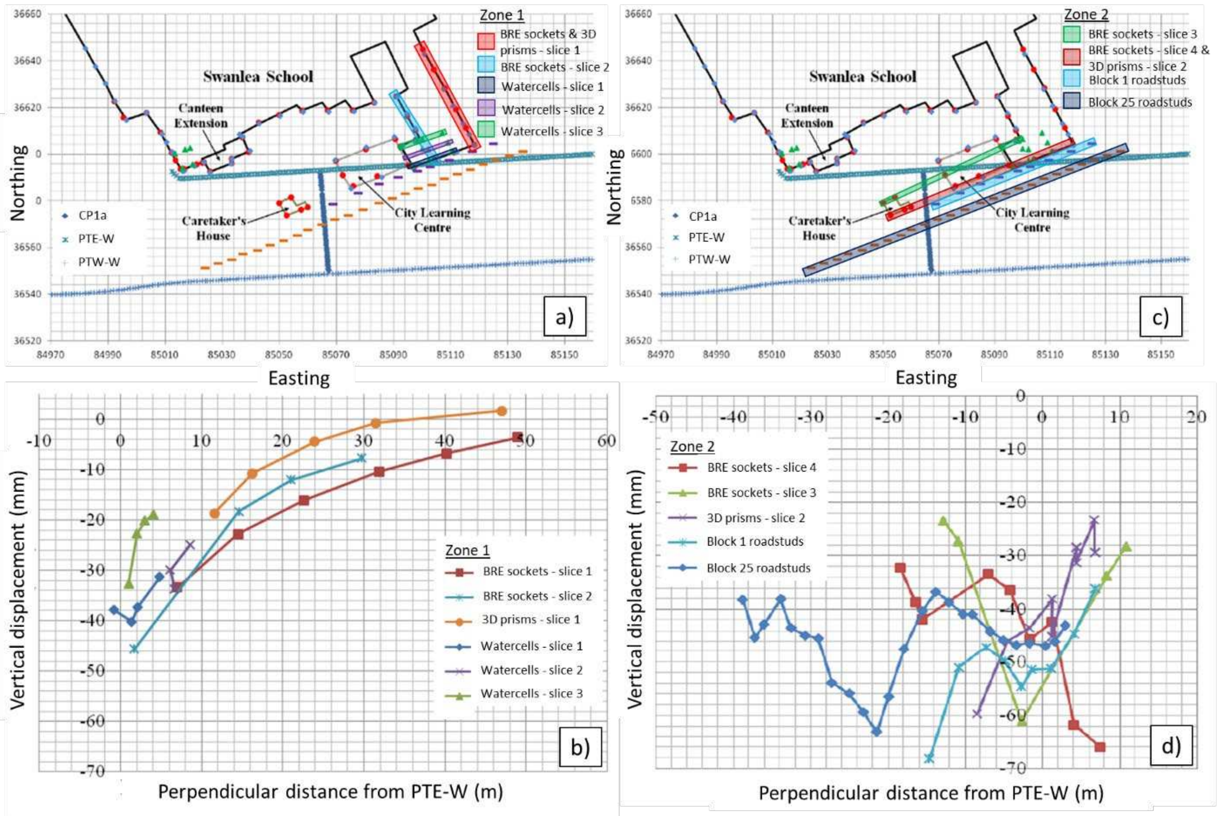

Figure 5: Linear slices taken for each type of monitoring data and settlement-distance graphs for: (a) & (b) Zone 1; and (c) & (d) Zone 2.

As shown in Fig. 5a, the linear slices taken in Zone 1 stop just short of PTE-W except for slice 1 of the water-level cells which crosses PTE-W. Fig. 5b shows that the Zone 1 settlement curves appear to follow a similar pattern. Looking at the data from the BRE sockets and 3D prism slices and slice 3 of the water-level cells, it can be seen that overall settlement increases with decreasing distance from the tunnel as expected. The gradient of these settlement curves also gradually increases with decreasing distance from the tunnel, that is, there is more differential settlement along the façade of the school with reducing distance to the tunnel. This means that more cracking would be expected to occur towards this end of the building. Fig. 5a shows that both slices 1 of the BRE sockets and 3D prisms are along the same façade of the school. However, there is an offset of 6 to 10 mm between the precise levelling and ATS measurements along the monitored lengths shown in Fig. 5b, with data from the BRE sockets indicating larger overall settlements than the 3D prisms. The reason for this is not known but could be due to different datum points being used for the two monitoring systems. In Zone 1, slice 2 of the BRE sockets shows the greatest overall settlement of approximately 46 mm. This monitoring point lies above PTE-W where larger settlements would be expected. However, the water-level cell monitoring point that lies above PTE-W in slice 1 of the water-level cells only recorded an overall settlement of approximately 40 mm i.e., 6 mm less than the BRE monitoring point. As observed above, different datum points were probably used for precise levelling and ATS measurements, and the water-level cells relied on the ATS datum (as noted in Section 2.3) which resulted in smaller measured settlements. In fact, the data from the water-level cells (slices 1 and 2) and 3D prisms could be readily fitted together to form one continuous curve. The accuracy from these systems would be expected to be and appears to be similar, judging from Fig. 5b.

As shown in Fig. 5c, the linear slices taken in Zone 2 cross both PTE-W and CP1a except for the 3D prisms and Block 1 roadstuds which stop short of CP1a. It can be seen in Fig. 5d that that the Zone 2 settlement curves have double troughs as expected with the lowest trough points lying above PTE-W and CP1a. Regarding the single trough shown by slice 3 of the BRE sockets, there were no monitoring points for 10 m either side of the middle monitoring point and therefore assumptions had to be made regarding the settlement in these areas. In Zone 2, slice 3 of the BRE sockets shows the greatest overall settlement above the centre-line of PTE-W of approximately 54 mm. The reason for this could be that this slice cuts through the centre of the City Learning Centre at this point. This building would have its largest load transferred vertically at its centre point resulting in increased settlement. Slices 3 and 4 of the BRE sockets show an increase in settlement from the piled main school building to the ground bearing City Learning Centre which lies directly above PTE-W. The Block 1 and Block 25 roadstuds have similar overall settlement patterns and seem to follow more of a 'greenfield' settlement pattern which is expected as these roadstuds are not located on the school structure. The Block 1 roadstuds recorded the greatest overall settlement in Zone 2 of approximately 68 mm. Another point to note is that the slices in Zone 2 are at quite an acute angle to PTE-W (not quite parallel) and so a lesser accuracy might be expected as the perpendicular offset is not so well defined. This would be an important consideration when assessing settlements during the course of the staged SCL works (with changing heading positions).

Fig. 5c shows that slice 4 of the BRE sockets and slice 2 of the 3D prisms (in pink) are along the same alignment in Zone 2. However, the settlement curves in Fig. 5d for each of these two data sets are quite different: the reason for this is not known. Overall, the greatest overall settlement recorded in Zone 1, away from the influence of CP1a, was just under 50 mm, while that in Zone 2, that extended across CP1a, was almost 70 mm.

5. Incremental settlements over significant time periods

Incremental settlements for specific construction activities during the time periods that they took place, as identified in Table 1, were plotted with distance from PTE-W along each linear slice for each type of monitoring data: slice 4 of the BRE sockets in Fig. 6a, and slice 2 of the 3D prisms in Fig. 6b, as identified in Fig. 5c, i.e., slices taken along the same alignment in Zone 2.

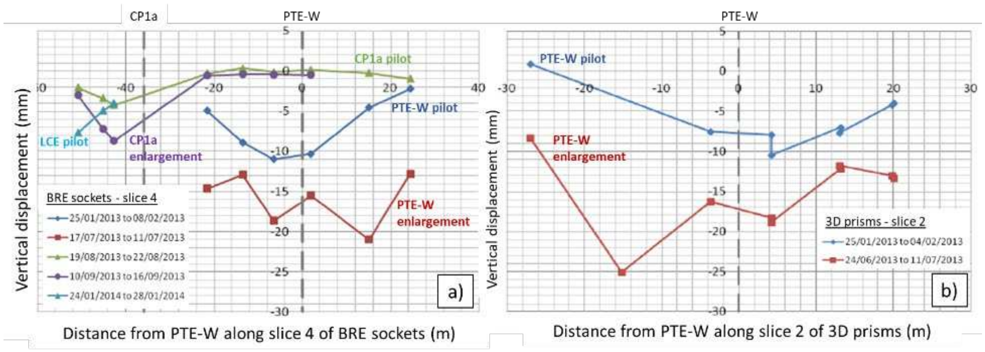

Figure 6: Incremental settlement-distance graphs along BRE sockets (a) and 3D prism (b) linear slices.

It can be seen in Fig. 6 that the greatest increase in settlement recorded by the BRE sockets and 3D prisms along corresponding alignments was during the period when PTE-W was enlarged. Some of the settlement profiles have a zig-zag form rather than a smooth trough which is probably a result of the different structural forms in which the two types of monitoring point (BRE socket and 3D prism) were installed with a mix of deep and shallow foundations and isolated structures i.e., the Caretaker's House. This is evident from the slice 4 BRE socket data, which indicate that construction of CP1a pilot tunnel and its enlargement only caused noticeable settlement in the vicinity of the Caretaker's House, with little effect on the City Learning Centre or the main school building. Apart from these effects, data from precise levelling have better accuracy than that from ATS measurements.

Incremental settlement-distance graphs along the Block 1 and Block 25 roadstuds shown in Fig. 5c, i.e., in Zone 2, are presented in Fig. 7 where settlement forms are similar to 'greenfield' settlement troughs. This can be explained by the fact that the roadstuds were located on the Durward Street pavements rather than the school structure. The greatest incremental settlements are again identified from when PTE-W was enlarged, with the Block 1 roadstuds (Fig. 7a) recording the greatest settlement of 27 mm. This is in contrast to the findings of Chen et al. (1999) who observed that more volume loss occurred from construction of the pilot tunnel for Angel Underground Station than for its enlargement. The settlement above the centre-line of PTE-W is approximately 25 mm and 20 mm for the Block 1 and Block 25 roadstuds respectively. The larger settlement recorded by the Block 1 roadstuds (Fig. 7a) can be explained by its closer location to the school as the structural loads from the school would increase the settlement here. It can also be seen that the construction of the CP1a pilot tunnel and its two construction phases of enlargement also caused a noticeable amount of settlement. However, there is a negligible difference in the incremental settlement caused by the CP1a pilot tunnel and that caused by its enlargement. The construction works for CP1a did not cause as much settlement as the construction of PTE-W since CP1a was a much smaller construction element. The accuracy of the more closely spaced Block 25 roadstuds (Fig. 7b) can be seen by the smoothness of the settlement trough with the lowest point being at the centre-line of CP1a.

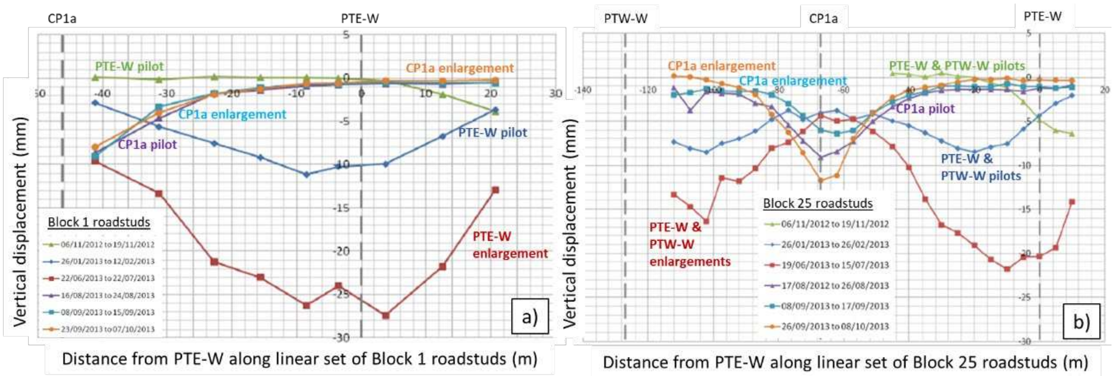

Figure 7: Incremental settlement-distance graphs along linear sets of Block 1 (a) and Block 25 (b) roadstuds.

6. Conclusions

Comparing the settlement data from the different monitoring techniques has allowed comparisons to be made between them, indicating that although their accuracies are similar, those from the precise levelling, especially of the roadstuds, is best. Expressing the data incrementally helps identify the effects of specific construction activities on the structures with different foundation types and joints between them. Various instances are noted where more detailed information would have helped explain some of the differences. This is always an issue when preparing a case study from historic data where the authors were not directly involved in the works.

The greatest settlement was caused by the construction of the PTE-W pilot tunnel and its enlargement, expected as this element was closest to the school with more volume loss occurring from construction of its enlargement than for its pilot tunnel.

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References

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