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A case study of review excavation monitoring data for the reliable back analysis

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Abstract

Construction monitoring is a common practice adopted in excavation construction, especially in urban areas. The good monitoring practice will not only provide assurance for construction risk management but also facilitate construction modification towards savings in cost and time. This paper presents an excavation case history of the Crossrail Tottenham Court Road Station-Western Ticket Hall (TCR-WTH), which has a large amount of monitoring data from excavation construction. The excavation of TCR-WTH has been successfully back analysed to calibrate design parameters. This enabled the modification of the construction under the observational method framework to meet the Crossrail tunnelling program, and ultimately achieve significant savings in construction time and material. The paper focuses on the subsequent review of the primary inclinometer and strain gauge monitoring data for the TCR-WTH. The review shows that it is possible to improve the quality of monitoring data through a robust data review process. The data value can be maximized during back analysis using reliable measurements. Therefore, it is important to test the reliability of instrumentation data when the observational method is adopted. The lessons learned from the TCR-WTH primary monitoring data review are shared in the conclusions.

Keywords: Monitoring data review, Excavation, Back analysis

1. Introduction

It has become routine to install instruments to monitor the construction activities. Especially in urban areas, where the impact on nearby 3rd party properties and the buried utilities could be severe. Through well-planned instrumentation and monitoring plans, the complex interactions between the ground and the existing structures or newly constructed structures can be measured and interpreted. This practice provides a way of securing safe construction.

Good observations have been recognised as valuable to understanding the ground behaviour, however, imperfect monitoring data does exist and can cause some significant effects on a back analysis. Peck (1969) pointed out some possible reasons for imperfect monitoring data, such as '*far too much dependence is placed on reports of the successful performance of instruments; the separation between who sees the need for the measurements and who plan and install instruments; less thoughts goes into the significance of the data and observations are made to fill gaps*.' Moreover, for back analysis, Peck suggested that the monitoring results '*should be regarded as working documents, issued whenever the information needs to be brought up to date.*' It reflects the dynamic character of monitoring data, measurements change with time. Hence, a back analysis investigates the 'real-time' construction performance at the time when the readings were taken.

Well-documented excavation case histories with reliable observation monitoring data are very important for the development of soil mechanic. For example, the Post Office Square excavation case in Boston (Whitman et al., 1991), with the multiple types of instrumentations, and high quality data has helped the understanding of Boston clay behaviour, validated new soil constitutive models through back analysis (Hashash & Whittle, 1996; Osman & Bolton, 2007; Kung, 2012), also tested different optimization approaches in back analysis (Jan et al., 2002). Another example is Taipei national enterprise Centre (TNEC) (Ou et al., 2000), where the thoroughly reviewed case monitoring data has contributed to research of braced excavation (Kung et al., 2009; Finno et al., 2007).

Therefore, it is critical to ensure the reliability of observations prior to conducting a back analysis. This will improve the credibility and efficiency of the back analysis process. This paper presents the subsequent review of the primary monitoring data for the Crossrail Tottenham Court Road Station, Western Ticket Hall (TCR-WTH) deep box excavation. It summarises some of the lessons learnt from the data review, and the consequential impact on the back analysis outcome.

2. Study Case: Crossrail Tottenham Court Road Station - Wester Ticket Hall

The TCR Station is located in Central London where Oxford Street crosses Tottenham Court Road. The WTH comprises one deep and one shallow boxes. The deep box is almost rectangular, measuring about 41 m × 31 m (Figure 1) with a maximum excavation depth of approximately 29.5 m. The excavation was constructed using the bottom-up construction method, within a 1.0m thick perimeter diaphragm wall and five levels of temporary props supporting the excavation.

A value engineering study was carried out before the TCR-WTH construction, which identified an opportunity for the observational method. This led to additional instrumentations being installed, and comprehensive real-time monitoring data was provided. The collaboration between the client, contractor, and designers enabled the adoption of the observational method, resulting in the elimination of the lowest level of temporary props (Yeow et al., 2014).

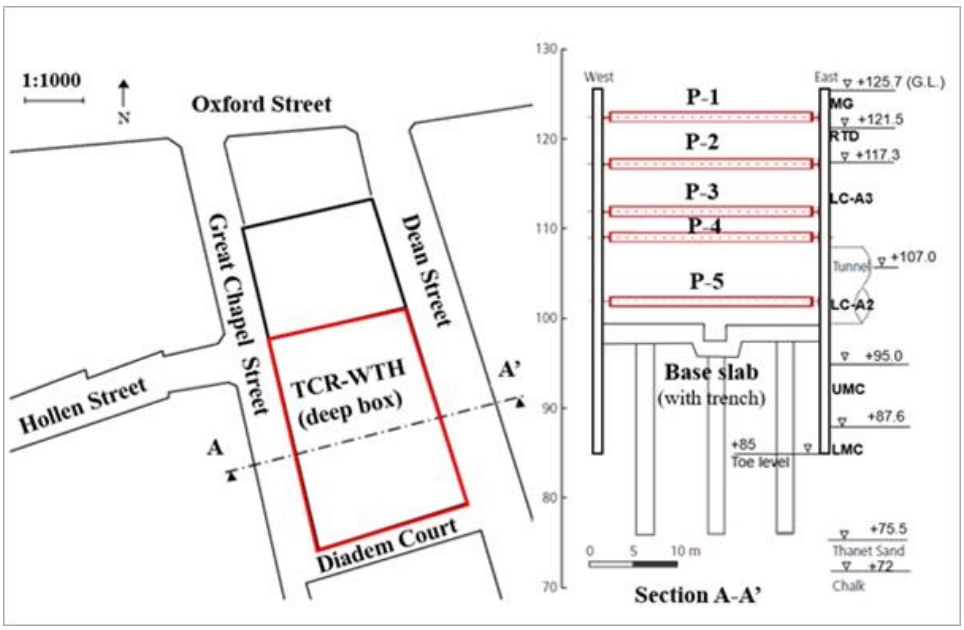

Figure 1: Layout and section A-A' of the TCR-WTH deep box (Chen, 2018; after Yeow et al., 2014)

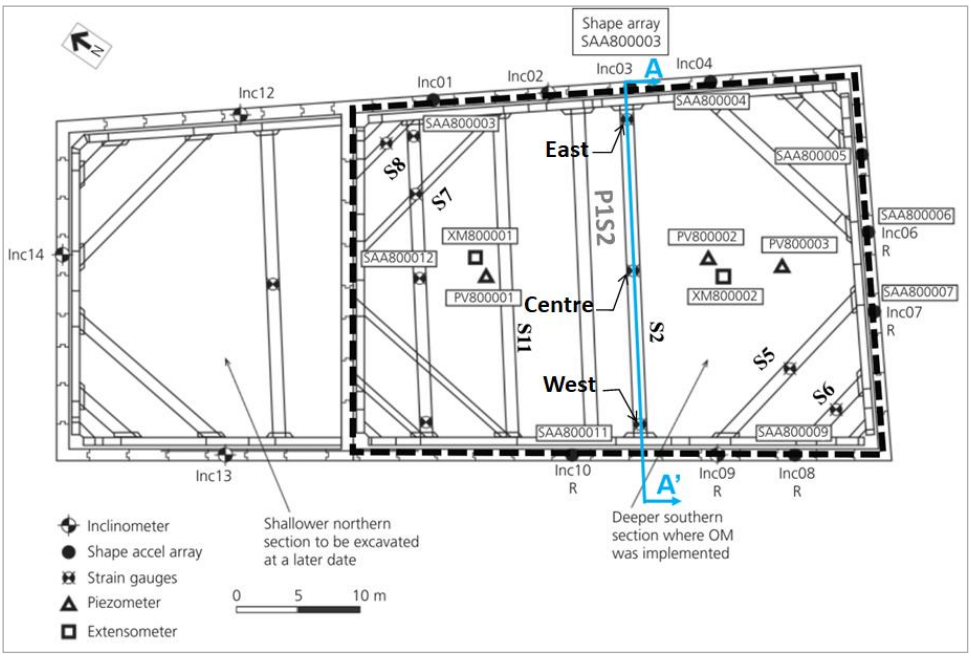

Figure 2: Instrumentation and Monitoring layout plan for the TCR-WTH (Chen, 2018; after Yeow et al., 2014)

A comprehensive monitoring system plan was designed for the TCR-WTH deep box construction to assess the performance of the retaining walls and construction risk control. The monitoring plan (Figure 2) comprised inclinometers (Shape-Accel-Arrays), vibrating strain gauges, piezometers, and extensometers. Additional prisms were installed at the capping beam level and the first level of props to cross-check the retaining wall movements. A couple of load cells were initially requested to cross-check the strain gauge readings, but not installed.

The primary monitoring data was selected as: 1) the wall deflection measured by the inclinometers; and 2) the temporary prop axial force measured by strain gauges. These data are reviewed and discussed in the following sections.

2.1 Review of Inclinometer data – wall deflection

The inclinometer data (SAA) from the early excavation stages of the TCR-WTH construction were less than the design calculated wall deflections, which had been used to set the triggers for the construction risk control management. The measured wall deflections were small and used to back analyse the WTH deep box excavation, for example, the SAA-8003 data recorded the maximum wall deflections, was applied in the back analysis.

As part of the back analysis procedure, the inclinometer data was reviewed. For instance, the SAA-8003 raw data was compared with the prism data at the capping beam level, and a manual correction to the raw data recorded after 14/09/2012 was included to ensure the compatibility between inclinometer and prism datasets (Ingram and Man, 2013). The reviewed SAA-8003 data on 11/07/2012 was used in the back analysis to derive the 'most probable' soil parameters for the modified TCR-WTH construction (Yeow et al., 2014). The reviewed SAA-8003 data is presented in Figure 3.

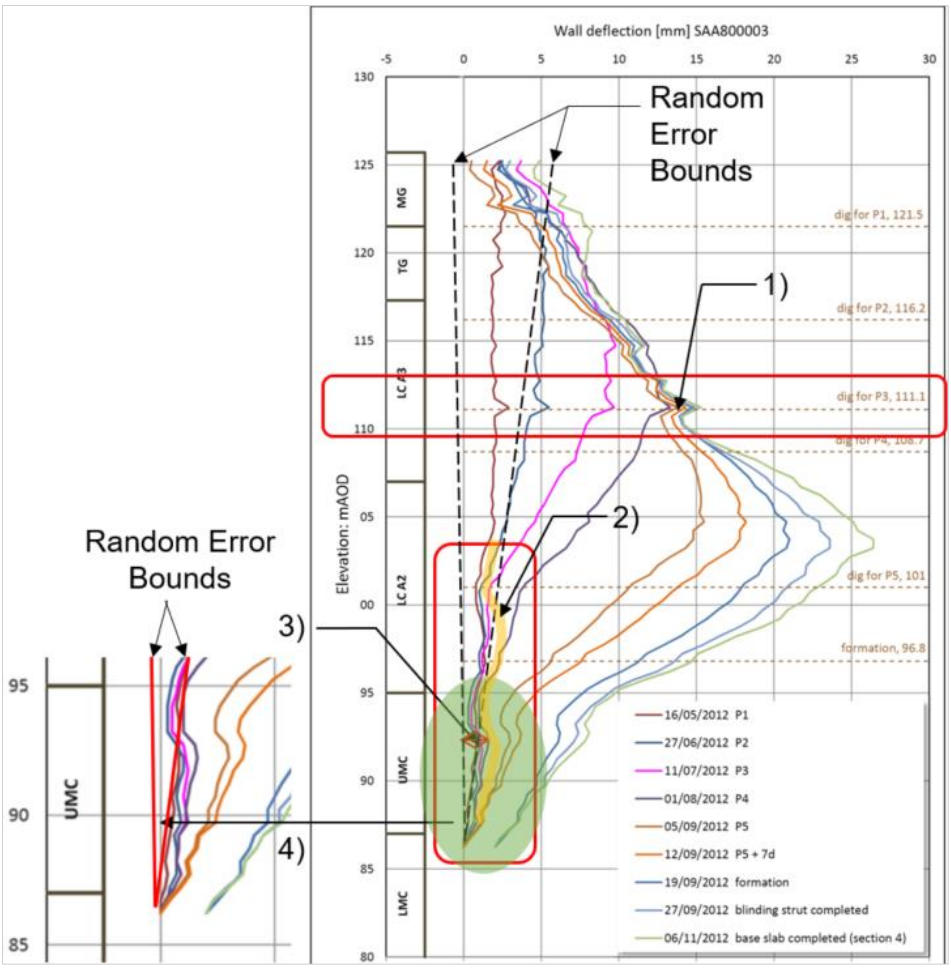

Figure 3: The reviewed SAA-8003 data (Ingram & Man, 2013)

Subsequently, a post-construction review of SAA-8003 data was carried out by Chen (2018) and it raised the following issues as shown by point 1 to 4 on Figure 3:

1) Anomalous displacements occurred at the level of +111 mAOD;

2) A few inflection points in the data profiles between the level of +90 mAOD and +100 mAOD, indicating the potential rotational error in the data;
3) A significant lateral displacement (>2mm) at the level of +92.5 mAOD was recorded before 01/08/2012 when excavation was taken place at least 16m above this level;
4) The 'corrected' SAA-8003 data for the bottom 10m was greater than the random error bounds given by SAA – according to SAA Manual (Measurand, 2013), the random error bound is given as ± (0.19 × √N) mm, N is the number of segments counting from the bottom.

Among the other available error diagnostics (i.e., sensor bias shift or sensor depth positioning) for inclinometer data, the rotation error was found to be the most significant in this SAA-8003 data correction. For an SAA segment, with a measured tilt angle, the rotation will introduce different apparent displacement distributions in the plane (i.e., X and Y directions). A displacement pattern with a positive increment along one axis accompanied by a negative increment in the perpendicular direction is the typical sign of the rotation error in SAA data.

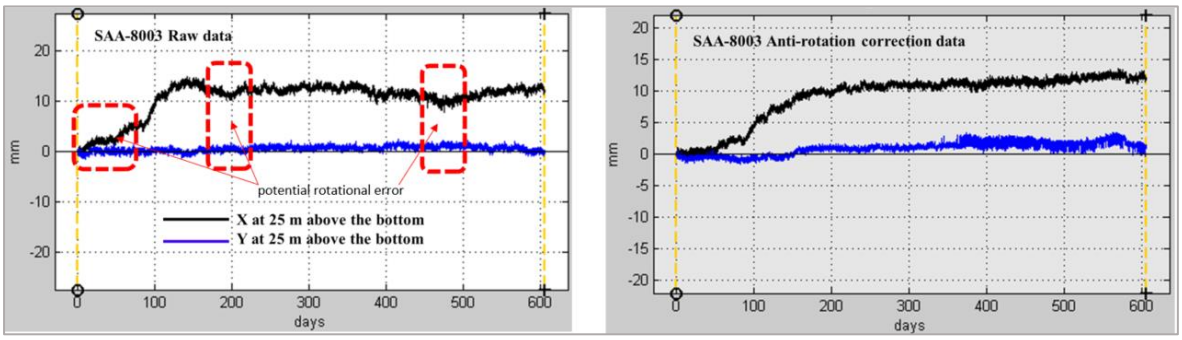

Figure 4: Plot of SAA-8003 readings at 25m above the bottom (approximately +111.2 mAOD). Left = raw data; Right = after anti-rotation correction. (Chen, 2018)

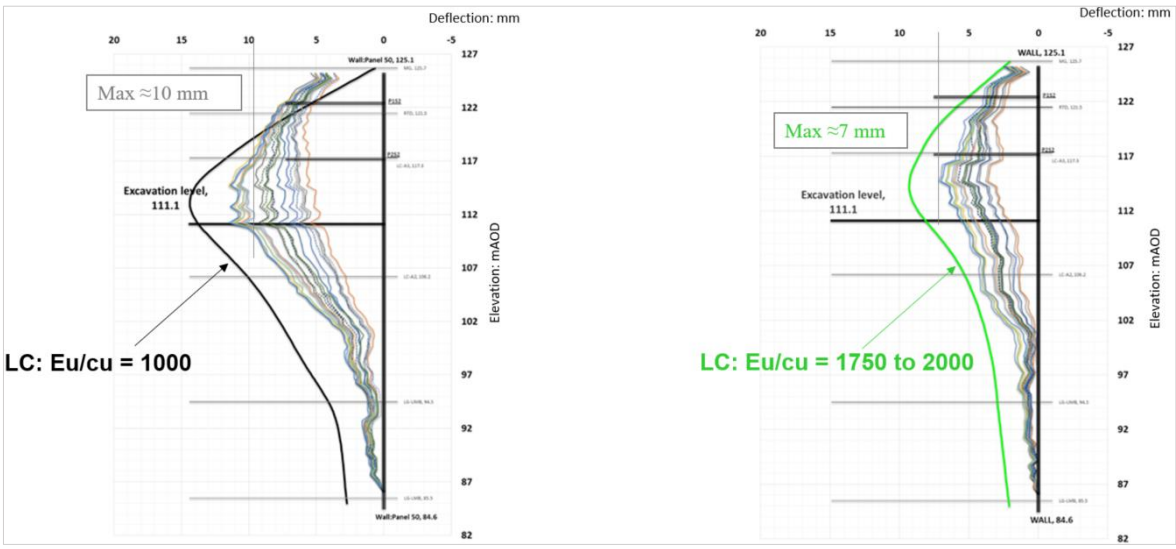

Figure 5: Comparison of wall deflection at excavate to +111.1mAOD. Left = SAA-8003 raw data Vs back-analysis prediction; Right = SAA-8003 anti-rotation corrected data Vs back-analysis prediction.

The rotation error diagnostic was performed on the SAA-8003 raw data, the distributed readings in X (transverse to the wall) and Y (along the wall) at 25m above the bottom (approximately +111.2mAOD) are plotted in Figure 4 as an example. Over 600 days of monitoring time, the rotation error displacement pattern coincided with three short periods as highlighted red box in Figure 4. It can be seen that the anti-rotational corrected readings in X direction gradually increased to peak value approximately of 10mm around day 200, a steady value was maintained till day 400, and a flat increase of a couple of millimetres afterward. Meanwhile, the anti-rotation corrected reading in Y direction showed a slight shift (within ± 2mm) along the wall. These movements are considered in association with a gantry crane lifting operation on the top of the capping beam. The anti-rotational corrected SAA-8003 readings are included in Figure 5 for comparison.

Ultimately, the anti-rotation correction led to the decreased maximum wall deflections and affected the back analysis results. An example of TCR-WTH deep box back analysis at excavation to the level of +111.1 mAOD is presented in Figure 5. The back analysis carried out during the TCR-WTH construction was based on the SAA-8003 raw data on 11/07/2012 with the maximum deflection of about 10 mm, which concluded the 'most probable' undrained stiffness of London Clay as E_u/c_u =1000 (Yeow et al., 2014). However, the anti-rotation corrected SAA-8003 data presented the maximum deflection of approximately 7 mm from the same excavation stage, therefore, the back analysis presented a stiffer undrained stiffness of London Clay as E_u/c_u over 1750 (Chen, 2018). Both back analyses were performed in a 2D finite element model, and the actual 3D excavation effect at deeper excavation stages was compensated using the strengthened stiffness value.

2.2 Review of Strain Gauge data – temporary prop axial force

During TCR-WTH deep box excavations, six steel tubular prop locations were selected at each propping level to monitor the axial forces. They are S2, S5, S6, S7, S8, and S11 and are indicated in Figure 2. For instance, the horizontal prop S2 at the 1st level is referred to be P1S2 (CHS Ø1016×16t), and its axial force values calculated from three monitoring points are presented in Figure 6. Three monitoring points are located along with the prop near two ends and at the centre of the prop: E = east end, W = west end, and C = central point. Each monitoring point comprises four strain gauges. The axial force was calculated using the averaged strains.

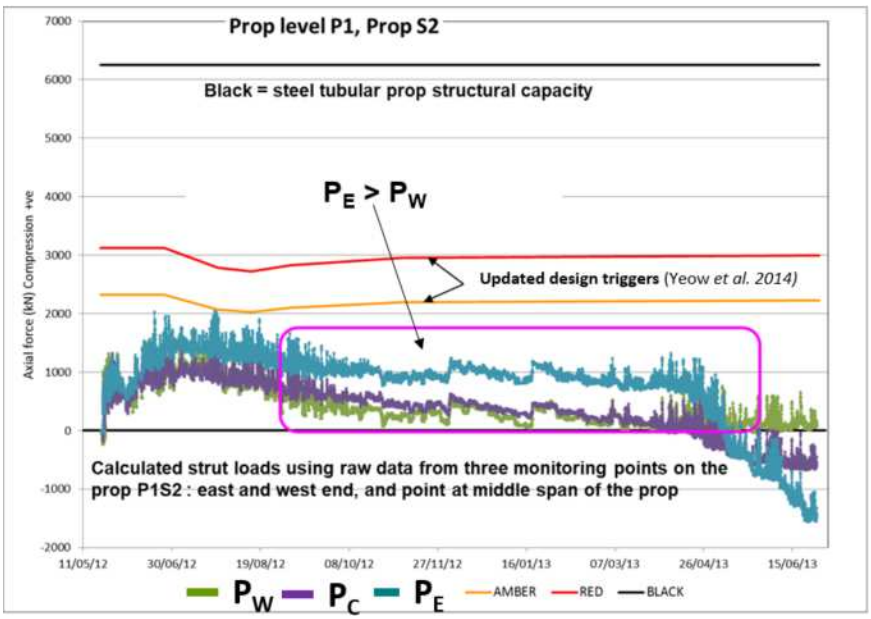

Figure 6: The calculated P1S2 axial force (Ingram & Man, 2013)

It is clearly shown in Figure 6, that the maximum calculated P1S2 axial force was below the amber and red trigger levels which were the updated values in the modified TCR-WTH design (Yeow et al., 2014), accounting for less than 1/3 of the structural capacity of the P1S2. The significant thermal loads in both diurnal and seasonal were observed. However, the large variation between the average axial force from three monitoring points of the same straight prop have raised concerns about strain gauge data reliability. For instance, the east monitoring point recorded force up to twice the load as the central or western monitoring points.

The post-construction review of the strain gauge data was referenced to the available as-built records, such as dated site photos (Figure 7), site meeting minutes, and resident engineer records. A few reasons were considered to cause poor performance in the interpretation of prop axial force, including:

1) Bending stress occurred in both the horizontal and the vertical planes due to the irregular shape of the box and uneven surface of the retaining wall. In addition, the as-installed four strain gauges were attached to the surface of the prop at 45 degrees from the vertical, missing the opportunity to accurately measure the bending stresses.
2) At two end monitoring points, strain gauges may have been positioned too close to the waler beams. Batten et al., (1999) pointed out the stress re-distribution could take place within the stress concentration zone (<3D, D is the outer diameter of steel tubular prop) at the steel prop connection joint.

3) Additional loads may have been introduced and locked in during the strain gauge baseline reading period, this is associated with the construction activities, for instance, the uneven excavation. Strain gauge baseline reading needs to be taken before struts are locked off.
4) The calculation of axial force ignored the additional bending stresses. Unfortunately, the as-installed gauges' position also added uncertainty in interpreting the bending stresses.

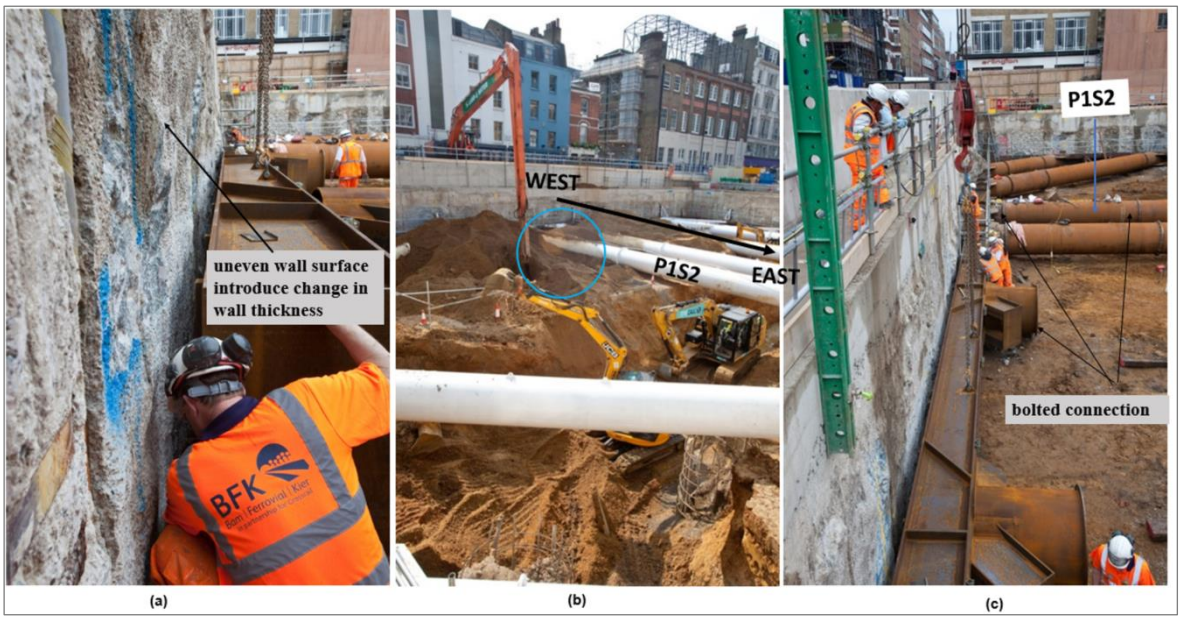

Figure 7: TCR-WTH site photos - (a) uneven wall surface; (b) uneven excavation sequence; (c) monitoring point close to the welding sections (Chen, 2018)

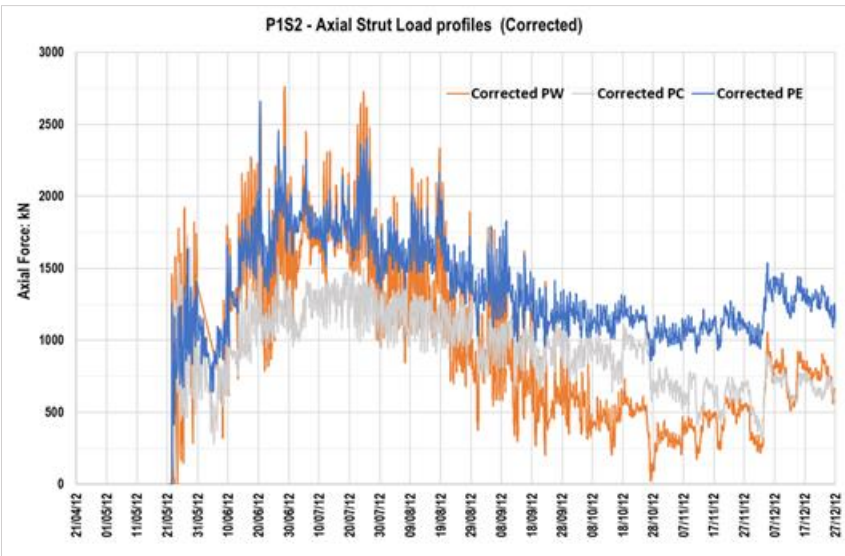

Figure 8: The corrected P1S2 axial force (Chen, 2018)

Attempts were made to correct the axial force calculation by addressing the faulty interpretation of stain gauge data and taking the biaxial bending stresses into account. The re-calculated P1S2 axial force was found that the maximum force increased to approximately 2000kN from the original 1500kN as shown in Figure 8, the discrepancy in the axial forces between the three monitoring points was narrowed but not fully eliminated.

3. Conclusions

The Crossrail TCR-WTH excavation case history provides a good example of monitoring data and the benefits of utilizing the data in the observational method. The post-construction review of the monitoring data illustrates

that the accuracy and reliability of data can be improved through appropriate data reviews, error diagnostic, and corrections. The quality of monitoring readings is depending on several factors, such as specification, calibration, installation, baseline, and continuing data review. These factors shall be incorporated into the monitoring plan for all instrumentation systems.

Key learning points from the TCR-WTH inclinometer monitoring data review and strain gauge data review are summarised below:

- Data error is associated with the installation and process of taking measurements. Skilful instrumentation technicians are needed for well-executed installation and conducting regular data reviews.
- A thorough instrumentation plan is needed, for instance, the strain gauge layout and positions. The monitoring specification needs to be tailored to individual project characteristics.
- A sufficient period is recommended for the baseline readings prior to the major construction activities. This period needs to be built into contractual agreements in individual projects.
- The routine inclinometer data review shall include the standard error diagnostic and error corrections. In the TCR case, the post-construction data review demonstrated it was possible to improve data reliability through the robust review process, however, the opportunity to maximize the value of data through the reliable back analysis has been missed.
- Inclinometers shall be extended by a redundancy length (i.e., 3 to 5 m depending on ground condition) below the wall toe level to ensure the fixity of the inclinometer at the bottom. Alternatively, the secondary reference method shall be included, such as a survey station with 2D/3D prisms of comparable accuracy (in relation to the TCR-WTH inclinometer toe movement, the prism accuracy of +/- 1.0mm is required) at multiple levels readings.
- When strain gauges are used to monitor prop force, data interpretation shall consider all influential factors, such as bending stress and thermal loads. Load cells shall be considered as well.

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