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Field monitoring of piling effects on a nearby masonry vault using distributed sensing

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ABSTRACT This paper presents a recent case study of monitoring the effects of piling on an adjacent old masonry vault in London. The monitoring scheme consists of 3 independent instrumentation sets that provide different types of information: (a) discrete total station point targets, (b) linear distributed fibre optic cable sensors and (c) surface distributed laser scanners. The availability of these sensors is able to shed some light on the actual response of the masonry structure through precise displacements and high-accuracy localised strains. The collected monitoring data show the location of cracks and provide indications for their opening magnitude. Relevant numerical analyses have also been conducted using (a) limit analysis mechanisms and (b) finite element deformation analysis which confirmed the observed field deformation mechanism and the presence of cracks within the structure. It is shown that such innovative sensing approaches can provide valuable detailed information about the real behaviour of structures that were not available before.

1 INTRODUCTION

Recent work during the London Bridge Station redevelopment involved construction of piles inside historic brick barrel vaults. The latter were monitored regularly by total stations in order to maintain safe operation of the transport systems throughout the course of the redevelopment.

Two additional spatially distributed sensing systems were used to provide more detailed monitoring data: (a) distributed Brillouin Optical Time Domain Reflectometry (BOTDR) and (b) laser scans.

This paper presents some of the monitoring data collected during piling within the masonry vault. Special emphasis is given on the relative merits of discrete total station prisms and distributed fibre optic (FO) and laser scan data, especially in detecting regions of localized cracks.

2 THE MASONRY STRUCTURE

Figure 1 shows a longitudinal section cut through the vault which also includes the geometric details of the arch and the local shallow soil stratigraphy. The arches were constructed on shallow concrete footings founded in made ground and soft alluvium.

During September to December 2013, 57 end-bearing piles were constructed under the arch. These are 450mm diameter CFA piles which terminate in London Clay.

3 MONITORING SYSTEMS

3.1 *Discrete-point total station prisms*

Total station devices use a laser beam and a precise servomotor and emit a modulated wave reflected from

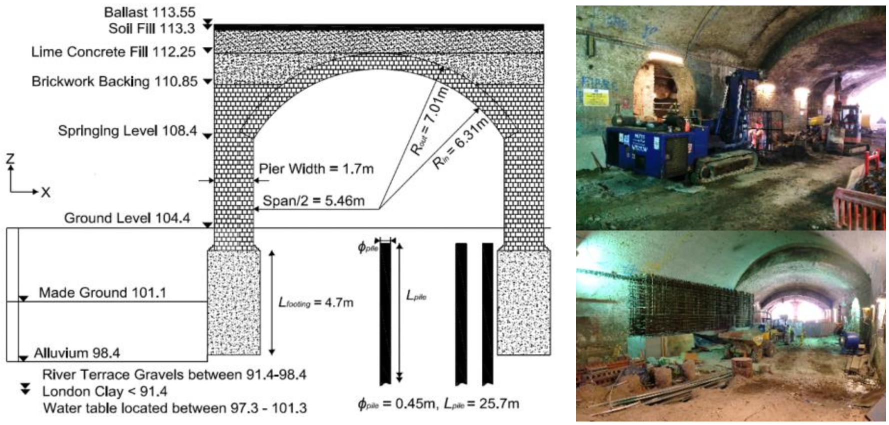

Figure 1. Longitudinal cross-section (left) and photos of the arch and piling works (right).

optical targets which is used by the device to determine the centre of the optical target and its relative location.

In this project a number of discrete-point prisms were installed in the masonry vault in an array of 3 prisms in each cross-section of the vault (Figure 2). The total station provides the exact location of the prisms and therefore using successive measurements, one can determine the relative displacements. Then by getting the difference between displacements of adjacent prisms and dividing this by their distance, one can obtain the averaged strain over that section.

3.2 *Distributed FO cables*

The distributed BOTDR technique uses optical fibre to monitor axial strains on civil infrastructure (Soga, 2014). A change in the Brillouin frequency of the back-scattered light within an optical fibre is linearly dependent on the applied strains. Therefore, the FO cables provide directly the axial strains within the monitored infrastructure (Soga et al., 2015).

Distributed FO sensing techniques have been used widely over the last 10 years to monitor various types of civil infrastructure, such as tunnels (Mohamad et al., 2010, 2012; Cheung et al., 2010), piles (Klar et al., 2007), retaining walls (Mohamad et al., 2011; Schwamb et al., 2014; Schwamb & Soga, 2015) and slopes (Amatya et al., 2008). The principle of FO sensing is based on the strain-dependent change of light frequency within a bare optical fibre (Soga, 2014). A detailed explanation of the background theory and examples of recent applications may be found by Soga et al. (2015).

In this masonry vault, a close loop of a FO cable was installed to monitor several points within the structure, and was installed as shown in Figure 2.

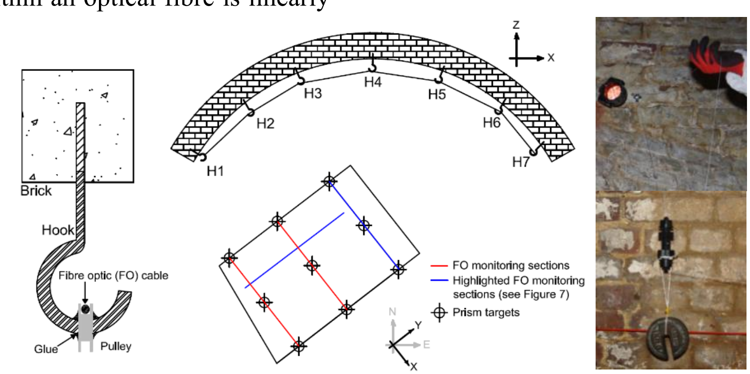

Figure 2. Attachment of the FO cables to masonry (left), arrangement of cables in arch (middle) and photos from the installation (right).

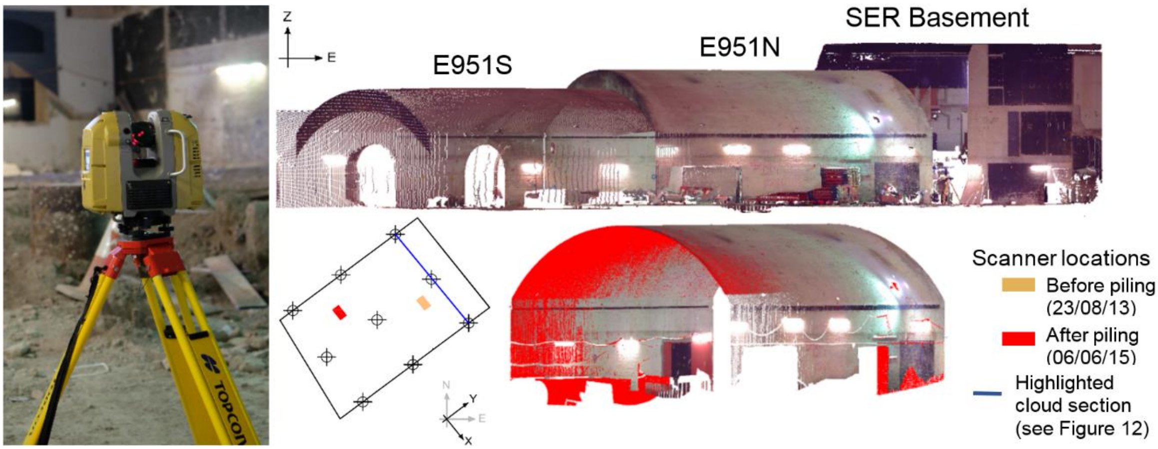

Figure 3. A laser scanner device (left), a colorized point cloud (top right) and locations of point clouds from laser scan surveys during piling (bottom right).

3.3 Distributed laser scans

Terrestrial laser scanners are geomatic devices equipped with a laser beam and precise servomotors, carrying out similar surveying operations to total stations. Several techniques exist to convert the laser scans to absolute structural displacements and these may be found elsewhere.

In this structure, laser scans were taken using firstly a FARO Focus 3D S20 laser scanner and later a Topcon GLS-2000 laser scanner. These provide a ranging error of 2mm and angle measurement error of 6 arc seconds (Figure 3). The data processing procedure took advantage of the open source software Cloud Compare.

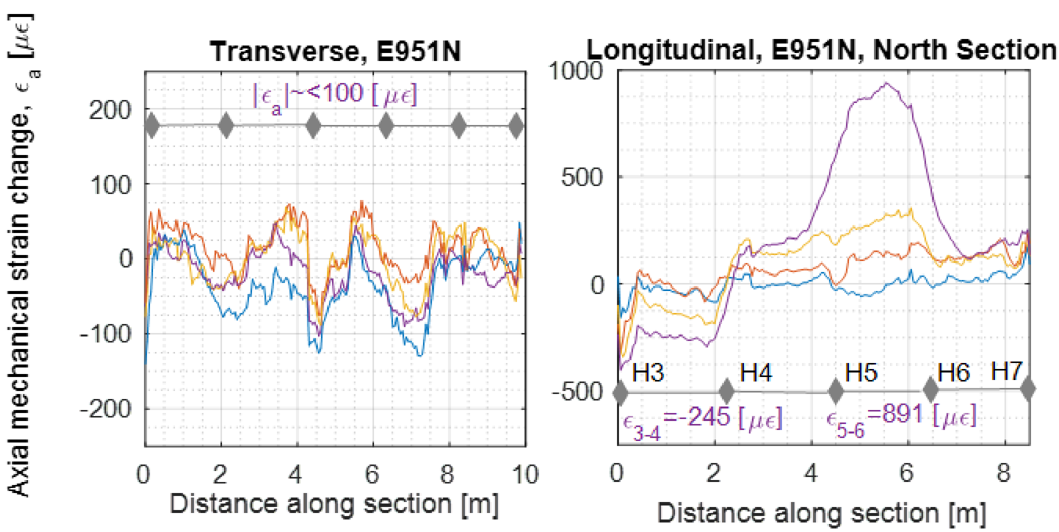

Figure 4. Change in axial mechanical strain during piling for selected sections

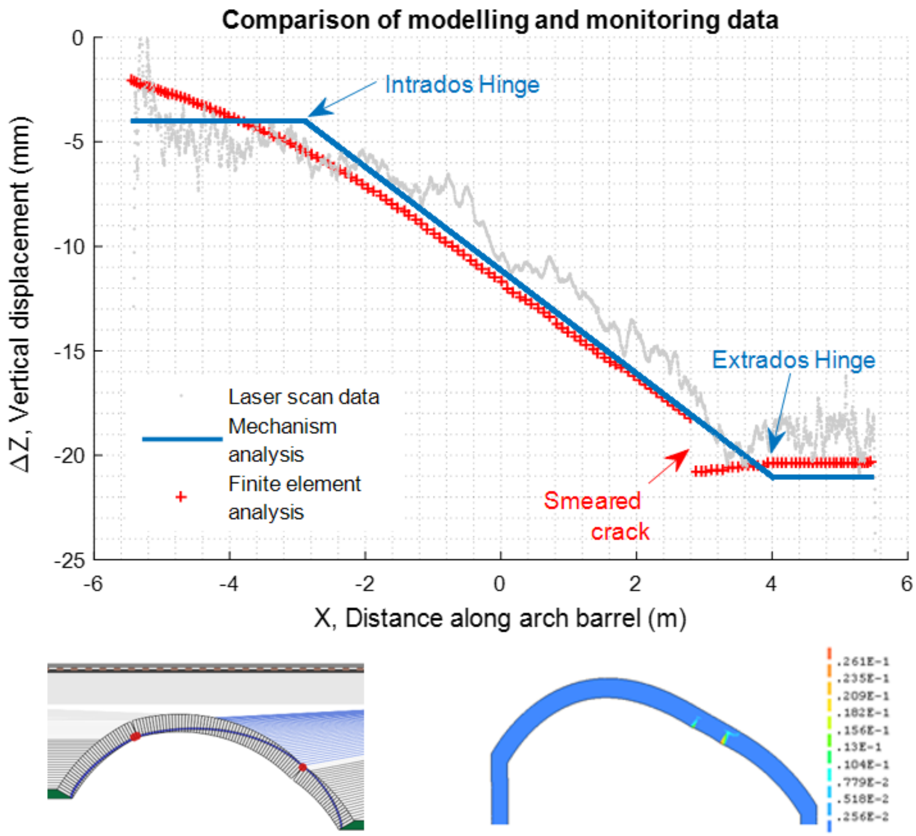

Figure 5. Comparison of vertical deformations from the laser scan (M3C2) method, mechanism and FE models.

4 MONITORING RESULTS

The monitoring results from the distributed FO cables are shown in Figure 4. It is shown that some sections do not show significant development of axial cable (and hence, structural) strains, whereas some sections show some high unexpected strain values which also exhibit some localized peaks. The latter peaks may suggest the development of localized tension cracks.

In order to check the monitored response from the 3 sensing systems, independent numerical analysis studies have been undertaken using limit analysis mechanism and finite element (FE) deformation models. Figure 5 shows the vertical displacements of one cross-section of the masonry arch (for which the FO cables showed some high values of axial strain) from the laser scans and the numerical analysis.

The latter figure shows that a localized crack is suggested by both the field monitoring data and the numerical analysis results. This is attributed to the nearby piling operations which may have caused some settlement of one of the vault piers and hence re-distribution of the arch stresses.

It is finally shown that the nature of the distributed FO and laser scan systems provides an advantage over conventional discrete sensing systems in determining localized deformations such as cracking.

5 CONCLUSIONS

This paper presents some monitoring data from a masonry vault at the London Bridge Station which experienced some movements due to nearby piling construction. Three independent monitoring systems have been deployed and the results have been analysed.

The analysis showed that the spatially distributed systems (fibre optics and laser scans) provide an advantage over conventional discrete systems, such as total station prisms, in detecting localized regions of high strains and possible cracking.

Relevant numerical analyses (both limit analysis mechanism and finite element deformation analyses) were able to match the observed trend of strains and displacements within the vault, therefore confirming the validity of the monitoring data.

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