The role of fibre optic instrumentation in the re-use of deep foundations

Rôle d'une instrumentation en fibre optique pour la réutilisation de fondations profondes

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ABSTRACT: The re-use of existing foundations, in particular piled foundations has increased in recent years due to the significant environmental and commercial benefits. However, there has been limited progress in assessing the condition of such piles by considering the effect of initial use and the impact from the subsequent demolition process which often requires a detailed study. This paper will provide details of a recent project in London that successfully reused all exiting piles beneath the site and optical fibre sensors were instrumented to the existing foundations in order to monitor the behavior of piles during the demolition of the existing building. The use of optical fibre instrumentation is believed to be the first of such an approach in observing the behavior of reuse piles during demolition in the UK and as urban environments become more congested particularly below ground, the approach discussed in this paper will become increasingly valuable. The monitoring data is presented and discussed in detail and the role of using these sets of data in assessing the reuse strategy is also highlighted in this paper.

RÉSUMÉ : La réutilisation de fondations existantes, en particulier de fondations sur pieux, a augmenté ces dernières années en raison des avantages environnementaux et commerciaux significatifs. Cependant, l'état des pieux suite à leur première utilisation et le processus de démolition sont souvent négligés. Ce document présente un projet récent à Londres où les pieux ont été instrumentés avec des capteurs en fibre optique, avant la compagne de démolition. Les fibres optiques permettent de mesurer des déplacements le long des pieux lors de la démolition. L'utilisation d'une telle instrumentation est une première au Royaume-Uni. Les données de la compagne de surveillance sont présentées et discutées en détail. Une stratégie de réutilisation des fondations sur pieux est également proposée dans ce document.

KEYWORDS: Re-use foundations, Optical Fibre Sensors (OFS), Brillouin back-scattering

1 INTRODUCTION

Foundation re-use can generate significant environmental and commercial benefits, and is becoming a popular engineering option, particularly in congested urban environments. Due to the many practical constraints, most redevelopments need to be constructed on the existing foundations together with a new pile system; therefore it is crucial to understand the geotechnical behaviour of reused piles and their compatibility with the new structure. This is often difficult without removal of significant parts of the substructure. Previous researches (Leung et al., 2011; Begaj-Qerimi&McNamara, 2010) have shown that pile behavior may change with time, due to consolidation and ageing, residual stress at the pile base and increased soil stiffness; hence reused piles are often stiffer than new piles. On the other hand, the building demolition process could potentially introduce ground heaving and the physical unloading of the reused piles can also generate tension cracks. These differences in pile responses need to be properly assessed in the design of a new pile system.

A recent project in London provided the opportunity to further develop the understanding of foundation reuse by installing fibre optic sensors in both existing piles and a borehole to observe the impact of the demolition process on the changes in piles behavior and ground response. The site is located at 6 Bevis Marks and near to Liverpool Street, London, UK, and it was proposed to reuse all existing foundation piles and the majority of the basement substructure on this project. This approach produced significant commercial and environmental benefits.

The existing piled foundations are large diameter under-ream piles, and there was a concern that these piles would be damaged during the demolition process. Such damage is usually caused either by the forces generated by the removal of significant load as the building is demolished, the tensile forces within the piles and surrounding soil, or physical damage caused by demolition of the substructure, pile caps and pile breaking down. This can lead to the reuse being questioned and ultimately being discounted.

This paper explains how optical fibre instrumentation was used to monitor pile and ground response under demolition and will present the data captured by the fibre optic instrumentation during the demolition process. It will show how the use of such sophisticated instrumentation was fundamental to the successful reuse of the existing piles on this project.

2 SITE DESCRIPTION

2.1 *Existing site and proposed redevelopment*

The existing building at 6 Bevis Marks was constructed in the early 1980's and comprised eight superstructure floors and two basements. The existing foundations system includes (i) piles located inside the basement, which is approximately 7.0m below pavement level, and (ii) piles constructed in the Bevis Marks pavement, which is approximately 3.5m below pavement level as shown in Figure 1. All existing piles were designed and constructed by Cementation Skanska as under-ream piles.

The local geology comprises made ground overlying Terrace Gravels, which in turn rests on London Clay. The top of the London Clay is within 2m of the existing basement level and all piles, both existing and new, are founded within this stratum. The existing piles were designed to carry total building loads of 350,100kN and 33,900kN for those inside and outside the basement, respectively. There are a series of heavily reinforced pile caps and ground beams, and their thickness varies across the site. Typically the ground beams are around 1000mm to 1500mm deep at pile positions, and the pile caps vary from 1500mm to 4150mm deep. This complex pile foundation system practically constrains the available physical space for designing new piles.

The scheme design was developed with the existing building arrangement and existing foundation arrangement in mind. However, with the proposed building being taller (sixteen floors in lieu of eight) and the main stability systems located in slightly different areas, the existing foundations proved to be inadequate as a whole. The result of technical studies demonstrated that the existing piles were overloaded by some 85,000 kN when compared to actual load carried originally.

To enhance the existing piles where they were found to have inadequate capacity, supplementary piles needed to be installed. Figure 2 shows the significant subsurface congestion beneath the site when new piles were installed.

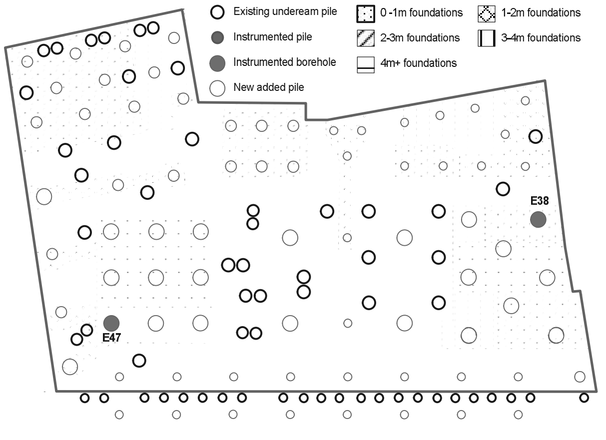


Figure 1. Pile layout and physical constraints to substructure.

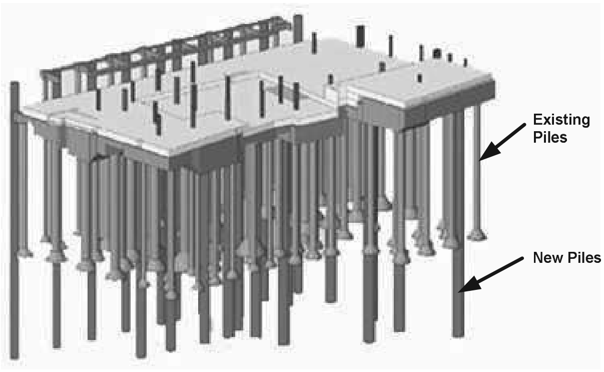


Figure 2. Foundation system including the existing and new piles.

2.2 *BOTDR sensing principle*

Brillouin Optical Time Domain Reflectometer (BOTDR) was adopted for this project. It provides sensitive strain measurement from the reflected light that travels along the standard single mode fibre optic cable. The entire fibre cable can be considered as the sensor itself. When the light travels in the optical fibre sensor, the majority of it travels through but a small fraction is back scattered as shown in Figure 3. In the back scattered spectrum, where only Brillouin spectrums are temperature and strain dependent, the frequency shift of the Brillouin spectrum indicates the local change in the fibre properties induced by the change of strain and temperature. Hence, the change in strain and temperature along the fibre optic sensor is proportional to the frequency shift, which can be detected by the BOTDR analyzer. The analyzer used in this study is capable to sample 1 m averaged strain or temperature at every 5 cm with an accuracy of 50 $\mu\varepsilon$ and up to a distance of 10km.

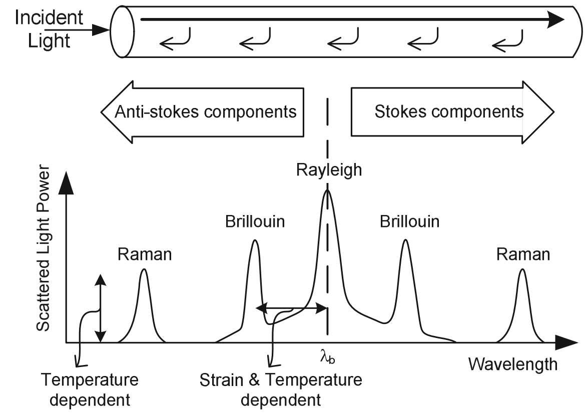
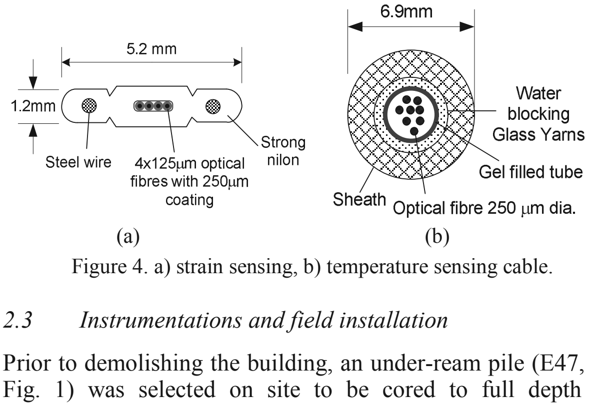


Figure 3. The spectrum of backscattered light.

Due to the principle of Brillouin backscattered sensing, the system registers strain induced by the elongation of the optical fibre itself and the strain resulted from temperature change. Therefore it is necessary to incorporate two different types of optical fibre sensing cables to compensate for temperature effect. Figure 4 shows two types of cables which have been carefully calibrated and widely used for infrastructure sensing (Klar et al., 2006; Mohammed, 2012). Figure 4a shows the strain sensing cable, which consists of four optical fibre members tightly bonded by strong nylon material. This is to ensure the strain can be fully transferred from the nylon coating to the optical fibre itself. Two steel wires at both ends reinforce the cable and make it robust enough to survive in the harsh construction environment. The temperature cable shown in Figure 4b consists of several optical fibres in a gel filled tube, so that it can contract and expand only under temperature effects, independent of mechanical strain.

The use of optical fibre technology has numerous advantages over conventional monitoring systems, it is capable of providing a continuous and full length strain profile and this makes it possible to monitor for cracking of the pile along its full depth. The continuous strain profile also provides a picture of what is happening over the full pile shaft; this would not be possible with traditional single point based system such as vibrating strain gauges or extensometers.



(a) (b)

Figure 4. a) strain sensing, b) temperature sensing cable.

2.3 *Instrumentations and field installation*

Prior to demolishing the building, an under-ream pile (E47, see Fig. 1) was selected on site to be cored to full depth for inspecting and assessing concrete quality. Fibre optic cables were attached to a flexible pipe and installed to the full depth of the cored hole. Table 1 lists the detailed level of the under ream pile. In addition, a new borehole was drilled to 35.5m adjacent to an instrumented pile in the basement and also instrumented to full depth to capture potential ground heave during the demolition process.

This paper will present the data recorded during the demolition process and summarise the results to highlighting the role of the instrumentation in the successful reuse of the deep foundations on this project. It will also include details of challenges faced in using the fibre optic sensors to instrument existing deep foundations, which is believed to be the first of such use in the UK.

Table 1. Summary of instrumented pile

	PileE47
Core length [m]	20.16
Coring length [mAOD]	7.46
Toe Level [mAOD]	-13.70
Original Design Toe Level	-13.00
Shaft Diameter [mm]	1500
Bell Diameter [mm]	3300

3 FIELD DATA ANALYSIS

There are ten sets of strain data that have been collected on five dates from 15/08/2011 to 05/10/2011 up to building level 3 of the demolition programme. All optical fibre strain sensing cables and optical fibre temperature sensing cables, installed in the pile and the borehole close to one of the piles, were monitored as close as possible to the removal of each floor. The data from 15/08/2011 taken when the 6th floor had been demolished and 05/10/2011 when the 3rd floor was demolished is presented in this paper to evaluate the pile and borehole performance. The original geotechnical design load on the pile was around 7,250 kN to 7,500 kN, but the structure takedown load on these piles (i.e. the load they experienced under use) is more likely to be around 65 percent of this at around 4,700 kN to 4,900 kN.

3.1 Pile E47

The first set of data was taken on 15/08/2012 and has been considered as the reference for comparing with the dataset collected on 05/10/2012. The profile of strain change between the two periods is shown in Figure 5(a). In general, the axial strain is reducing from the top to the middle part of the pile (0-9m) in the range between 0 and 100 micro-strain, and the axial strain change becomes reasonably small in the base part of the pile (9-17m). After integration of the strain profile, the calculated overall vertical heave between the two periods is less than 1mm at the pile head as shown in Figure (b).

Pile E47 was initially constructed with a design concrete strength f_{cu} of 30 N/mm^2, with a corresponding modulus of elasticity varying from 20 to 32 *GPa* as suggested by BS 8110-2:1985. The concrete strength data taken from the tests on the full length cores in pile indicates that the concrete strength in-situ is between 47 N/mm^2 to 56 N/mm^2. The modulus of elasticity of this concrete can be calculated, allowing for creep and degradation, as ranging from 26 GPa to 43GPa. Figure 5(c) shows the load profile by assuming the pile Young's modulus is 26GPa. Hence, the axial force reduction at the top of pile can be estimated to be around 3,830 kN, which roughly corresponds well to the load removed between the two periods.

It is believed that nominal starter cages were installed into all of the original under-ream piles on this site and are likely to be between 9m and 12m in lengths. Reinforcement details for the existing piles were not available, as is often the case with reuse projects. The cage toes were observed in the strain measurements at 10m to 13m as a change in the strain profile, which indicates the pile is experiencing tension forces around the base of the reinforced section. It is suspected that this is as a result of the different Young's modulus between the reinforced and unreinforced sections of the pile.

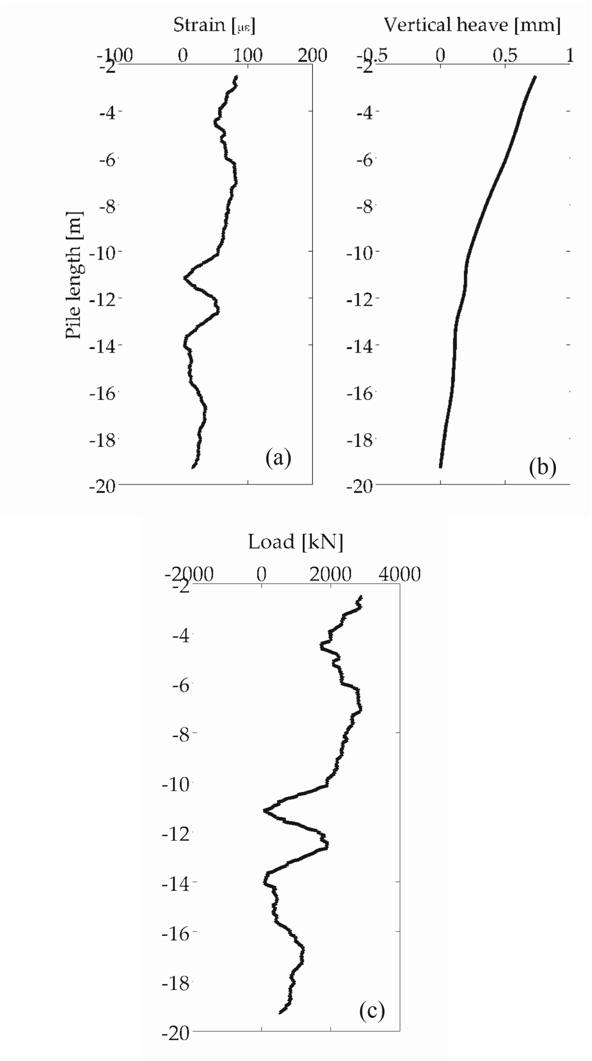


Figure 5. The calculated pile performance due to the demolition activities: a) axial strain along the pile; b) vertical heave; c) pile load.

3.2 Borehole

In comparison to the pile reaction to the demolition of the substructure, the magnitude of change in strain along the borehole is less pronounced than the results observed from the pile, which ranges within 50 micro-strain and within the accuracy range of the BOTDR system. The calculated strain profiles are shown in 6 including the strain profile along the borehole and the interpreted vertical heave is about 0.4 mm at the top. Due to the limitation of the BOTDR system, it is difficult to obtain the accurate vertical displacement profile from such small strain measurement, and the data shown in Figure 6 are the best approximation of the ground movement from the borehole measurements.

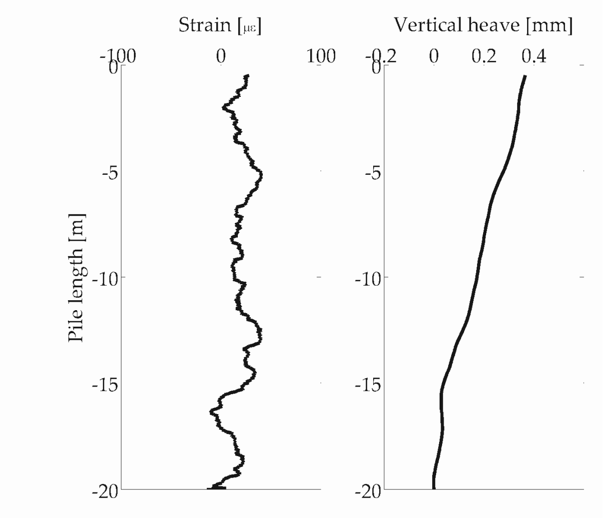


Figure 6. Strain profile along the borehole with interpreted ground heave profile.

3.3 Discussion

The magnitude of vertical movement measured from pile E47 during the demolition is smaller than 1mm. The resulting force generated at the top section of the pile is estimated to be around 3,800 kN by assuming the pile Young's modulus is 26GPa, and this is relatively large for a pile reinforced with only a nominal steel cage and justifies the concern towards the integrity of the pile post demolition. The significant advantage of using optical fibre instrumentation is that a continuous and full length strain profile is measured, which allows assessment of the potential for cracking of the pile as a result of the demolition induced (load removal) strains. This would be visible as localized sharp peaks within the strain profile and from such data it would even be possible to calculate potential crack thickness. There are no signs of cracking along pile E47 throughout the whole depth and as such there appears to be no visible signs of any detrimental effect of the demolition process up to the 05/10/2011.

With regard to the instrumented borehole, very small strain variation was observed during the monitored demolition process. Such small strains are indicative of small heave forces generated. This could be as a result of both the location of the borehole, which was close to the edge of the basement, and almost certainly as a result of the confining effect of the existing piles and basement slab.

There remain a large number of exiting piles that have not been instrumented and will be reused. Nevertheless, the monitored piles and borehole gave a good indication of the typical response of the existing piles beneath 6 Bevis Marks to the removal of building load during demolition. The results were an essential part of the proofing process and validated the reuse strategy.

4 CONCLUSIONS

Currently the primary source of information available for considering foundation reuse are limited to "as built" design and installation records. Although in the future these may be more comprehensive than what are currently available on development sites, the extent of re-use will be limited to the quality of such records. This will in turn constrain the future development options for such sites and is likely to influence the asset values of the site and the existing development, and the viability of redevelopment.

There are developments taking place continuously where more piles are being added to those installed previously, either re-using the existing piles, but more often than not, ignoring the capacity of existing piles, further restricting the future development potential. In the UK high capacity bored piles have been widely used since the 1950s and it is not unusual for a site to be on its second or even third set of piles, all of which will obstruct and constrain further developments.

Traditionally, low strain pile integrity testing is carried out to confirm that new piles have been constructed correctly and no discontinuities exist. It is also used to assess the integrity of existing piles for reuse, usually with mixed success. Such testing is often not appropriate for pile reuse as,

- To carry out a low strain integrity test, the top of the pile needs to be exposed and structurally separated from other foundations. This is not possible where pile caps, slabs and basement substructures are to remain in place for reuse.

- Such testing only confirms if there is a crack, not how big it is or what is below it. When demolishing an existing building, the expected ground heave may crack the piles to some degree, such cracks are expected to be small and to close up upon pile reload but these tests cannot confirm this.

An alternative solution is to install fibre optic strain measuring devices into existing piles that have been cored full depth and into future piles on installation, producing a smart foundation system. Making this provision for the future will not only increase the potential for re-use and increase its asset value, but is also likely to make the asset more valuable when compared to other properties where such "future proofing" has not been incorporated. Such an approach will allow monitoring of how the piles actually perform under loading, unloading, reload and during the life cycle of the building. Results could be used to further advance our understanding of actual foundation response during the construction phase and operation of such buildings.

5 ACKNOWLEDGEMENTS

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