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The response of a piled structure to tunnelling and jacking

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ABSTRACT: New London Bridge House is a piled structure that was influenced by the construction of London Bridge underground station as part of the Jubilee Line Extension Project. The part of the building that is of interest is a lift shaft structure that was added to the main building following its construction. Tunnelling-induced movements of the lift shaft were to be kept within a limited tolerance to avoid any separation of the structure from the main building. This was achieved by using a series of jacks at the base of the lift shaft. This paper describes the underground construction that was carried out near the building, and the protective measures that were implemented to minimise movements. Results from monitoring of the lift shaft by precise levelling, during the different phases of construction are presented and the effectiveness of the protective measures is discussed.

1 INTRODUCTION

The construction of the Jubilee Line Extension (JLE) provided a unique opportunity to carry out field studies investigating the response of a wide range of existing structures to tunnelling. This allowed, *inter alia*, the practical appraisal of the effectiveness of a variety of traditional and novel protective measures. The extension begins at Green Park, passes under the Thames at Westminster and runs east to Canary Wharf and Greenwich. Of the eleven stations along the extension route, the station at London Bridge was undoubtedly one of the most complex.

This paper presents monitoring data showing the response of one of the piled buildings at London Bridge, New London Bridge House (NLBH), to the JLE works. Prior to the JLE construction, a twin lift shaft structure was added to the southern face of the NLBH. The new construction was designed to minimise the effects of future tunnelling for the JLE and incorporated eight jacks built into the shaft basement to provide a means of controlling relative settlement. The results from monitoring the shaft by precise levelling during the different phases of construction are presented and the effectiveness of the protective measures is discussed.

2 SITE DESCRIPTION

2.1 Site geology

The geology of the site has been described in detail elsewhere (Withers et al. 2001). Fluvial and glacial deposition/erosion has created a clearly stratified geological section producing soil layers nearly horizontal with a relatively consistent thickness across the construction area. A soil profile including the main tunnel geometry is shown in Figure 1. Tunnel excavation at London Bridge encountered mainly London Clay, although some excavation was carried out in the strata above and below extending to the Upper Mottled Clay of the Lambeth Group during construction of the eastern ventilation shaft and running tunnels at the eastern end of the site.

The hydrogeology of the area is controlled by two aquifers, the "upper aquifer" being the superficial Terrace Gravel deposits overlying the London Clay, and the "lower aquifer" comprising the basal units of the Lambeth Group, the Thanet Beds and Upper Chalk. Of the two aquifers, the upper is unconfined whereas the lower is generally confined. To facilitate excavation through the upper aquifer, groundwater was excluded by constructing cofferdams or by injecting grout in the ground or by a combination of the two methods.
2.2 London Bridge area

A comprehensive description of the London Bridge area has been given elsewhere (Field, 2001 and Riley, 2001).

London Bridge Station is situated in Southwark, southeast London. The area has been a major transportation interchange with links to the existing Northern Line underground route and to the surface railway station adding both to the utility of the JLE project and the complexity of the construction. The general topography of the area has greatly altered due to past construction activities. During construction of the railway station, a new road named London Bridge Street was built on a series of brick arches to provide pedestrian and vehicular access to its entrance and concourse. As a result, London Bridge Street is an elevated street that rises towards the east up to approximately 5m adjacent to NLBH. Figure 2 shows the location of NLBH within the London Bridge area.

2.3 New London Bridge House

NLBH is situated on the northern side of London Bridge Street (No. 25), adjacent to the NSE railway station. The building is in two parts, one a low-level structure, curved in plan, the other a 24-storey reinforced concrete office block with a double basement car park. This paper is only concerned with the tower block. Constructed in 1972, the building has a distinctive mottled grey mosaic tile and extensively glazed façade. The structure is founded on 1.4m diameter piles which are underreamed to 3.4m. The piles extend to approximately 80m Project Datum (−20m Ordnance Datum). NLBH is situated within 10m (in plan) of the centre-line of the eastbound station tunnel at London Bridge station. The pile bases are approximately 2m above the axis level of this tunnel.

Prior to the JLE construction, a piled lift shaft was added to the main building to facilitate an increase in the volume of staff accessing the building. The lift shaft was founded on a group of 600mm diameter bored piles. The elevation of the bored pile bases varied between −17 and −23m OD. The lift shaft was connected to the main building by a series of L-shaped angle bracings.

3 UNDERGROUND CONSTRUCTION

Underground construction at London Bridge comprised two station tunnels, a concourse, escalator tunnels and a network of shafts and interchange passages (Figure 2). Construction for the JLE at London Bridge commenced in July 1994 and was completed in July 1997. In general, it was possible to excavate within the London Clay using open face tunnelling methods, SCL and hand-mining.

3.1 Running tunnels

The 5.4m diameter running tunnels were excavated from 20 June 1995 to 3 August 1995 using the sprayed concrete lining (SCL) method. Excavation was carried out in two stages: a 3.0m heading and a 2.4m invert. The thickness of the shotcrete temporary lining was about 150mm. Shotcrete sections were reinforced with 7mm diameter steel mesh of 150 x 150mm spacing and with lattice girders consisting of three 12-16mm diameter reinforcement bars, which were installed around the tunnel perimeter after each 1m of advance.

3.2 Station tunnels and concourse

Station tunnels were excavated from 29 November 1995 to 1 March 1996 as enlargements of the 5.4m diameter pilot tunnels (driven as part of the running tunnels). The 8.7m diameter station tunnels were excavated in three levels: a 3.5m heading at
the top, a 2.5m bench in the middle and a 2.7m invert at the base. The thickness of the shotcrete temporary lining was about 300mm (two layers of 150mm). Shotcrete sections were reinforced as described above for the running tunnels. Following the excavation and application of the sprayed concrete lining, a permanent spheroidal graphite iron lining was installed in the station tunnels.

The concourse tunnel was constructed from 8 August 1996 to 13 September 1996 using a similar technique with a pilot tunnel followed by an enlargement.

3.3 Eastern escalator tunnel
The eastern escalator tunnel was excavated using hand-mining techniques in two sections. The first section started in the car park of NLBH, whereas the second section was erected underground, from a break-out of the long pedestrian subway and continued down to the eastern end of the concourse tunnel.

4 PROTECTIVE MEASURES
In view of the potential adverse effect of the JLE works on a number of existing structures at London Bridge various protective measures were adopted to alleviate tunnelling-induced disturbance.

4.1 Compensation grouting
Earlier studies by Zeidler et al. (1997) and Powderham et al. (2001) indicate that NLBH was not directly affected by compensation grouting.

4.2 Permeation grouting
Permeation grouting of the Terrace Gravels was undertaken close to NLBH as part of the eastern escalator works. This was undertaken to facilitate the excavation of the escalator and ventilation/escape shafts through the water-bearing Terrace Gravels by reducing their permeability and increasing their strength.

4.3 Jacking
A jacking system was incorporated into the new lift shaft to maintain the relative position of the lift core to the adjacent NLBH. The operation of the jacking system was largely based on the results from precise levelling of monitoring points associated with each jack. Shims of suitable thickness were inserted to maintain the effects of jacking.

5 STRUCTURAL MONITORING
Structural monitoring included precise levelling, construction joint monitoring and calliper readings.

5.1 Precise levelling
Figure 3 shows a schematic plan of the precise levelling points installed at the basement of the additional lift shaft in relation to the JLE tunnel alignment. Some of these were installed beneath the jacks and some, due to access problems, were adjacent to the jacks. Points 1 to 6 were in the basement, below the jacks and points 7 & 8 were at street level, adjacent to the jacks (see Figure 3). The superstructure itself was not monitored but its vertical movements were determined from the thickness of the shims used.

Precise levelling was carried out based on techniques described in BRE Digest 386 (BRE, 1993). The equipment used for the survey was a Leica © NA2 optical level with parallel-plate micrometer and a Leica © NA 3003 digital level with a 2m long bar-code invar staff. Levels were brought in to the NLBH area from the surrounding area not affected by the JLE works.

5.2 Construction joint monitoring
Construction joint monitoring was carried out at various levels of NLBH to check that the lift shaft structure did not move horizontally relative to the main part of the building using a series of Avon-gard tell-tales. These were located on the 5th and 16th floors and at the top of the building in the lift motor room. The overall control of the jacking operations was also exercised in careful accordance with observations of any differential movements. There was no significant movement of the lift shaft away from the main building and essentially no damage to NLBH has been reported as a result of the JLE works.
Figure 4 shows the absolute settlement of the eight monitoring points at substructure level during and after completion of the JLE works at London Bridge. The time sequence of the various construction activities is also plotted on the top of the same figure. Settlements during pilot tunnel construction (i.e. within first 30 days) were within 2mm, indicating the effectiveness of the first stage of tunnel construction. During this period only minimal jacking was performed, as the structure's movements were so small. This was followed by a period of no relevant construction activity in which ground movements can be largely attributed to consolidation-induced settlement.

During the subsequent phase of station tunnel enlargement the substructure experienced greater movements, with point J8, closest to the eastbound tunnel, settling up to 24mm. The settlement of all points showed a clear increase during the final stages of the station tunnel enlargement. These settlements relate directly to the tunnelling-induced volume losses from the eastbound tunnel. Similar pile responses to volume losses have been observed in model pile studies (Jacobsz et al., 2002). In the study by Jacobsz, critical zones have been identified where large pile settlements can be expected.

After completion of the station tunnel enlargement, settlements continued, but at a reduced rate, due to consolidation effects and also construction of the concourse and eastern escalator tunnels. It is unlikely that the construction of the western and eastern ventilation tunnels significantly affected the lift shaft structure.

As with immediate movements, the greater magnitudes of settlement took place at the front of the lift shaft (i.e. points J3, J4, J7 and J8) with the greatest settlement occurring at point J8 (up to 48mm). It is interesting to note that after its initial settlement at this time, the level of point J8 remained constant (while the other points gradually settled) before starting to rise. Some of the other points also appear to rise, the reason for this is not clear. Details of why the under-ream pile beneath J8 was incorporated into the new lift shaft structure foundation are unknown. What is significant is that this pile, being shorter than the straight-shafted piles, has its base within the critical zone identified by Jacobsz et al. (2002), and so was prone to greater settlements. This is evident from the leveling data.

Figure 5 shows a plan of tunnelling activity related to time during station tunnel enlargement. The shaded areas on the plan view correspond to the total excavation completed by the date defined in the legend. Figures 6 and 7 show the substructure response in relation to the various constructions stages defined in Figure 5. The results suggest that the lift shaft settled fairly uniformly with the magnitude of settlement increasing progressively with the distance of the tunnelling front from the line of monitoring. It is quite evident that after stage E there was a sudden increase in the vertical movement of all points, with point J8 settling at a greater rate. This dissimilar behaviour of point J8 can be attributed to the partial loss of end-bearing capacity of its nearby short under-ream pile whose base is likely to be within the critical zone of influence (Jacobsz et al., 2002).
Figure 5. Plan view of tunnelling activity related to time during station tunnel enlargement.

Figure 6. Substructure settlements at points J3, J4, J7 and J8 during tunnel enlargement plotted against (a) the end of periods A to F (see Figure 5) and (b) time.

Figure 7. Substructure settlements at points J1, J2, J5 and J6 during tunnel enlargement plotted against (a) the end of periods A to F (see Figure 5) and (b) time.
7 CONCLUDING REMARKS

Based on the results presented and discussed above, the following conclusions are drawn.

1. The construction of the complex works at the JLE London Bridge Station was implemented without adverse effects on the piled structure and in particular its adjacent lift shaft.

2. Buildings prone to tunnelling-induced settlements can be effectively protected using compensation jacking.

3. Piled structures can be subjected to tunnelling-induced settlements, the magnitudes of which are dependent on the position of the pile toe relative to the tunnel.

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