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Building response to tunnel step-plate junction construction - the former Lloyds Bank Building, St James's, London

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ABSTRACT: The former Lloyds Bank building, located in the St James's area of London, was affected by the construction of the step-plate junction that connects the southbound tunnel of the existing Jubilee Line and the eastbound tunnel of its new extension. The step-plate junction is located directly below the building footprint. As a protective measure, compensation grouting within the underlying London Clay was implemented from a shaft sunk adjacent to the building, to control the tunnelling-induced ground movements and building deformations. The response of the building to the construction activities was monitored by various methods, including precise levelling in the basement and total station surveying of the facades. The results of this monitoring together with contours of grout injection intensity are presented in this paper together with a discussion of the observed response of the building. The maximum building settlements resulting from the construction works of about 20 mm increased by about 10 mm in the following two years. Horizontal strains and displacements determined from the total station surveys were found generally to be negligible.

1 INTRODUCTION

The construction works described in this paper formed part of the Jubilee Line Extension Project (JLEP), London, information about which is given by Burland *et al.* (2001, 2002). Prior to the new extension, the final southern leg of the Jubilee Line ran from Green Park to its terminus at Charing Cross. The spur to Charing Cross does not form part of the new extension and step-plate junctions (SJPs) were required to join the existing running tunnels with the new ones connecting Green Park to Westminster stations. The eastbound SJP was built at a short distance from Green Park station in the St James's Park area of London. It was constructed largely beneath the former Lloyds Bank building, No.16 St James's Street (Fig. 1).

This building was monitored as part of the Imperial College LINK CMR (Construction, Maintenance and Refurbishment) research project (Jardine, 2001). The results from total station surveying of the facades of the building, undertaken during the works, are presented and compared with those from precise levelling in the basement, and discussed in relation to the overall response of the structure to the various excavation phases and compensation grouting episodes.

A more detailed account of the structure, construction works and building response is given by Standing *et al.* (2002a).

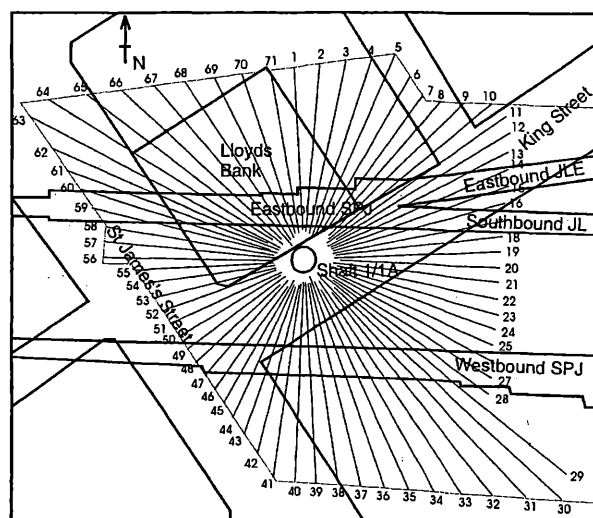


Figure 1. Plan of the St James's area in vicinity of Lloyds Bank with details of subsurface works: shaft 1/1A with TAMs radiating from it and eastbound SPJ.

2 GEOLOGY AND GROUND CONDITIONS

At Green Park, St James's Street is located roughly perpendicular to one of the Thames Gravel terraces and as a result falls from its northern junction with Piccadilly. Street level along the west-facing facade of the Lloyds Bank building falls from about 111.2 mPD to 110.6 mPD (metres Project Datum, i.e. Ordnance Datum plus 100m). The level in King Street, along the south-facing facade, is about 110.4 mPD.

During the drilling of a borehole within the building to install subsurface extensometers, a substantial 5.8-m thickness of unreinforced concrete and fill beneath the basement slab (108.2 mPD) was encountered. Beneath the fill were layers of Alluvium (1.4 m thick) and Terrace Gravels (2.5 m thick), with the surface of the stiff overconsolidated London Clay lying at 98.5 mPD.

3 BUILDING DESCRIPTION

The Lloyds Bank building was built in 1910 and occupies a corner site at the junction of St James's and King Streets and measures 34 m by 34 m in plan, (see Figs. 1 and 2) within the St James's conservation area. The site itself has been occupied since at least 1770, when Robert Herries established the banking business of Herries, Farquhar & Company at No. 16 St James's Street. Although this building has recently been completely renovated and is no longer used as a bank, in this paper it is described and referred to as it was at the time of the works.

The building is approximately 27 m high having six storeys, the sixth being contained within a dormered mansard-style roof; there is also a basement. The external elevations (i.e. the two street facades) are clad in Portland Stone, in classical Georgian style. The steel and concrete filler joist floors are supported by load-bearing brick walls externally and a steel frame internally. Within the central banking hall and general public areas, all the walls, from floor to ceiling, are elaborately finished in marble.

The structure's basement extends some 3 m beneath both the St James's and King Street pavements and contains many substantial walls. The foundations of the building consist of strip footings of stepped brickwork bearing on to a deep mass concrete raft, at least 1.2 m thick, which appears to support all the masonry walls and atrium columns.

A building defect survey of the Lloyds Bank building was undertaken prior to the underground construction with the conclusion that the building was structurally sound.

The building had previously experienced tunneling-induced ground subsidence during the construction of the original Jubilee Line some 30 years ago, the southbound running tunnel passing beneath the building footprint on a similar horizontal and vertical alignment to that of the JLE eastbound SPJ.

4 CONSTRUCTION WORKS

The Lloyds Bank building was affected by several separate, related construction activities, including:

(a) excavation of the compensation grouting shaft, 1/1A, and subsequent installation of the *tubes à manchette* (TAMs);

(b) excavation of the eastbound running tunnel SPJ; (c) compensation grouting ground treatment operations undertaken during step-plate construction.



Figure 2. View of Lloyds Bank from St James's Street.

4.1 Grout shaft 1/1A

Ground treatment shaft 1/1A was constructed in King Street immediately adjacent to the structure (Fig. 1). The shaft penetrated the existing basement vaults of the building, which extend beneath the carriageway in this area and had an inner diameter of 3.35 m to a depth of about 1.5 m into the London Clay. The diameter was then increased to 4.57 m and kept at this until the bottom of the excavation 21 m below ground level, i.e. to about 3 m below the proposed elevation of the TAM array to provide a sump, to aid drilling and grouting operations. No annulus grouting was undertaken in advance of the shaft sinking. Shaft construction was by conventional underpinning methods with each ring being formed and back-grouted before excavation for the next ring commenced. The shaft was lined with precast concrete bolted lining segments, 600 mm wide and about 510 mm deep, except at proposed compensation grouting TAM levels where specially fabricated steel segments were used to enable installation of TAMs. A mass concrete plug approximately 1.1 m thick was formed at the base of the shaft.

4.2 JLE eastbound step-plate junction

The JLE eastbound SPJ runs directly beneath the Lloyds Bank building, at a depth of about 24 m below ground level, connecting the existing southbound running tunnel of the Jubilee Line with the JLE eastbound running tunnel (see Figure 1). The step-plate comprises four sections of the following inner diameters and lengths: (i) 5.75 m and 24.6 m; (ii) 6.5 m and 4.8 m; (iii) 8.0 m and 7.2 m, and (iv) 10.0 m and 6 m. These were constructed within the stiff to very stiff London Clay, adopting traditional hand-mining methods, incorporating in part a combination of pilot tunnel and enlargement. The step-

plate was built around the existing southbound running tunnel, which had to be maintained operational throughout its construction.

To expedite the works and allow tunnelling to progress simultaneously in both easterly and westerly directions, i.e. with double-face workings, precast concrete lined pilot tunnels of 4.57 m and 2.74 m i.d. respectively, were excavated alongside the existing southbound running tunnel. No compensation grouting ground treatment works took place during this time. The pilot tunnels were contained entirely within the excavation envelopes for the permanent works. During enlargement, the pilot tunnels were generally over-cut and their linings demolished with the advance of the excavation face for the finished tunnel. The 4.57 m i.d. pilot tunnel commenced from a breakout within the JLE eastbound running tunnel. Excavation subsequently proceeded as a full-face drive. Immediately following each advance, the tunnel lining was erected, bolted and the annulus around the units, and within one metre of the excavation face, back-grouted to limit ground loss. On completion of each ring installation, excavation recommenced. Once a stable ring of lining units had been formed the advancing tunnel lining was utilised to support the temporary timber support to the face. The enlarged tunnel was lined with bolted and grouted spheroidal graphite iron (SGI) units, which could be used as support soon after installation. Excavation of the pilot tunnels for the eastbound SPJ took place between 2 and 23 May 1996. The corresponding tunnel enlargement works were undertaken between 6 June and 16 October 1996.

The *westbound* SPJ (see Fig. 1) was completed about a month ahead of the eastbound. Of this westbound SPJ, its 5.75 m diameter section would have had most effect on the Lloyds Bank building, but as it was excavated at the same time as the enlargements to the eastbound SPJ, this would have been largely obscured by these nearer, larger excavations.

4.3 Protective measures

A Stage 3 building damage assessment (Burland, 1995), made in the early 1990s indicated that a maximum ground settlement of about 43 mm would occur within the building footprint with a corresponding maximum building slope of 1:515. In making the potential damage assessment, the Lloyds Bank building was classified as Risk Category 3: Moderate (Boscardin and Cording, 1989). Although the structural integrity of the building was not considered to be particularly sensitive to the anticipated ground movements, it was considered that other building components, such as the internal finishes, could be adversely affected by overall building movements. Mandatory compensation grouting ground treatment was therefore subsequently incorporated into the construction contract.

Compensation grouting was performed from shaft 1/1A, with a radial TAM layout (see Fig. 1). The TAMs, up to 70 m long, were installed from 16 August to 19 September 1995, at a level of approximately 95 mPD, i.e. about 3.7 m below the interface between the Terrace Gravels and the London Clay. The depth of cover between the TAMs and the crown of sections of the eastbound step-plate junction varied from 2 to 4 m.

Compensation grouting beneath Lloyds Bank took place from 20 November 1995 to 9 October 1996. Prior to the main works the ground and TAMs were conditioned (from 20 to 27 November 1995) with a total injected grout volume of 30.8 m³.

Concurrent grouting (i.e. grouting concurrent with tunnel excavation) was implemented typically after each 1 to 2 m length of step-plate advance (i.e. one or two tunnel rings). There were two phases of concurrent compensation grouting: a short, initial phase from 28 February to 5 March 1996, as the JLE eastbound running tunnel approached the building; and a longer, more sustained phase from 15 July until 25 September 1996 when enlargements to the SPJ were completed. About 12.3 and 67.1 m³ of grout were injected in the respective phases. Grouting was not carried out for the initial stages of SPJ construction when tunnel excavation was advanced in both directions simultaneously, i.e. the pilot tunnels and the 8.0 m and 6.5 m enlargements were completed without compensation grouting protective measures.

A grouting exclusion zone was implemented to avoid high grout pressures being applied close to the excavation face and any unsupported lengths of tunnel. The majority of injections were terminated after the specified volume of grout had been injected.

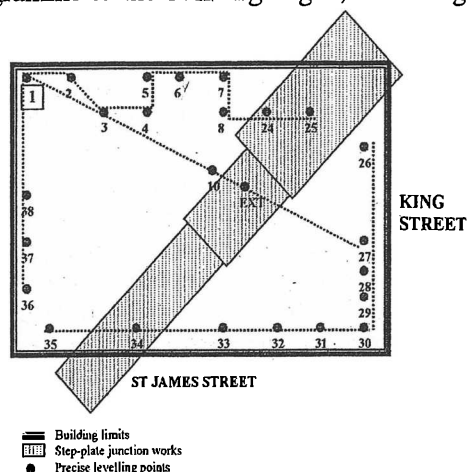
Two grout mixes were employed during the compensation grouting operations. A relatively 'fluid' cement-bentonite grout was used for conditioning the ground, while for the compensation grouting works proper a PFA/OPC grout mix with a low water/cement ratio was employed. The use of two different grout mixes was for operational convenience (for further grouting details, see Harris, 2001).

During the course of the underground construction works, about 110 m³ of grout was injected from the TAMs. The quantity of grout over specific periods of construction activity has been interpreted using contours of grout injection intensity (Viggiani, 2001). Grout intensity units are litres/m² of plan area which, as an average thickness injected, can be related directly to millimetres of hypothetical heave.

5 INSTRUMENTATION AND MONITORING

The data presented in this paper are from precise levelling and total station facade monitoring of the building, undertaken by the LINK CMR research team (Standing *et al.*, 2001). The layout of BRE pre-

cise levelling sockets, installed within the walls of the basement, is shown in Figure 3. Surveys were started at and have been plotted relative to monitoring point number 1. Although this point was furthest from the works, it would have still been subject to tunnelling-induced movements and so the data presented are relative rather than absolute. Sets of base readings were taken prior to the works (commencing in June 1995) and subsequent movements are shown relative to these readings. Monitoring continued until December 1998 when an extensive renovation programme to the building began, involving demoli-



tion of parts of the inner structure.

Figure 3. Schematic layout of precise levelling points.

Monitoring of the St James's Street and King Street building facades was undertaken using a high precision, Leica TC2002, total station. Measurements were made to retro-reflective prisms fixed to the two facades at roughly three levels. The layout of targets is shown in Figure 4.

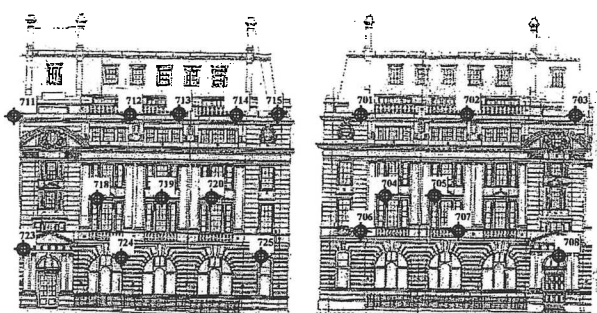


Figure 4. Layout of facade monitoring targets.

The positions of the targets, and their subsequent horizontal displacements have been related to a local co-ordinate system, set up with horizontal axes roughly parallel and perpendicular to St James's and King Streets. Movements are relative to a reference point, positioned well outside the zone of influence of the works. Seven surveys were made, the first two within two days of each other at the end of February 1996, with the following four surveys being under-

taken at about three-monthly intervals. The final survey was made almost two years after the first one, in December 1998. In assessing the building responses, the first survey has been used as the reference survey. It should be noted that at the time of the first survey the eastbound running tunnel was in the vicinity of Lloyds Bank and almost 31 m³ litres of grout had been injected beneath it. These activities would undoubtedly have caused building movements. Consequently, displacements presented do not represent overall absolute building movements.

The accuracy of the precise levelling within the building is estimated to be ± 0.3 mm. For the total station surveying the combined accuracy of measurement and analysis are estimated to be of the order of ± 0.5 mm in the vertical direction and ± 1.0 mm in both horizontal directions.

6 BUILDING RESPONSE

The monitoring results are discussed in relation to the subsurface works and ground treatment operations to illustrate the corresponding building responses.

6.1 Precise levelling

Precise levelling data from points installed in the rear wall parallel to St James's Street are plotted against time in Figure 5. Data for the entire monitoring period are shown along with an enlargement relating to the initial period. The dates marked on the first plot relate to dates of total station surveys.

Data from the overall monitoring period indicate that during the construction of the pilot tunnel and enlargements (starting at the end of February 1996, i.e. roughly corresponding to the first total station surveys, and finishing 25 September 1996) there was a progressive settlement increasing towards the step-plate junction. The greatest settlement was about 15 mm, immediately over the largest section (i.e. point 25, see Figure 3). The small reversal in settlements just after this time, clearly visible for points 24 and 25 (see change just after total station survey of 10 September 1995), resulted from the final phase of compensation grouting. The influence of grouting prior to that time is barely discernible, although concurrent grouting took place during the course of the step-plate enlargement, as discussed in the next section. The maximum long-term consolidation settlements are about 8 mm, again directly above the largest opening, the rate of settlements can be seen to be reducing.

The enlarged section of data is shown to illustrate the effects of TAM installation and give an indication of the accuracy of the readings. The heave of points 4 to 8 is a consequence of the spacing of the TAMs and their sequence of installation. At the lo-

cation of these points (see Figs. 1 and 3) the TAMs are at quite a wide spacing. Above the step-plate junction, i.e. close to the St James's Street and King Street facades, TAMs were installed in a denser configuration. The movements indicate that small, localised rotations took place as parts of the building settled, causing some to heave. Figure 6 shows precise levelling data for the St James's Street side of the building and its settlement of 2 to 3 mm during TAM installation.

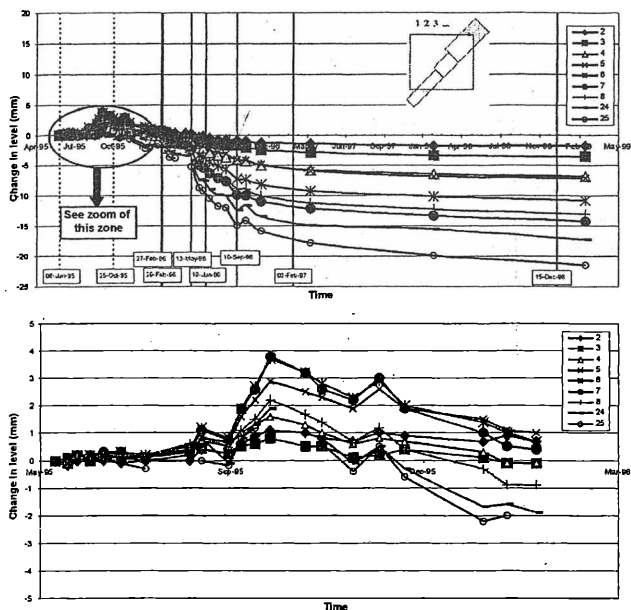


Figure 5. Precise levelling data from points along the rear wall of Lloyds Bank (see insert) plotted against time.

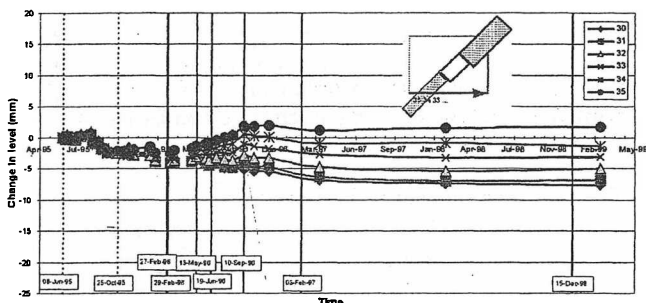


Figure 6. Precise levelling data from along the St James's Street side of Lloyds Bank (see insert) plotted against time.

Further evidence of building rotations can be seen by the heave of points 34 and 35. However, these movements are relative to point 1 (see Figure 3), absolute movements are discussed later using the total station results.

Precise levelling data plotted against distance along lines transverse to the 6.5 m step-plate section and longitudinal to its four sections are given in Figures 7 and 8. The data are discussed in terms of three general periods. The first, from the start of monitoring to May 1996, corresponds to the sinking of the ground treatment shaft, subsequent TAM installation and conditioning, and eastbound running and pilot tunnel excavation. Observed movements were small,

with both maximum heave and settlement of 5 mm (the heave occurred in the vicinity of point 36, but this profile is not presented in this paper).

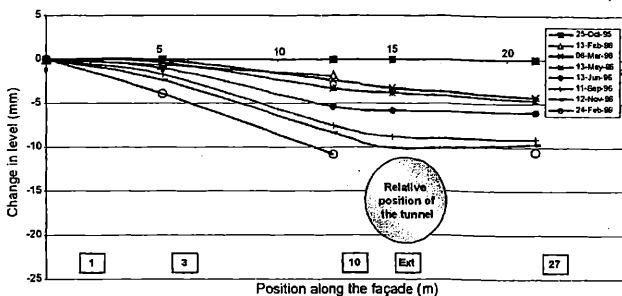


Figure 7. Precise levelling data transverse to the 6.5 m section of the step-plate junction plotted against distance.

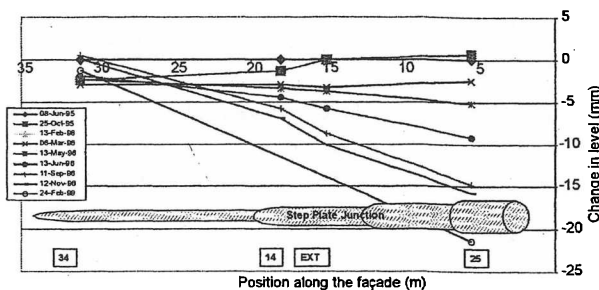


Figure 8. Precise levelling data roughly parallel to the step-plate junction plotted against distance.

The second period, from June until October 1996, when the excavation of the step-plate enlargements and concurrent grouting took place, resulted in more significant movements. Differential settlements of up to about 10 mm occurred along the rear wall of the building and along the line of the step-plate itself (Fig. 8). By this time there was a maximum settlement of about 15 mm above the 10 m section of the step-plate. The maximum resulting deflection ratio was compressive and less than 0.02 %. Other settlement profiles plotted along different lines within the building show smaller differential movements. The overall pattern of movement suggests that the building responded in a relatively rigid manner to the underground construction works with a maximum slope, in the transverse sense of about 1:1700. Most settlement occurred directly above the 8 and 10 m sections of the step-plate with a small rotation that caused an apparent heave at the opposite corner (apparent because the movement is relative to point 1).

The long-term consolidation movements recorded from November 1996 until February 1999 are essentially uniform in nature. The rate of settlement has progressively reduced, with settlements of no more than 5 mm occurring over the final two-year period.

6.2 Compensation grouting

There were three phases of compensation grouting. Initially a pre-treatment phase was carried out during

November 1995. The main purpose of the grout injected during this period was to condition the ground in readiness for concurrent grouting. The distribution of the grout was widespread with densities of about 5 to 10 litres/m² resulting in almost negligible observed movements.

Grout injection for the 7-day period of concurrent grouting at the end of February 1996 was concentrated above the JLE eastbound running tunnel adjacent to the corner of the Lloyds Bank building, as the tunnel drive approached the structure: 12.3 m³ of grout were injected over this short period. No noticeable heaving of monitoring points was recorded during this time.

The grouting during the period from July until September 1996 was concurrent with SPJ construction. Significant movements were observed as the enlargements to the eastbound SPJ were undertaken. Grout injections were predominantly above areas where excavation took place. More than 67 m³ of grout were injected into the ground over this time.

The total volume of grout injected beneath the Lloyds bank building during eastbound SPJ construction is presented in Figure 9.

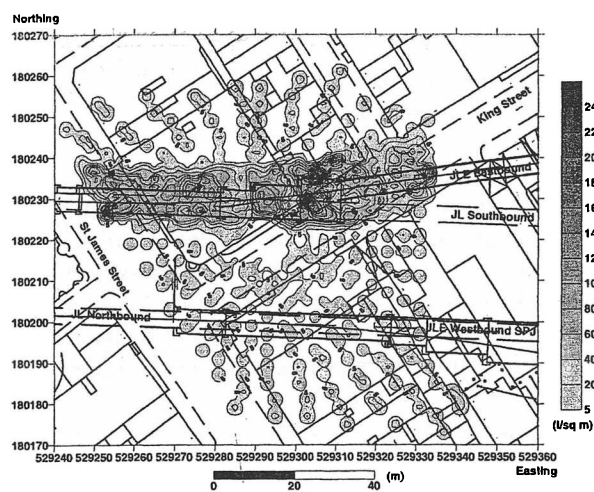


Figure 9. Grout density contours for entire period of grouting.

6.3 Total station surveying

The results from the analysis of the total station survey data are presented and discussed in terms of three components of movement: vertical (z), and horizontal, in-plane (x) and out-of-plane (y). The total station data for Lloyds Bank are presented as profiles of change in displacement plotted against distance along relative lengths of the building. Unless otherwise stated the data are relative to a reference point located on a building further along King Street, about 75 m from the end of the Lloyds Bank building. The profiles on each figure relate to the times at which the total station surveys were performed during the course of the construction works. Results from the second survey, performed two days after the first, provide an indication of the accuracy of the

measurements. It should be noted that the retro-reflective targets used for the total station measurements extended beyond the Lloyds Bank part of the St James's Street facade (i.e. points 721 and 722). In the following figures 723 roughly corresponds to the position of precise levelling point 35 and the enlargement of the existing Jubilee Line tunnel was roughly beneath point 724 (see Figures 3 and 4).

Vertical movements from measurements to the lower level of targets on the St James's and King Street facades are presented in Figures 14 and 15 respectively. Along the St James's Street facade, there are negligible movements at points 721 and 722 and even beneath the Lloyds building itself, settlements are very small at the end of construction (represented by the 9 October 1996 survey), being just over 6 mm towards the corner of the building. The greater movements at point 725 compared with 724, which was closer to the works, probably result from a small overall rotation of the building caused by the excavations for the larger sections of the SPJ on the opposite side. In the longer term, settlements increased uniformly to a maximum of about 14 mm, diminishing away from the construction works.

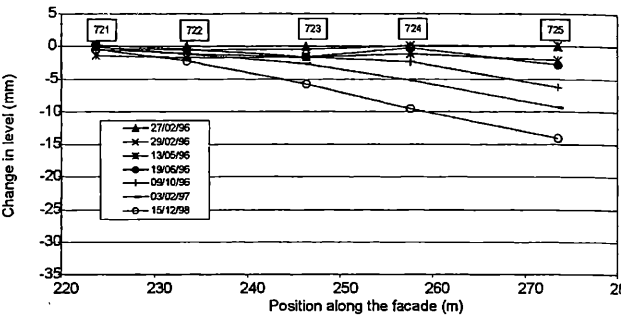


Figure 10. Vertical displacements from total station measurements to lower level of targets along St James's Street facade.

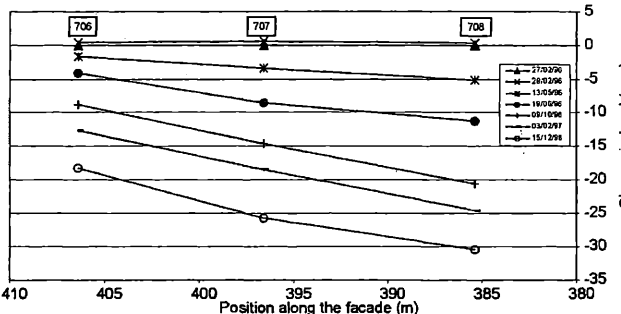


Figure 11. Vertical displacements from total station measurements to lower level of targets along the King Street facade.

Along King Street, the settlements towards the western end (i.e. point 706) were slightly greater than point 725 on St James's Street, i.e. being about 9 mm on 9 October 1996 compared with 6 mm. This is consistent with the excavation being mostly on that side of the building. The magnitude of settlement increases uniformly towards the larger excavation works, reaching a maximum of just over 20 mm. These settlements reflect the combined effect of

the excavation works and the concurrent compensation grouting (see Fig. 9). At the end of the monitoring period, the maximum settlement was just over 30 mm. The effect of using an internal point as datum for the precise levelling measurements is evident when comparing respective survey points 25 and 708 (see Figures 8 and 11). There is a difference of about 8 mm between their apparent vertical displacements, but the points are only a short distance apart. This indicates that point 1 also underwent settlement. It is possible that the point used as a datum for the total station measurements was also affected by tunnelling settlements, but these were probably negligible at that location.

The in-plane horizontal displacements along the two building facades at the upper and lower levels of targets are shown in Figures 12 and 13. The data have been expressed relative to end points (725 and 706) in each case, roughly corresponding to corners of the building because datum points tend not to be as stable in the horizontal sense as vertically (see Standing *et al.*, 2002b for a similar example).

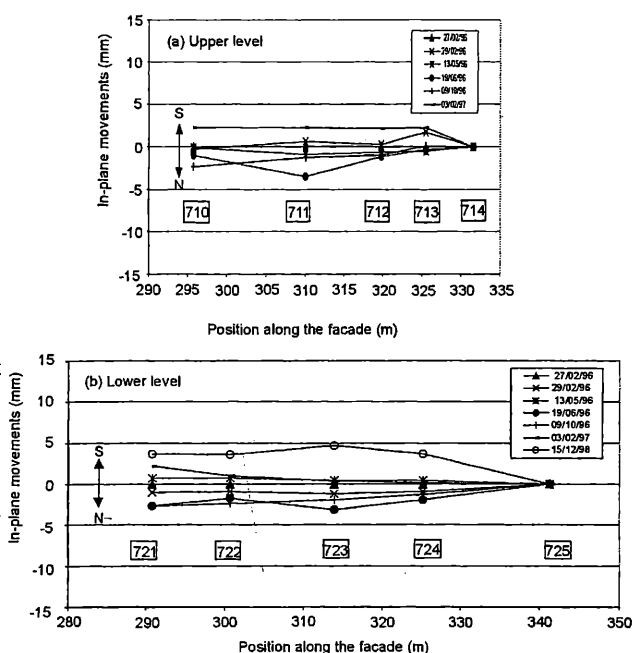


Figure 12. Relative horizontal in-plane displacements from total station measurements to (a) upper and (b) lower levels of targets along the St James's Street facade.

The north-south relative horizontal displacements deduced from the total station measurements to the upper and lower levels of targets on the St James's Street facade are shown in Figure 12a and b (i.e. Lloyds bank and the buildings adjacent to it). Displacements are small, being within ± 5 mm. Where the lines are generally flat (i.e. between points 710 and 712 and points 721 and 723 at the upper and lower levels respectively) there are negligible strains. The strains that do develop occur are within the Lloyds Bank building and are very small.

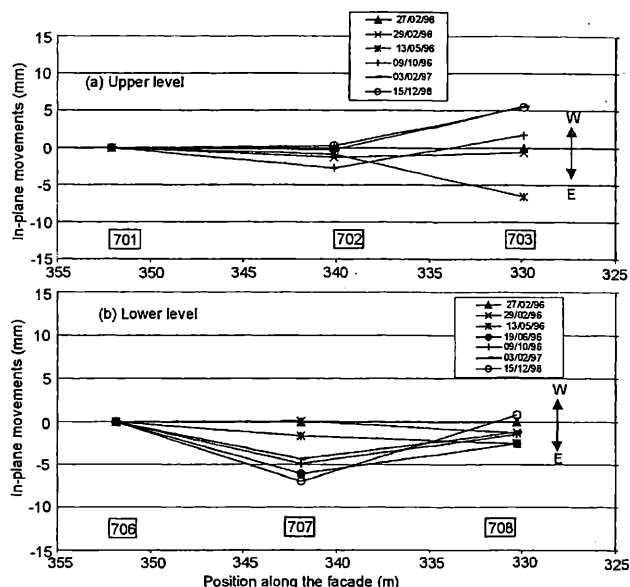


Figure 13. Relative horizontal in-plane displacements from total station measurements to (a) upper and (b) lower levels of targets along the King Street facade.

There are greater horizontal in-plane displacements and strains indicated along the King Street facade, particularly at the upper level (see Figs. 13a and b). As it is the westernmost point that is taken as fixed, movements to the west and east are compressive and tensile respectively. The two parts of Figure 13 indicate that strains occur at different positions along the facade at the upper and lower levels. At the upper level they develop towards the eastern end of the building while they are within the central part of the facade at the lower level. At the upper level a small tensile displacement is indicated from the survey 13 May 1996 (see Fig. 13a) when the SPJ construction took place in the absence of concurrent grouting operations. Horizontal displacements at the lower level at that time were also tensile but much smaller. The magnitudes of these tensile horizontal strains were about 0.07% and 0.01% at the upper and lower levels respectively and relate to damage categories of negligible and slight (Burland, 1997). Strains were generally compressive after this time, as construction proceeded with concurrent grouting and in the longer term. At the lower level, tensile and compressive strains are indicated, with negligible net strains. The settlement profiles shown in Figure 11 are generally sagging and so would be associated with compressive strains, as reflected particularly by the compressive displacements measured on the final two surveys. The maximum compressive strains at both levels are between about 0.05% and 0.07%.

Out-of-plane relative horizontal movements for one section of the King Street facade are shown in Figure 14. The displacements are plotted relative to the lower level target. A progressive outward development of displacement with height and time is indicated with maximum movements of about 4 mm. This is consistent with a downward and southward

rotation of the facade caused by the excavation of the step-plate.

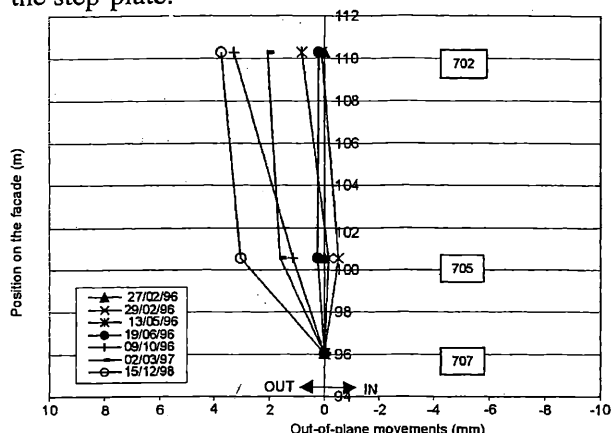


Figure 14. Relative horizontal out-of-plane displacements from total station measurements to a vertical section on the King Street facade.

6.4 Recorded damage

It is understood that no damage to the Lloyds Bank building as a result of the construction of the east-bound JLE step-plate junction was reported.

7 CONCLUSIONS

Monitoring by precise level and total station of the Lloyds Bank building was undertaken to observe its response to the construction of a step-plate junction beneath it and protective compensation grouting.

The maximum settlement observed from the total station measurements during the construction works was just over 20 mm. This occurred mainly from the excavation for the 8 m and 10 m sections of the SPJ. Precise levelling gave a smaller maximum value of 15 mm, as the datum was within the building itself. The building response appears to be relatively stiff as the settlement profiles are generally almost straight. The maximum slope measured was about 1:1700 along the length of the SPJ, while the maximum deflection ratio was less than 0.02%, transverse to it. Settlements increased uniformly by about another 10 mm in the longer term.

As was observed on a number of other structures monitored during the JLE works, the magnitude of both the in- and out-of-plane horizontal movements are significantly smaller than those observed vertically. The magnitudes of the horizontal displacements are very small. The strains determined are generally negligible, the exception being for the survey made during excavation work when there was no concurrent grouting. Tensile strains developed at this time were very small, being about 0.07%. Similar magnitudes of strain (but compressive) also developed in the longer term.

The small horizontal strains and deflection ratios would imply that the damage category for the build-

ing was negligible. This is consistent with the fact that no known damage to Lloyds Bank was reported.

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