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Settlement, rotation and distortion of Piccadilly Line tunnels at Heathrow

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ABSTRACT: This paper is based on monitoring results obtained during the construction of the new Heathrow Express tunnels in London, where at the Central Terminal Area (CTA), in London Clay, three large tunnels pass beneath the existing Piccadilly Line Tunnels with limited clearance. Extensive monitoring was undertaken in the existing tunnels including precise levelling and distortion checks. Aspects of the settlement have been reported in a previous paper (Cooper and Chapman, 1998). The results have been analysed and curves showing settlement, rotation and distortion along the existing tunnels are presented in the present paper. The results are discussed and conclusions are presented. Analysis is presented of the asymmetry noticed in the settlement curves caused by driving a second tunnel alongside the initial tunnel. A comparison is made with relevant previously published work.

1 INTRODUCTION

Some of the settlement effects on the existing Piccadilly Line tunnels at the Central Terminal Area Station (CTA), caused by the construction of three new Heathrow Express tunnels between 1994 and 1996 in London Clay, have been described in an earlier paper (Cooper & Chapman.1998). The layout at CTA and methods of construction are described in that paper. When dealing with existing railway tunnels affected by new tunnelling, in addition to settlement, track rotation is important because of the potential effect on the running of trains. Distortion of the tunnel lining is also important to ensure that adequate clearance is maintained between trains and the tunnel lining. This paper describes settlement, rotation and distortion of the inner Piccadilly Line tunnel, caused by driving the Concourse, the first of the three new tunnels. In addition, the asymmetry of the settlement troughs caused by driving the upline and downline platform tunnels in succession, one each side of the Concourse tunnel, is discussed further.

Figures 1 and 2 show the plan and section of the new and existing tunnels at Heathrow CTA Station. The three new 9m. diameter Station tunnels, cross beneath the 3.81m diameter Piccadilly Line at a skew angle of 70^0, with a vertical clearance of only about 7m. In the section of Piccadilly Line affected by the new tunnelling, from the existing station headwall there is a length of about 16m of cast iron bolted lining to the tunnel varying from 7.5m to 3.8m diameter. The rest of the Piccadilly Line tunnels are lined with 3.81m diameter concrete unbolted expanded segments.

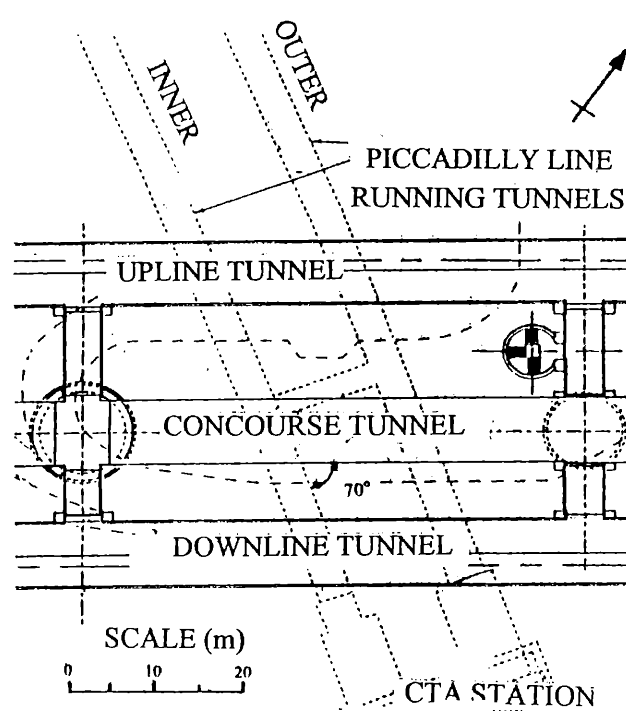

Figure 1. PLAN AT CTA STATION, HEATHROW.

It was originally intended to construct all three Heathrow Express tunnels by the NATM or shotcrete method, all having a similar cross section with a flattened invert. The tunnels were to be driven by the "half face" method. However, a major

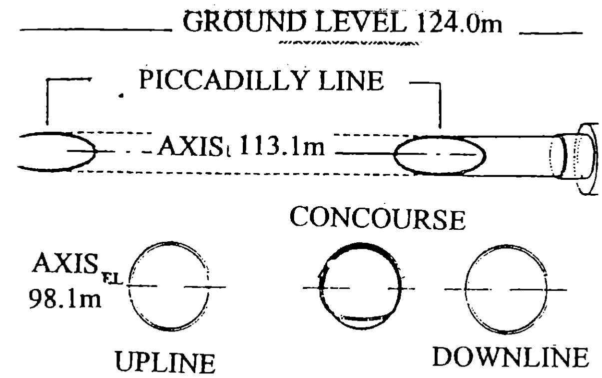

Figure 2. CTA STATION HEATHROW, SECTION OF NEW AND EXISTING TUNNELS.

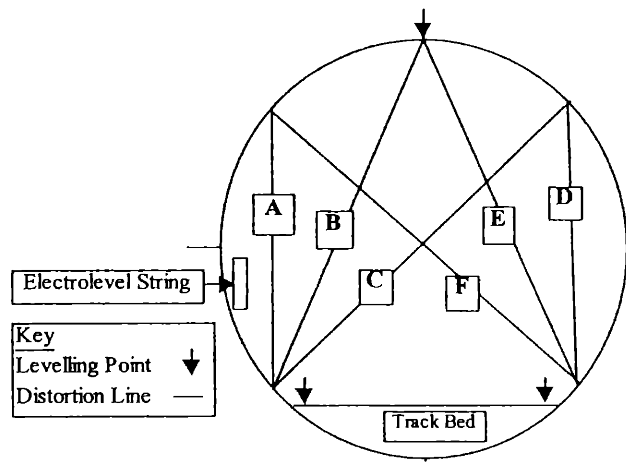

Figure 3. TYPICAL SECTION OF MONITORING LAYOUT IN PICCADILLY LINE TUNNEL.

tunnel collapse occurred on 21/10/94, after driving the Concourse tunnel..

Subsequently, the new upline and downline platform tunnels were redesigned as shield-driven, circular, bolted, precast concrete-lined tunnels, using pilot tunnels for construction.

A monitoring system, as illustrated in Figure 3, had been installed before the start of tunnelling, over the predicted zone of settlement in each of the existing Piccadilly Line Tunnels.

The monitoring system comprised:

- A single string of 3m long electrolevel beams, installed at tunnel axis level,
- Arrays at 6m intervals of three precise levelling points, one each side of the running rails, with the third point in the tunnel crown
- Arrays of five tape extensometer points coinciding with the levelling arrays, consisting of eye bolts at the tunnel crown, shoulders and knees

Manual precise levelling could only be carried out in London Underground's engineering hours, between about 0100 and 0430 hours daily. Whilst tunnelling was affecting the Piccadilly Line, the electrolevels were read once a day and precise levelling and extensometer readings were taken twice a week or more frequently. In this paper, the electrolevel results are not discussed.

2 MOVEMENT CAUSED BY CONCOURSE

2.1 Progress

Curves of tunnel settlement, rotation and lining distortion have been plotted for various dates whilst the Concourse was being driven beneath the Inner Piccadilly Line tunnel, between August and October 1994. The curves have been plotted for a length of just over 30m each side of the Concourse. Due to the 70^0 skew angle between the new and existing tunnels this represents a settlement trough width of about 56m. It is considered unlikely that the new tunnel would cause significant settlement beyond that range.

The dates for the plots were chosen in order to illustrate movement of the existing tunnel as the new tunnel approached and passed beneath. The relevant dates are shown in Table 1 together with an indication of tunnelling progress in terms of distances from the new tunnel to the centre line of the existing tunnel. In column 2, the position of the drift face is logged because this initiates the movement ahead of the tunnel. In column 3, the invert of the tunnel enlargement is logged because this indicates the stage when the shotcrete lining is closed and the trend of the major short-term settlement normally approaches zero.

Table 1 Tunnelling Progress Record

Date	Distance from drift face to centre of Piccadilly Line m.	Distance from enlargement invert to centre of Piccadilly Line m.
26/08/94	-14	-38
28/08/94	-13	-34
03/09/94	-9	-23
11/09/94	0	-20
17/09/94	8	-9
22/09/94	17	-4
14/10/94	52	35
21/10/94	Major tunnel collapse	

2.2 Settlement

Settlement curves along the existing Piccadilly Line tunnel at CTA, derived from the mean of the three monitoring points at each array, are shown on Figure 4. The curves illustrate the progressive increase in

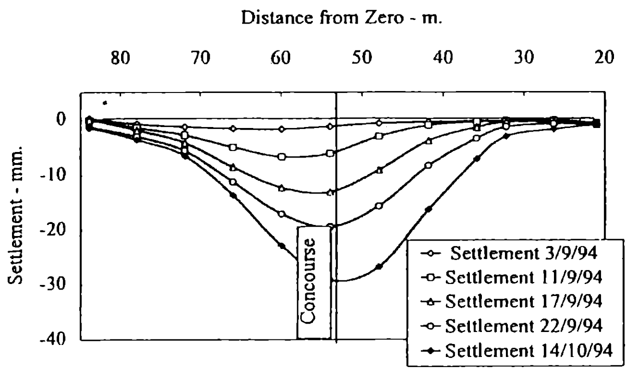

Figure 4. SETTLEMENT CURVES, INNER PICCADILLY LINE, CAUSED BY CONCOURSE.

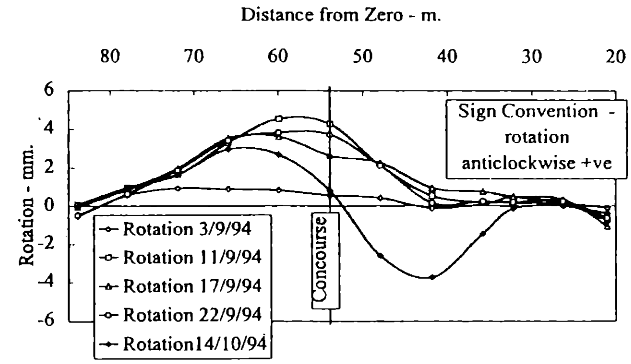

Figure 6. CURVES OF ROTATION ALONG INNER PICCADILLY LINE TUNNEL AT CTA WHILST DRIVING CONCOURSE.

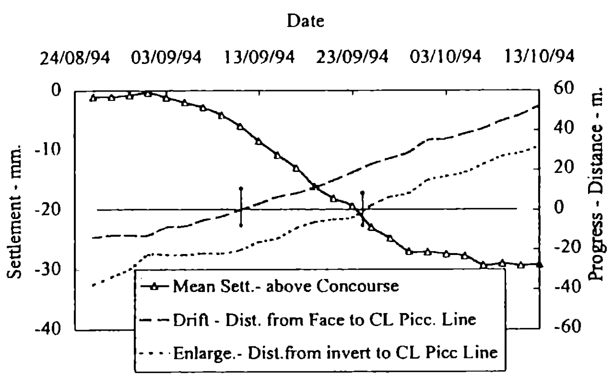

Figure 5. PROGRESSIVE SETTLEMENT OF PICCADILLY LINE ABOVE CONCOURSE DURING ITS CONSTRUCTION.

settlement as the new tunnel passed beneath. The latest curve, dated 14/10/94, is substantially the maximum settlement caused by driving the concourse tunnel. A hiatus lasting about 8 months, following the major tunnel collapse on 21/10/94, gave an opportunity to take further medium-term movement monitoring checks before resumption of work in August 1995. These showed very little change in settlement from that at 14/10/94.

The settlement curves in Figure 4 indicate some asymmetry. This is considered to be due to the presence of the existing cross passage, shown on Figure 1, which joins the Inner Piccadilly Line tunnel at about 3m from the crossing of the Concourse centre line and also due to the presence of the existing station box and associated length of cast iron lining. Figure 5 shows a curve of mean settlement plotted against time, at the position in the Piccadilly line tunnel directly above the new concourse tunnel. The curve is in the form of an "S" as would be expected. The plot indicates that about 30% of the short-term settlement took place after the enlargement invert closure had passed beneath the existing tunnel centre line.

2.3 Rotation

It is important for owners of rail tunnels that track rotation is monitored to ensure that train running is not affected. Rotation of the tunnel lining has been computed by taking the difference in level between the two invert monitoring points at each array. The lateral distance between invert monitoring points was 2500mm and it would be possible to express rotation in angular units, however, for simplicity, rotation has been expressed in mm.

Plots of rotation along the existing inner Piccadilly Line Tunnel are shown on Figure 6. A sign convention of clockwise positive, looking from the existing CTA station, has been adopted.

The dates chosen for the plots are the same as those for the settlement curves. The rotation curve for date 14/10/94, after tunnel completion, is shown to be of sinusoidal form. It is suggested that this is because of the skew angle of the tunnel crossing. It may be deduced that after the Concourse tunnelling had passed the Inner Piccadilly Line, the vectors of ground movement behind the tunnel would tend to cause the existing tunnel to rotate clockwise. By reference to Figure 1, because of the skew angle this would be more marked on the northeast side. The rotation along the tunnel in August 1995 was checked and found to be similar to that at 14/10/94.

2.4 Distortion

Checks of distortion of the tunnel lining in rail tunnels are important to ensure that the clearance from the kinematic envelope of running trains is maintained. Fewer distortion measurements were taken than precise levelling measurements whilst driving the Concourse tunnel and distortion measurements are not always available on the same dates as rotation and settlement measurements.

Although six measurements across the tunnel lining were taken at each array shown on Figure 3, the maximum distortions generally occurred across the diagonals C and F, at approximately 45^0.
Curves based on distortions at C and F, the only

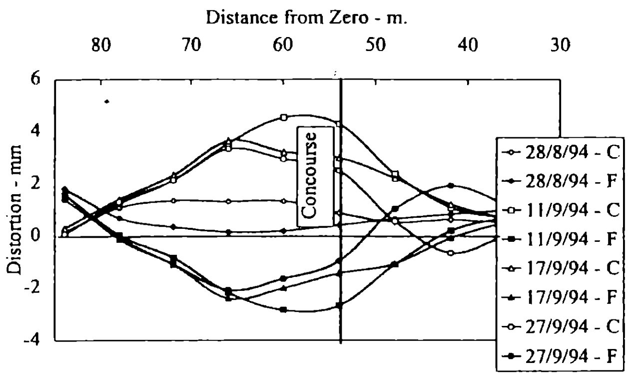

Figure 7. DISTORTION OF PICCADILLY LINE LINING WHILST DRIVING CONCOURSE.

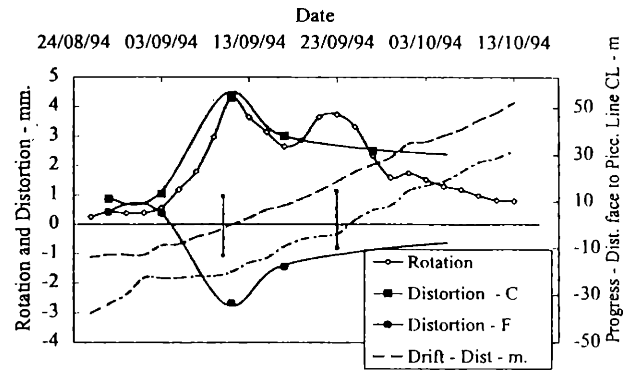

Figure 8. PROGRESSIVE ROTATION AND DISTORTION OF INNER PICCADILLY LINE TUNNEL WHILST DRIVING CONCOURSE.

measurements analysed, have been plotted on Figure 7 at four dates, 28/8/94, 11/9/94, 17/9/94 and 27/9/94. The sign convention adopted is outwards positive.

It is noted that the distortions of lines C and F mirror each other. This is as might be expected since the lining is an approximate circle and compression at a diameter would be accompanied by extension at the diameter at right angles to it. However, the distortion curves for line C appear to be displaced upwards relative to the zero line by about 1mm. and curves for lines C and F cross at about +1mm. No explanation has been found for this.

2.5 Distortion and Rotation with time

Figure 8 shows curves of rotation plus distortion at lines C and F plotted against time at the array immediately above the Concourse. The progress of the drift and enlargement of the concourse are also shown and the dates when the drift and enlargement passed beneath the Piccadilly Line are highlighted.

The plot of rotation illustrates one of the mechanisms of the rotation. As the drift face approached the existing tunnel, the latter rotated anticlockwise to a maximum of about 4.5mm. When the drift face passed beyond the existing tunnel the amount of the initial rotation was reduced by about 1.5mm. As the enlargement approached, the rotation again increased, followed by a reduction as the tunnel face passed beyond the existing tunnel. As noted earlier, the curves representing distortion at C and F mirror each other. The curve at C also may be seen to follow fairly closely with the rotation curve. Unfortunately no distortion data is available between 17/9/94 and 27/9/94 and after 27/9/94.

It may be conjectured, however, that if further readings had been taken, the second hump in the rotation curve may have been mirrored by the distortion at C. On Figure 8 it is shown that rotation and distortion exhibit reducing trends after the tunnel face had passed. The residual rotation and distortion were measured in August 1995 before tunnelling for the outer tunnels started to affect the Piccadilly Line tunnels. In August 1995, the approximate movements recorded immediately above the Concourse tunnel were

Rotation –	+0.5mm
Distortion line C	+0.8mm
Distortion line F	+1.6mm

Rotation and distortion in the Piccadilly Line tunnels caused by driving the upline and downline station tunnels at later stages of the project have been computed. These are not presented in this paper, however, the maximum recorded rotation was 8mm and the maximum distortion was 7.5mm. It was found that as for the Concourse tunnel alone, the distortion on line C generally tended to follow the shape of the rotation curves.

3 ASYMMETRY OF SETTLEMENT CURVES

Asymmetry of the surface settlement trough caused by the second tunnel when driving two tunnels side by side, has been reported by Cording & Hansmire, (1975), Perez Saiz et al, (1981), Lo et al, (1987), Addenbrooke & Potts, 1996), Mair & Taylor, (1997) and Cooper & Chapman, (1988). In Cooper & Chapman, (1998), the asymmetry of settlement curves caused in the Piccadilly Line tunnels by the Upline and Downline Station tunnels at Heathrow was briefly discussed. Suggested explanations offered were either, opening up of fissures above the first tunnel, or alternatively, hanging up of the first tunnel until further tunnelling triggered settlement.

Figure 9 shows the settlement trough at CTA Heathrow caused by the total Upline Station tunnel derived by adding the settlement caused by the pilot and enlargement tunnels. The Upline Station Tunnel and Pilot were driven during the period from August 1995 to February 1996, after completion of the Concourse tunnel. The dotted curve is a mirror

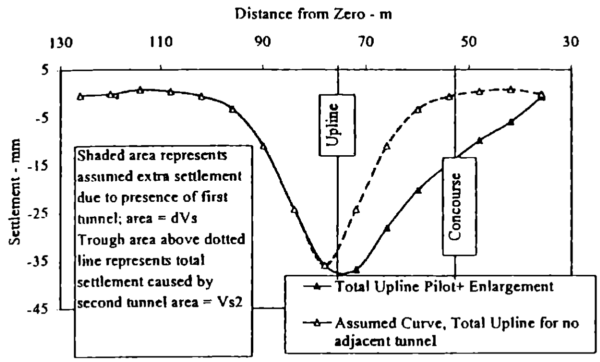

Figure 9. CURVE OF SETTLEMENT CAUSED BY DRIVING UPLINE STATION TUNNEL, INNER PICCADILLY LINE TUNNEL AT CTA.

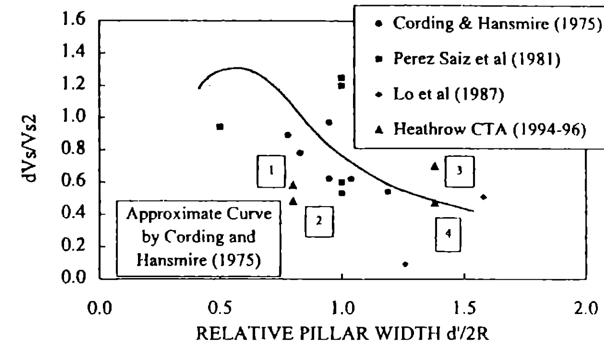

Figure 10. PLOT OF "PILLAR WIDTH AGAINST EXCESS SETTLEMENT VOLUME OVER SECOND TUNNEL" AFTER CORDING & HANSMIRE 1975.

image of the trough limb remote from the concourse. The shaded area is the assumed extra settlement caused by the presence of the Concourse tunnel.

Figure. 10 is a plot of dV_s/V_{s2} against relative pillar width d'/2R, reproduced from Cording & Hansmire (1975),

Where R is the tunnel excavated radius, d' is the clear distance between tunnels, V_s2 is the volume of trough caused by second tunnel and dV_s is the excess settlement volume due to first tunnel

The curve drawn on Figure 10 is an approximation of the curve drawn on the graph in Cording & Hansmire, (1975).

Points from Heathrow, shown as solid triangles have been plotted on Figure 10, based on the geometry at CTA. Point "1" represents the data from Figure 9. The three other points that have been added are from settlement of the Inner tunnel caused by the Downline Station tunnel plus settlement of the Outer tunnel caused by the Upline and Downline Station tunnels (reference Figs 1 and 2), marked "2", "3" and "4" respectively. Whilst points 3 and 4, derived from the Upline/Concourse on the Inner and Outer tunnels show reasonable correlation with other points, points 1 and 2, from the Downline/Concourse show significantly lower values. The following, by Mair & Taylor (1997), is a suggested explanation for the asymmetry: "... the ground in the region where the second tunnel is to be constructed will already have been subjected to appreciable shear strains associated with the construction of the first tunnel, resulting in reduced stiffness and hence higher volume loss is likely...". This explanation is now considered more credible than that offered in Cooper & Chapman (1998), noted above. It is difficult to envisage the suggested fissuring of the London Clay above the tunnel since the clay remains in compression. However the stiffness of the existing tunnel may cause "hanging up".

4 CONCLUSIONS

This paper deals with settlement, rotation and lining distortion caused to the existing Piccadilly Line tunnels at CTA Station, Heathrow, by driving the Concourse, the first of three new 9m diameter parallel station tunnels in close proximity underneath with limited vertical clearance. Aspects of asymmetry of settlement troughs are also discussed

By analysing monitoring measurements, curves of settlement, track rotation and lining distortion at 45^0 diagonals have been plotted along the existing tunnels in the zone affected.

In addition, curves showing settlement, track rotation and lining distortion at the position in the existing tunnel immediately above the new Concourse tunnel have been plotted against time. Plots of new tunnelling progress, have been included.

Minor asymmetry is noted in the settlement troughs, accounted for by the presence of the existing cross passage and the adjoining CTA Station.

The maximum rotation caused whilst driving the Concourse was 4mm and it has been noted that the maximum rotation recorded on the project was 8mm after driving subsequent tunnels.

The mechanism of rotation as the Concourse tunnel face approached and passed beneath the existing tunnel is discussed.

The plots of the distortion at the diagonals "C" and "F", showed that the plot of F mirrored that of C. It was also noted that the plot of C matched the rotation plot. It is demonstrated, that rotation was accompanied by ovalisation of the existing tunnel lining.

The asymmetry associated with the trough caused by a second tunnel when two tunnels are driven side by side is discussed in relation to the new Upline and Downline Station tunnels driven after and alongside the Concourse tunnel. This asymmetry was mentioned earlier in Cooper & Chapman (1998).

The asymmetry was first reported by Cording & Hansmire (1975) and it has been followed up by subsequent researchers. For a number of conditions for tunnels at varying distances apart, Cording & Hansmire (1975) plotted the ratio $dV_s./Vs2$, against the distance apart normalised by diameter.

Figure 10 is based on their plot and shows their points, with their original curve. Additional points from other sources are also plotted. All these other points relate to surface settlement. Four additional points from the Upline/Concourse and the Downline/Concourse on the Inner and Outer Piccadilly Line tunnel at CTA are also plotted. The correlation of the Heathrow points with the original plot varies.

No theoretical methods have been found by the authors which are commonly used to predict rotation and distortion of an existing tunnel when new tunnelling is undertaken nearby. However, part of a research project underway at Birmingham University is aimed at formulating methods for this.

ACKNOWLEDGEMENTS

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