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Measures to limit structure settlements during construction of the station complex at Southwark

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ABSTRACT: As part of the Jubilee Line Extension Project a new underground station complex is being constructed at Southwark. The station will comprise a 9.2 m diameter lower concourse tunnel, two 7.0 m diameter platform tunnels, three inclined 5.75 m escalator tunnels together with associated shafts and Adits. The station is sited directly beneath the heavily trafficked Railtrack viaduct between London Bridge and Charing Cross which is subject to stringent criteria relating to settlements and angular distortions. This paper discusses the construction of the lower concourse tunnel in particular, with emphasis on the mitigation of tunnel induced settlements. The success so far of the methods employed are assessed.

1.0 INTRODUCTION

The Southwark Station complex is part of Contract 103 of the Jubilee Line Extension which also comprises running tunnels between Waterloo and London Bridge, almost entirely below a heavily trafficked Railtrack viaduct linking Charing Cross and London Bridge stations.

The Contract was let to Aoki/Soletanche joint venture, with the running tunnels sub-let to Costain/Taylor Woodrow joint venture.

The sensitivity of the structures and the small amount of clay cover for the station tunnels led to the need for a combination of techniques to prevent settlement reaching the structures and best possible mining practice. This paper describes the techniques used to limit settlement and the instrumentation to monitor their performance, with reference to the construction of the lower concourse tunnel.

2.0 THE STATION COMPLEX

Figure 1 is a plan of the station which comprises two 7.0 m diameter platform tunnels linked by adits to a 9.2 m diameter lower concourse tunnel. Three 5.75 m diameter escalator tunnels link the lower concourse tunnel to the cut and cover station box. There are

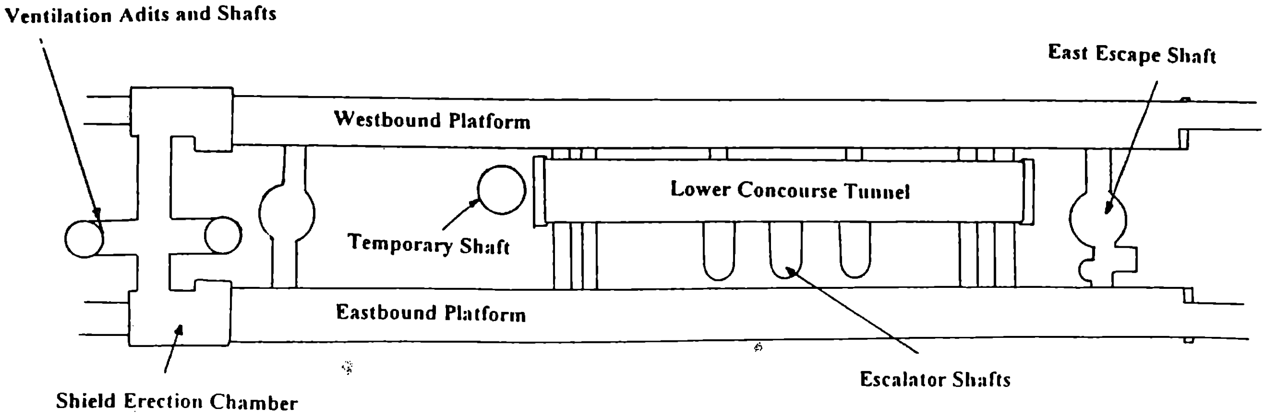

Figure 1 Station Layout

escape and ventilation shafts at each platform end.

The tunnels are being constructed by traditional hand-mining methods and are lined with Precast Concrete (PCC) or Spheroidal Graphite Iron (SGI) segmental linings.

A temporary access shaft has been sunk for construction of the lower concourse tunnel and shield chambers have been built at the west ventilation shafts for construction of the two platform tunnels.

The first major tunnels under construction are the lower concourse tunnel and the shield chambers. The westbound platform tunnel is due to commence when the concourse is approximately 50% complete followed sequentially by the eastbound platform tunnel. Escalator and adit construction will run concurrently with the above works.

3.0 GEOLOGY

The geology as shown on Figure 2 comprises stiff London Clay generally 11 m below ground level, overlain by 6 to 7 metres of water bearing Terrace Gravels which are in turn overlain by peaty Alluvial deposits and Made Ground. Figure 2 also indicates the proximity of the Lower Concourse Tunnel crown to the London Clay/Terrace Gravel interface, approximately half a tunnel diameter (4.5 m). To maintain the safety of the works a general rule was applied that in areas of clay cover of less than one tunnel diameter measures had to be taken to prevent the ingress of water and materials from the Terrace Gravels. Typical geological hazards identified included:

i) Scour holes in the top of the London Clay (Berry 1979) which could present water bearing granular material in the face or just above the crown.

ii) Fissures or "greasy backs" which could precipitate a wedge failure into the tunnel face and ultimately the ingress of Terrace Gravels. These features are particularly hazardous if they are lubricated by water.

4.0 ALLOWABLE MOVEMENTS & PREDICTED SETTLEMENTS

Contractual limits imposed upon the Contractor for the Railtrack viaduct were:

1. Maximum settlement of 25 mm total.
2. Differential settlement in any direction 1:500.

Settlement predictions were derived from the method described by New and O'Reilly (1982) using a volume loss of 2.0% for hand built tunnels. The combination of tunnels, enlargements and shafts resulted in maximum predicted greenfield figures of 140 mm, with 60 mm predicted for the Lower Concourse tunnel.

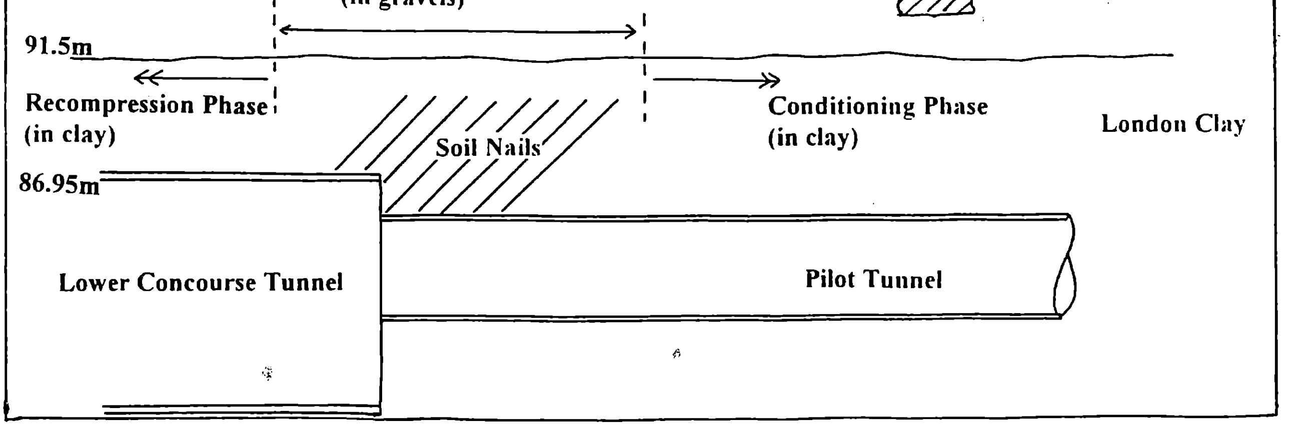

Figure 2 Longitudinal Section of Lower Concourse

5.0 MEASURES TO LIMIT MOVEMENT

5.1 *Construction Techniques*

Due to the size, limited clay cover and sensitive location of the tunnels it was essential that best possible construction methods be employed, thus reducing the risk of face instability and reducing settlements. To achieve these a joint approach was taken by JLE and the Contractor. The agreed construction method comprised:

1) A 3.85 m diameter pilot tunnel to be driven prior to the main excavation of the lower concourse as shown in Figure 2.

On construction of the enlargement, this would reduce the face area open at any one time and allow easier control of the face by dividing it into smaller elements, and act as a dowel restricting the movement of the soil mass towards the open face. The pilot tunnel was of SGI and was advanced one ring at a time with each ring being fully grouted prior to excavation for the next. This ensured that no voids were left and that the ground/pilot interaction was maximised. All circle bolts were installed to maximise the dowelling effect.

2) Soil nails installed from the pilot to strengthen and stabilise the London Clay above the crown, reduce movements into the face and hence reduce settlements. The soil nails comprised 25 mm diameter Dywidag bars installed at 45° off the vertical and radially in an arc from shoulder to shoulder at 1.2 m spacings along the length of the tunnel (see Figure 2). They were installed by open hole auguring, the bar inserted and full column grouted to be within 1.5 m of the London Clay/Terrace Gravel interface. This allowed the drilling to act as probing ahead. The soil nails were also designed to act as pins to prevent blocks of clay falling into the excavation as per rock bolts.

An alternative to soil nails to prevent collapse and inundation of the face could have been to stabilise the Terrace Gravels by permeation grouting. This was discounted as future compensation grouting in treated Terrace Gravels may have resulted in high fracture pressures, with possibly excess pressure being exerted at the tunnel face.

3) During the enlargement of the Lower Concourse Tunnel, the face was to be divided into five benches with each stage fully supported before the excavation of the next begins. Full face timbering was required, held by walings and strutted off large steel soldiers.

Initial cycle time to excavate, build and grout one ring of the enlargement was in excess of 40 hours.

Therefore grouting behind the face timbers of each stage was required so as to fill any voids between the excavated face and the timbers and to limit the scope for ground relaxation. With improved cycle times this requirement has been relaxed but is under constant review.

Excavation to the end of 1995 has progressed smoothly with the tunnel face being stable throughout with little overbreak. There was no movement of the face detected during the 2 week Christmas shutdown.

5.2 *Ground Treatment*

To prevent unacceptable settlements affecting the viaduct piers, ground treatment by means of grout injection was employed. The Contractor proposed a combination of permeation and compensation grouting, injected via sub-vertical Tube á Manchettes (TAMs) with injection points at 0.33 m centres, installed 2 to 3 m within the London Clay.

The permeation grouting comprised the injection of micro-fine cementitious material within the Terrace Gravels to form a 'semi-rigid slab' 1.6 m thick, and 1.5 m above the London Clay interface below the footings of the viaduct. The semi-rigid slab was intended to even out settlements and to protect the footings from compensation grouting within and below the slab.

The Contractor proposed three phases of compensation grouting as indicated in Figure 2.

1. Conditioning phase - pre-stressing the soils below the piers ahead of the face to enable immediate reactions from compensation grouting.

2. Compensation phase - carried out as tunnel induced settlements begin to affect the piers. Controlled quantities of grout are injected to compensate for the predicted volume losses along the settlement trough. These predictions were continuously updated using the results from the instrumentation monitoring.

3. Recompression phase - to recompress the soils once the tunnel heading has passed.

It was considered, that with the limited clay cover to the tunnel crown, there was a possibility that the compensation grouting phase taking place in the clay immediately above the face may result in an unacceptably high risk of fracture pressures possibly causing face instability. Therefore the compensation phase was targeted in the untreated Terrace Gravels below the semi-rigid slab. The volumes of injection were kept relatively low and good communication between men at the tunnel face and those above ground carrying out the grouting works was maintained to enable grouting to be immediately halted if any face movement was observed.

The compensation grout comprised a bentonite cement mix with various additions of pfa and chemical hardener. Generally 30-50 litres per sleeve in any one pass was injected at pressures up to 6 bar, with the injection locations being pre-programmed in a systematic way so that settlements over the width of the trough were adequately compensated. Approximately four times the actual volume losses were injected at any one location to ensure that the majority of movement was accounted for.

5.3 *Instrumentation*

A comprehensive array of instrumentation was installed to enable the effects of tunnel settlement and the grouting process to be adequately monitored.

Each pier had a string of electrolevels monitoring tilts, and an array of wall mounted precise level studs. Sub-surface instrumentation comprised 2 or 3 rod extensometers at the locations given in Figure 3.

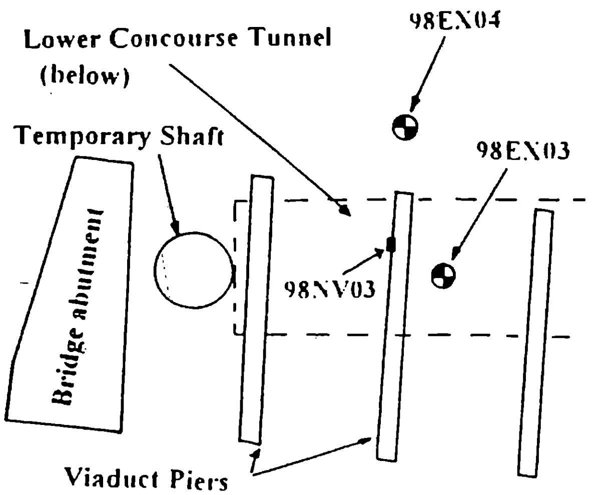

Figure 3 Instrument Locations

6.0 MONITORING RESULTS IN RELATION TO CONSTRUCTION

Observations from the monitoring are based on the behaviour of pier 98 in response to the tunnelling and grouting works, its location is indicated on Figure 3. Figure 4 presents precise levelling data for a point above the centreline of the lower concourse (98NV03), together with volumes of grout injected in that area against time. Figure 5 presents rod extensometer data from a location 10 m from the tunnel centreline (98EX04) again with the volumes of grout-injected against time. A rod extensometer (98EX03) over the centreline was lost due to surface works.

The electrolevels were used more as a 24 hour alarm system and were not used for analysis.

With reference to Figures 4 and 5, the settlement behaviour of the pier and the soils at sub-surface in response to works in the zone of influence are as follows.

6.1 *Pilot Tunnel*

The breakout of the pilot tunnel from the access shaft 10 m away appears to have generated minor settlements. During the excavation approximately 6 mm of settlement developed at a fairly steady rate, temporarily interrupted by small volumes (0.2 to 04 m^3) of compensation grouting.

The effects of the grouting can be seen to have a small effect on the extensometers, indicating that uplift was not restricted to the pier. Generally the influence of the pilot tunnel was small with negligible movement recorded.

6.2 *Westbound Running Tunnel*

A further 3.5 mm of settlement occurred over 4 weeks since completion of the pilot tunnel, with soil nail installation being the only works in the vicinity.

The centreline of the Westbound Running Tunnel is approximately 19 m away from the monitoring point and 3 mm settlement was recorded. This was reversed by compensation grouting, with up to 2 m^3 of grout a day being injected beneath the whole pier.

The grouting is picked up by the extensometer, showing some heave in the Terrace Gravels, and slight settlement in the London Clay. This confirms that the grout was injected in the Terrace Gravels, near to the London Clay interface, and may indicate some downward pressure onto the clay.

6.3 *Initial Break up for the Lower Concourse Enlargement*

After the running tunnel had gone past, a further 5 mm of settlement occurred due to excavation approx 15 m away of a contiguous piled walled box, part of the pedestrian link to Waterloo East. The extensometers also show some settlement, (2 mm) the majority in the

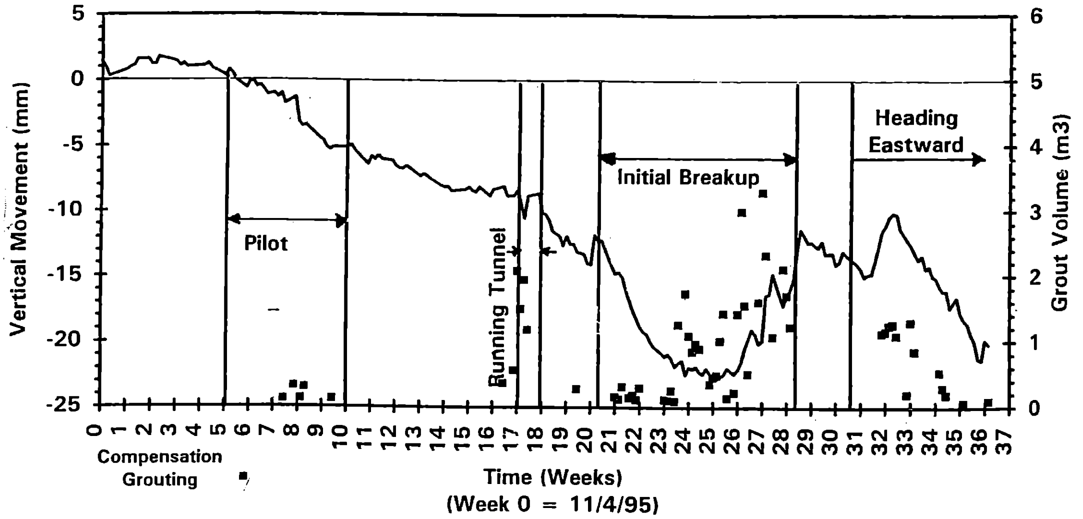

Figure 4 Settlement and Grouting vs Time

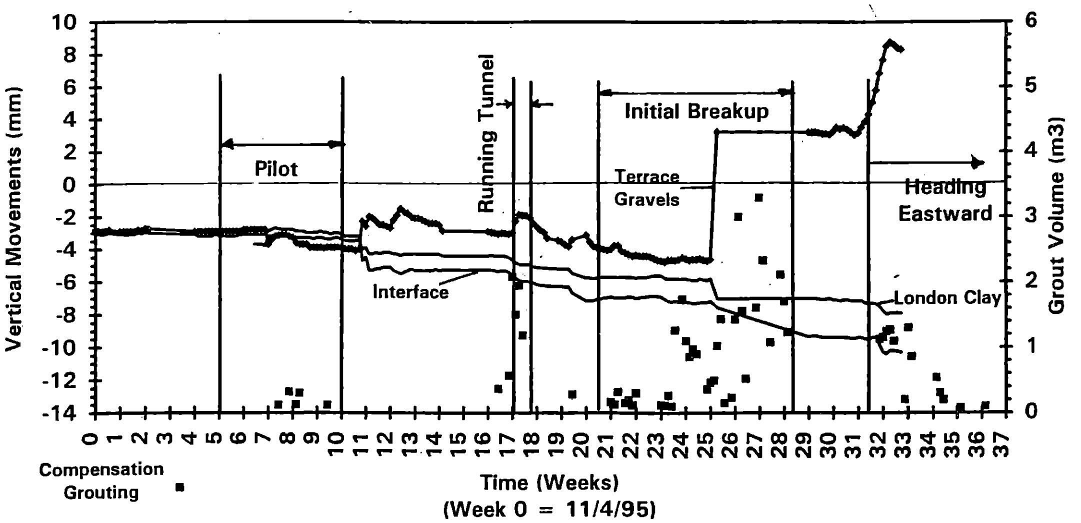

Figure 5 Subsurface movement and grouting vs Time

Terrace Gravels, possibly indicating some relaxation of ground since grout injection.

The break up from the enlargement took place approximately 10 m out from the temporary shaft, beneath pier 98. The tunnel was enlarged westward back to the shaft, where a headwall was constructed prior to heading eastward. Ten millimetres of settlement was recorded with minimal compensation grouting due to the proximity of the face. As the face moved away so the volumes of compensation grouting could be increased, with a maximum of 3.2 m³ being injected per day, some of which was within the clay.

The grout injections had the effect of limiting the settlements to a further settlement of 2 mm. After time, the grouting began to push up the pier resulting in a total recovery of the settlement.

There is a lack of extensometer readings over this period, but it does appear that grouting within the gravels heaved the upper rod by 7 mm. There is no influence from the tunnel excavations, as the rods are below the zone of influence.

6.4 *Lower Concourse Enlargement heading east*

After the initial break-up, the enlargement was progressed eastward. After 2 mm settlement, grout injections of greater than 1 m³/day produced 5 mm of uplift. As volumes of grout lessened, so settlement increased with 11 mm being recorded until further uplift was generated. Since beginning this heading, the residual settlement is 7 mm.

By the end of 1995, the enlargement had progressed to approximately 10 m east of Pier 98.

Total settlement from the lower concourse comprised: 6 mm from the pilot; 10 mm from the initial break-up, which was totally recovered; 7 mm from the enlargement heading east; a total of 13 mm actual settlement as opposed to the 60 mm originally predicted.

7.0 EFFECTS OF SHAFTS ON THE GROUND TREATMENT

During the conditioning phase of grouting it was noticed that significantly less uplift was being achieved on viaduct piers adjacent to shafts. Continued use of conditioning grouting eventually resulted in horizontal cracking around the perimeter of the shaft linings. The nature and orientation of the cracking indicated that this was a result of tensile forces being generated in the linings. It appears that as the grout was introduced into the ground and tended to cause uplift of the soil mass, friction between the soil mass and the shaft lining was mobilised with the shaft acting as a vertical dowel. The forces generated were sufficient to cause failure of the PCC linings in tension where the segments were restrained by bolts.

The problem was overcome by cutting the circle bolts at a number of locations thus dividing the shafts into several discrete elements. This enabled the shaft elements to move in line with the soil mass, enabling the anticipated uplifting of the piers to occur without further damage to the shaft linings.

On completion of the ground treatment works, any opening of joints will be made good.

It is suspected that the vertical TAMs may also act as small dowels, in effect pinning the ground. This may limit settlement but also inhibit uplift by grout injection. There is little evidence as yet however as to whether this is occurring.

8.0 CONCLUSIONS

Predicted settlements of 60 mm from excavation of the Lower Concourse tunnel have been limited to a maximum of 13 mm. Compensation grouting has been shown to be effective in limiting these potentially large settlements.

The tunnel measures are harder to quantify, but the face has been observed standing up with little overbreak to the end of 1995.

The availability of compensation grouting should not detract from the need to keep actual face losses to a minimum. Construction methods such as those described together with the highest standards of workmanship are essential to prevent unnecessarily large face losses reaching the surface.

A proactive approach to the compensation grouting with constant review should also be adopted, and possible limits to its effectiveness such as shafts and TAMs acting as vertical dowels be considered.

9.0 REFERENCES

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