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The measurement of ground movements due to tunnelling at two control sites along the Jubilee Line Extension

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ABSTRACT. The paper describes a research project involving field measurements of the response of the ground due to bored tunnelling at two control sites along the route of the Jubilee Line Extension Project. One site is at St James's Park, Westminster in London Clay and the other is at Southwark Park in Woolwich and Reading beds and Thanet Sands. Details of the instrumentation, their layout and precision are given and some preliminary results are presented.

1. INTRODUCTION

The construction of the Jubilee Line Extension has provided an opportunity to carry out field studies of tunnel-induced subsidence and its influence on buildings. Burland *et al* (1996) give details of a collaborative research programme which has been established for this purpose. One of the projects making up this programme is to measure the response of the ground due to bored tunnelling at two greenfield "control" sites along the route of the Jubilee Line Extension Project. The first site is located in St. James's Park, Westminster and the second in Southwark Park, south of the river Thames. At both locations state-of-the-art instrumentation is being used to measure the three-dimensional ground movements and the accompanying earth pressure and piezometric responses above and adjacent to the bored tunnels. This paper describes the two control sites, and the instrumentation and monitoring techniques being employed. Some results from the St. James's Park site are given.

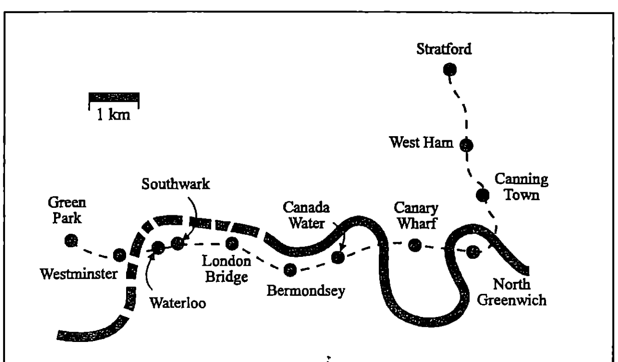

Figure 1. Route plan

2. SITE LOCATIONS AND GEOLOGY

An overall route plan highlighting the two control site locations is given on Figure 1. The two sites offer the opportunity to investigate ground response to tunnelling in different geological materials, one predominantly clay and the other granular.

St. James's Park control site is shown in plan on Figure 2; two 4.75m OD bored running tunnels pass beneath the instrument array, diverging slightly towards Green Park. A simplified section detailing the subsurface instrumentation and relative tunnel positions is shown on Figure 3. Both tunnels are constructed in London Clay overlain with 3-4m of Terrace Gravels, and topped with 3-4m of sandy alluvium and made ground. At the instrumented section the depths of the westbound and eastbound tunnel axes are 31m and 20.5m respectively. The two tunnels are approximately 21m apart in plan. The deeper westbound tunnel passed beneath the site in April 1995, while the eastbound tunnel was constructed in January 1996.

The second site in Southwark Park, located between the Canada Water and Bermondsey station excavations, is shown in plan on Figure 4. Two parallel 5.0m OD running tunnels 27.5m apart pass beneath the instrumented section with nearly identical axis depths of 20.8m. The geology comprises Thanet Sands at depth overlain by the Woolwich and Reading bed succession of Glauconitic Sands, Pebble Beds, Lower Mottled Clay, Lower Shelly Clay, Laminated Sands and Silts and a possible layer of weathered Upper Mottled Clay. The Woolwich and Reading beds are blanketed with 4-5m of Terrace Gravels and topped with 3m of clayey alluvium and made ground. A section indicating the geology, tunnel geometry and subsurface instrumentation array is shown on Figure 5. The westbound tunnel passed under the site in January 1996; the eastbound is expected in the middle of 1996.

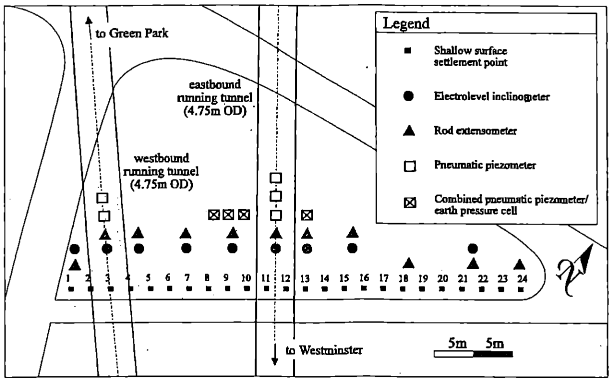

Figure 2. St. James's Park control site plan

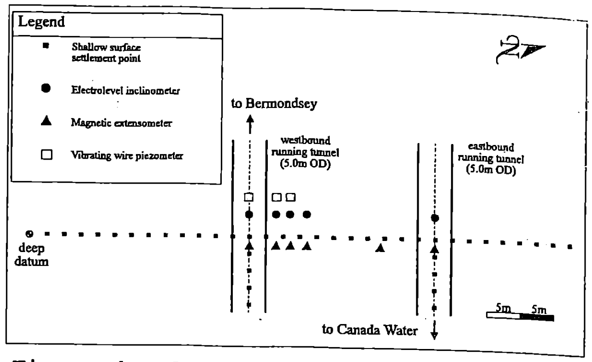

Figure 4. Southwark Park control site plan

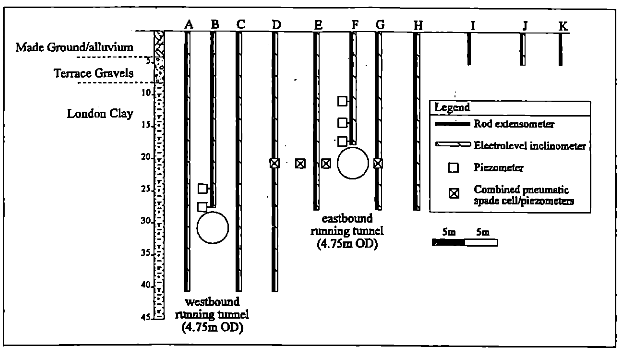

Figure 3. St. James's Park control site instrumented section

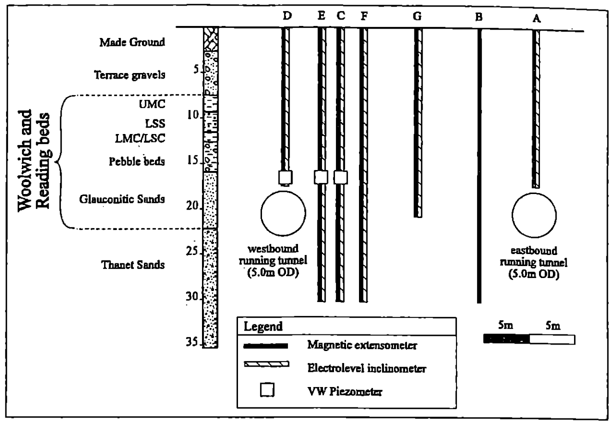

Figure 5. Southwark Park control site instrumented section

3. CHARACTERISATION OF GROUND BEHAVIOUR

The ground behaviour of the control sites is considered in three main contexts: displacements, pore pressure changes and total stress changes. A careful record of time is kept throughout the measurement of these quantities so that the ground behaviour can be related to tunnelling activities and climatic conditions. During the periods when the tunnelling operations are in the vicinity of the control sections, measurements are taken continuously on a 24 hour a day basis.

3.1 *Displacements*

Displacements are measured at the surface and subsurface in the ground around the tunnels as shown in Figures 2 to 5. The majority of surface monitoring points and subsurface instrumentation are orientated in lines perpendicular to the tunnels to allow vertical and horizontal measurements to be made in the transverse plane. Observations of displacements parallel to the tunnel axis are also carried out to assess the magnitude and nature of transient movements occurring as a tunnel approaches and passes.

3.2 *Pore pressure and total stress changes*

Pore water pressures are measured at various levels and distances from the vicinity of the tunnel crown and its axis as shown in Figures 3 and 5. In this way changes in the pore water pressure regime due to the effects of tunnelling and also due to long-term and seasonal changes can be assessed.

At St James's Park total ground stresses are measured at four points from the axis level of the eastbound tunnel. The measurements complement those made of load and displacement in a specially constructed instrumented lining installed in line with them (see Davies *et al*, 1996).

4. METHODS OF MEASUREMENT OF GROUND SURFACE MOVEMENTS

Ground surface movements are monitored using shallow settlement points, comprising concrete columns 1.5m deep, 100mm diameter sleeved with PVC tubing over the upper half with an extended BRE socket embedded in the top (refer to BRE digest 386). These points are arranged in a line at 2.5m centres, extending beyond the end of the zone of influence on at least one side of each tunnel.

4.1 *Total station surveying*

The total station used at the control sites is a Leica TC2002, a model TC1610 was also used for part of the work. The instrument is accurately set up over one of two designated positions marked by nails beyond either end of the line of shallow settlement points. At the opposite end a tripod is set up with a prism accurately centred on the nail.

The positions of the instrument and prism are coordinated by sighting onto reference targets, which are retro-reflective prisms, placed on structures well outside of the zone of influence and also by sighting onto the prism set up at the opposite end of the line.

The precise coordinates of each shallow settlement point are determined by sighting onto a demountable target; with a retro-reflective prism mounted on a rotating head, which screws into the BRE sockets. The exercise is carried out for all points from both ends of the line closing back onto the reference points.

The advantage of this method of measurement is that the positions in space, in three dimensions, are obtained from one set of observations which can be carried out in a relatively short period of time. After analysing data from the westbound tunnel drive at St James's Park the accuracy of the total station surveying was found to be about 1-2mm. The accuracy is not as good as that obtained using the methods which are about to be described. Each of the following methods measures one component of movement independently.

4.2 *Precise levelling*

Vertical displacements are measured using a Leica NA3003 electronic precision level with a bar coded invar staff. A datum level is brought in from outside the zone of influence of tunnelling (a deep datum at Southwark Park) and levels are taken on each point using a BRE levelling plug. The reference heads of the rod extensometers also installed on the site are always incorporated into the levelling survey.

The instrument resolves to 0.01mm, the realistic accuracy that can be achieved is 0.1mm. Closing errors are usually less than 0.3mm.

4.3 *Measurement of horizontal strains with a micrometer stick*

Measurements of relative horizontal movements between adjacent settlement points are made using a micrometer stick with a gauge length of 2.5m. The device was manufactured by the Building Research Establishment (BRE); a similar device is described by Burland and Moore (1974). Two posts with ball seatings at the top are screwed into adjacent sockets. The stick comprises an aluminium beam of square section with a series of precisely machined holes at one end and a slot at the other to allow movement. The ball seatings on the posts locate in one of the holes and the slot.

A micrometer mounted at the slotted end is screwed in until contact is made between the metal plunger and the ball seating. To facilitate repeatable reading an electrical circuit is set up in a box on top of the beam so that when contact is made the circuit is closed and a light (LED) is illuminated. Sets of three readings on the micrometer are taken for each span, relocating the slotted end of the beam each time. Temperature is also measured for each span using a thermometer mounted on top of the beam.

Readings on the micrometer can be resolved to 0.001mm, the reading from each set of three are usually within 0.05mm which is the representative accuracy for each set.

At Southwark Park additional shallow settlement points were installed for a short distance along the tunnel axis so that longitudinal strains from the advancing tunnel can be determined.

4.4 *Measurement of longitudinal horizontal movement by collimation*

A total station and collimation device are required for this exercise. The total station is set up at one of designated points and its position and bearing established at the start of the collimation exercise as described in Section 4.1. The vertical cross-hair is then set so that all the BRE sockets can be seen from one fixed horizontal angle through the telescope. A marker is placed at an appropriate point so that the same angle can always be located to obtain repeatable results.

The collimation device made at Imperial College comprises a digital vernier calliper mounted on a bracket that is slid onto a post which is screwed into each BRE socket in turn. A trimmed reflective surveying target is fixed to one end of the callipers. By opening or closing the callipers the target can be brought into line with the vertical cross-hair seen through the telescope of the total station. The collimator can be rotated on its post so that it is perpendicular to the line of sight. This is checked with a cross-beam on the vernier arm.

The operation is carried out by the total station observer directing the collimator operator to open or close the vernier callipers. When alignment between the total station and collimator is achieved the reading on the vernier is taken. The exercise is repeated for all points from both ends of the line.

The accuracy of results from such measurements has not yet been established as the data has not been fully analysed. The vernier has a resolution of 0.01mm, and it is anticipated that a sub-millimetre accuracy can be achieved by comparing measurements on points outside the zone of influence with those where movements occurred.

It is worth noting that the collimation exercise is quite time consuming and not practicable at night. Longitudinal tunnelling movements occurring at night were therefore monitored using total station surveying.

5. METHODS OF MEASURING SUBSURFACE GROUND BEHAVIOUR

The subsurface instrumentation at both sites were installed by the BRE using a light cable percussion rig with the boreholes cased through granular material where necessary.

At St James's Park, the verticality of the boreholes was checked prior to installation of instrumentation using a mapping kit comprising temporary inclinometer tubing with spacers and an inclinometer torpedo. The boreholes were backfilled with a cement-bentonite-pfa grout on completion of installation. Samples of the grout were always taken so that the grout stiffness could be checked and compared with the ground conditions.

The philosophy of the layout of subsurface instrumentation was to concentrate the devices around the tunnels where most movement occurs and adequately distant from them to define the zone of influence. The position of instrumentation was chosen to ensure that compatible measurements of vertical and horizontal displacement could be made at the same levels and tunnel offsets where possible.

5.1 *Measurement of sub-surface vertical movement*

The different ground conditions at the two control sites necessitated the use of different types of extensometer device. The equipment for both types was supplied by Soil Instruments Limited.

Rod extensometers: At St James's Park rod extensometers are used to measure subsurface vertical movement. Stainless steel rods extend from the required depth to the surface where measurements are made. Up to eight rods can be incorporated into each borehole. The base of each rod is held in place by an anchor with three prongs which are hydraulically jacked into the surrounding soil. Each rod is sleeved to the surface where it passes into a reference head with machined guides into which a dial gauge can be inserted. The dial gauge plunger thus makes contact with the top of the rod, which has a domed head which can be adjusted to an appropriate level prior to movements occurring. Measurements are therefore made relative to the reference head.

Readings on the dial gauge can be resolved to 0.005mm. The accuracy of measurements in absolute terms is 0.1mm which is governed by the precise levelling of the reference head.

Magnetic extensometers: Ground conditions at Southwark Park necessitated casing the boreholes over most of their depth and so it was not practicable to use rod extensometers. Spider magnets, comprising a ring magnet with attached legs which spring out to the sides of the borehole, are installed at the appropriate depths. The magnets are pushed down the outside of a plastic tube, extending over the depth of the borehole, which remains in place during casing withdrawal and grouting. Up to fifteen magnets are installed per hole, though more could have been accommodated. The tube is connected to a reference head on completion of the borehole.

Measurements are made by running a reed-switch sensor down the tube on a tape which passes through a vernier device which is screwed to the reference head. The sensor is activated as it comes into the magnetic field at each level. Readings can be resolved to 0.1mm, which is the accuracy of the precise levelling carried out on the reference head. The accuracy of measurement of subsurface movement using this system is about 0.2mm.

5.2 *Measurement of subsurface horizontal movement*

At both sites horizontal displacements are measured using electrolevel devices provided by the BRE, installed within inclinometer tubing grouted into the boreholes. Up to sixteen electrolevels are located in each tube. The keyways of the tubing are orientated orthogonally to the tunnel axis. Each electrolevel is mounted on a short carriage which is pushed to the appropriate depth and has an independent cable leading to a socketed end at the surface. The majority of the electrolevels are orientated transverse to the tunnels. Most of those directly above the crown are positioned to measure longitudinal movements as the tunnels approach and pass.

The devices can be read manually at the surface using a Fylde hand-held read-out unit which energises the electrolevel for 5 seconds before taking the reading. During the time of the tunnel passing, the electrolevels are connected to multiplexers and automatic logging units so that readings are taken continuously and stored on computer.

The electrolevel devices measure changes in vertical rotation and have a resolution of one second of arc. A realistic accuracy of the devices, taking into account temperature and electronic factors, is 20 seconds of arc. The amount this relates to in terms of horizontal translation is dependent on the gauge length between electrolevels. Displacements are determined by integrating the rotations measured at each point in the tube along its length usually assuming the lowest device is a datum with no movement (in the case of the electrolevels above the tunnel crowns movements will be related to measured ground surface displacements at that point).

5.3 *Measurement of pore water pressures and total stress*

At St James's Park pneumatic piezometers and spade cells were installed as shown in Figs 2 and 3. The porous ceramic tips of the piezometers were fully deaired prior to installation within a filter of saturated sand. The borehole was then grouted to the ground surface.

The spade cells, which also have a piezometer incorporated in them, were pushed approximately 0.5m into the London Clay from the base of the borehole, so that the pressure face is facing the tunnel axis.

Both types of device are read with a digital pneumatic bubbler readout unit which supplies pressurised nitrogen to the sensing diaphragm. The accuracy of the measurements should be better than 5kPa once steady conditions have been reached.

At Southwark Park the ground conditions precluded installation of spade cells in the vicinity of the tunnels. Three vibrating-wire piezometers were installed above the westbound tunnel taking the same precautions of saturating the ceramic stones.

6. OBSERVED SURFACE AND SUBSURFACE SETTLEMENTS AT ST. JAMES'S PARK

During the critical periods of tunnel progress detailed monitoring of the developing ground responsewas undertaken by the research group at Imperial College to capture.

Figure 6 shows the measured surface settlements caused by construction of both the westbound and eastbound running tunnels at St. James's Park. Each set of data represents construction-induced settlements only (ie. "longer-term" consolidation or seasonal settlements are omitted). The volume losses calculated by integrating the two settlement profiles and expressed as a percentage of the nominal excavated tunnel face area are 3.3% for the westbound and 2.9% for the eastbound. The inset plot of Figure 6 showing the logarithm of settlement, s, divided by maximum settlement, s_{max} versus the squared offset distance from the tunnel axis, y^2, suggests that the displacement profiles do not follow exactly a Gaussian distribution. It is also apparent that the eastbound subsidence profile is asymmetrical about the tunnel axis with a significantly wider trough exhibited nearer the previously constructed westbound tunnel.

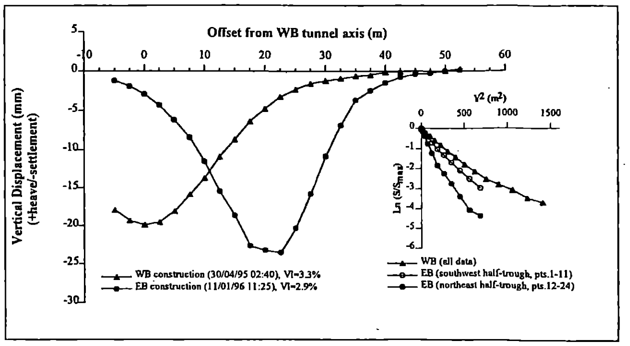

Figure 6. Vertical displacement profiles for tunnel construction at St. James's Park

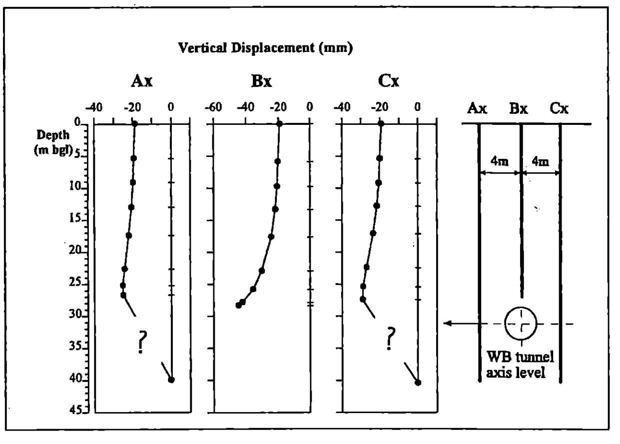

Figure 7. Subsurface vertical construction displacements above westbound running tunnel at St. James's Park

Subsurface construction displacements above the westbound running tunnel are shown in Figure 7. A significant increase in displacement with depth above the centre line is observed and some asymmetry is apparent on either side of the tunnel axis.

7. CONCLUSIONS

Two greenfield "control" sites have been described along with the scope of instrumentation installed and the measuring techniques adopted. The geology above the tunnels at the two locations is very different: predominantly London Clay at St. James's Park and Woolwich and Reading beds at Southwark Park. The methods of tunnelling are also different.

A sample of some of the processed data from St. James's Park is given as an example of the quality of measurements. This constitutes a fraction of the data yet to be processed and analysed.

At present both tunnels have been constructed at St. James's Park and the westbound at Southwark Park; the remaining tunnel is to be constructed mid 1996.

It is planned that monitoring of the instrumentation at the control sites will continue for at least five years to observe long-term effects.

The results from the study will be correlated with measurements from monitoring carried out on several buildings along the route of the Jubilee Line Extension as described by Burland *et al* (1996).

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