Behaviour of an Anchored Diaphragm Wall in Stiff Clay

Comportement d'un Mur Diaphragme Ancré en Argile Dure

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SYNOPSIS An anchored diaphragm wall in stiff London clay, supported by 4 rows of anchors, has been instrumented so that displacements, both surface and internal, could be monitored during and after excavation of an 8 m deep cutting. Pore pressures and anchor loads have also been measured. The effects of the anchors have been two-fold: firstly, appreciable horizontal displacements have occurred beyond the limit of the anchors and secondly, there has been a block movement of the anchored zone, with horizontal and vertical movements becoming quite large (up to 50 mm and 30 mm respectively). Horizontal strains in this zone have reached up to 0.34% (extension). Nevertheless, the component of displacement along the anchors is of the order of only 2 to 3 mm, and the loads have remained nearly constant, indicating satisfactory performance of the anchors. Thus, the installation of ground anchors does not preclude the possibility of high horizontal and vertical movements.

INTRODUCTION

The Neasden Lane Underpass is situated in north London and forms part of a two level interchange provided for the relief of the North Circular Road. The Underpass is just over 1 km long and is largely in cutting up to 10m deep, with retaining walls supporting the excavation in London Clay (stiff, silty and highly fissured).

Various types of retaining structures were considered in the optimisation of the design and construction. Both the conventional R.C. retaining walls and diaphragm walls were adopted in the final design.

The underpass was planned to cut through a surburban environment with the aim of minimum disturbance. The problem of constructing high retaining walls close to existing buildings was tackled by the choice of diaphragm walls with multilevel ground anchor supports. Due to general lack of experience of the long-term performance of ground anchors in clay, the Consulting Engineer decided to monitor the construction and subsequent behaviour. The Department of the Environment agreed to the installation of suitable instrumentation and called in the Building Research Station to advise and to coordinate the measurements.

GROUND CONDITIONS

The site is covered by 2 mm of topsoil and made-up ground, overlying stiff brown fissured silty London clay. At an average depth of approximately 8 m, the brown clay grades into grey-blue fissured London clay containing dustings of silt in its fissures. At a depth of about 30 m, the Woolwich and Reading beds are encountered.

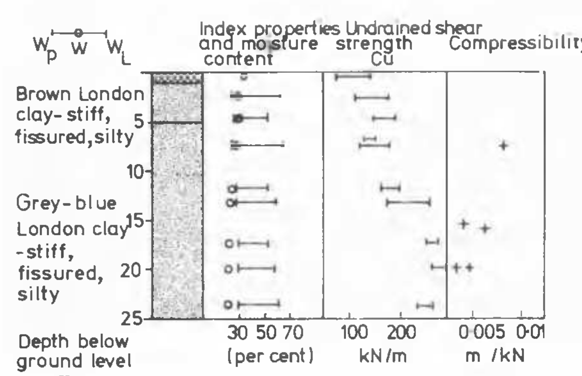

Fig. 1 Typical soil properties

Relevant soil properties obtained from the laboratory testing programme are shown in Fig. 1, namely a plot of the undrained shear strength, moisture content and index properties along with a typical borehole log. The shear strengths are in the same range as those measured by Hooper and Butler (1966) for London clay.

GROUND ANCHORS

Test Anchors

Ten test anchors were constructed vertically, in the vicinity of the instrumented section, with the number of underreams varying from seven for 500 kN working capacity to three for 200 kN. The tested anchors were M/s Fondedile multi-bell type with 535 mm diameter underreams spaced at 1150 mm centres in a 175 mm shaft. Typical test results showed an initially linear load-displacement curve, with yield beginning at a load approximately proportional to the number of underreams.

Permanent anchor details and installation

Four rows of anchors were installed in the diaphragm wall. Each panel, of nominal thickness 600 mm and width 4.57 m, contained eight anchors. The optimum angle of inclination of the anchors to the horizontal was 20°, although in some panels inclinations up to 40° were used to minimise the encroachment beneath nearby houses. Holes of length 16 m to 18 m and 175mm diameter were augered, followed by underreaming with spoil removal by circulation of water in the bore. After completion of underreaming, the hole was filled with water/cement grout and the anchor tendon inserted. Tendons were supplied greased and covered by an extruded polypropylene sheath. The sheath was removed over the anchor length, and the tendon was degreased and the strands separated. In the upper three metres of the anchor length concrete grout was washed away and the free length of the bore was protected against collapse of the clay by installing a 150 mm diameter plastic pipe.

Each anchor, prior to tensioning to working load, was test-loaded to 0.77 of the ultimate tensile strength of the tendon for a period of five minutes. After the reloading, the load in each strand was checked and the anchor was destressed. Subsequently the anchors were restressed to 115% of the design working load and rechecked after 24 hours. If the losses exceeded 5% the required load was restored and checked again after 24 hours, before permanent anchoring of the tendons.

INSTRUMENTATION

The deformation of the wall and the surrounding ground was expected to lie mainly in a plane perpendicular to the line of the cutting, due to the plane geometry. The choice of the test panel was influenced by the suitable position of Elm Way which allowed instruments to be installed very nearly at right angles to the underpass, as shown in Fig. 2. Initial conditions must be known accurately so that, where possible, readings of instruments were taken before excavation of the diaphragm wall had begun.

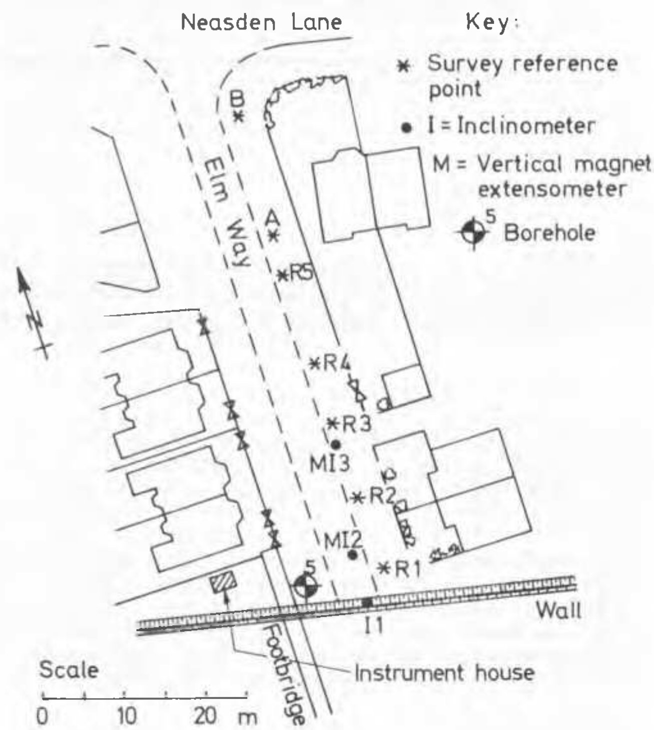

Fig. 2 Plan of instrumented area

All movements were referred in elevation to a datum point B, at a distance of 60 m from the cutting, and in plan to the base line AB.

Displacements

The deformation of the ground mass behind the diaphragm wall was studied in two parts. The vertical and horizontal movements at the surface were measured with reference to the datum points A and B, shown in Fig. 2. The movements of points beneath the ground surface were measured by means of magnet extensometers (for vertical movements) and inclinometers (for horizontal movements). These internal movements were then related to the surface movements.

The various instruments referred to are described briefly here. The magnet extensometer consists of a number of small ring magnets, secured in the ground by a combination of springs and grout, with an internal guide tube of P.V.C. passing through them. The position of each magnet is recorded by the operation of a reed switch that is lowered down through the tube with a steel tape. The system is described in detail by Burland, Moore and Smith (1972). Two such extensometers were installed at distances of 4 m and 19 m behind the diaphragm wall, each to a depth of 13 m, equal to the depth of the wall.

The inclinometer installation (see Green, 1973) consisted of an aluminium guide

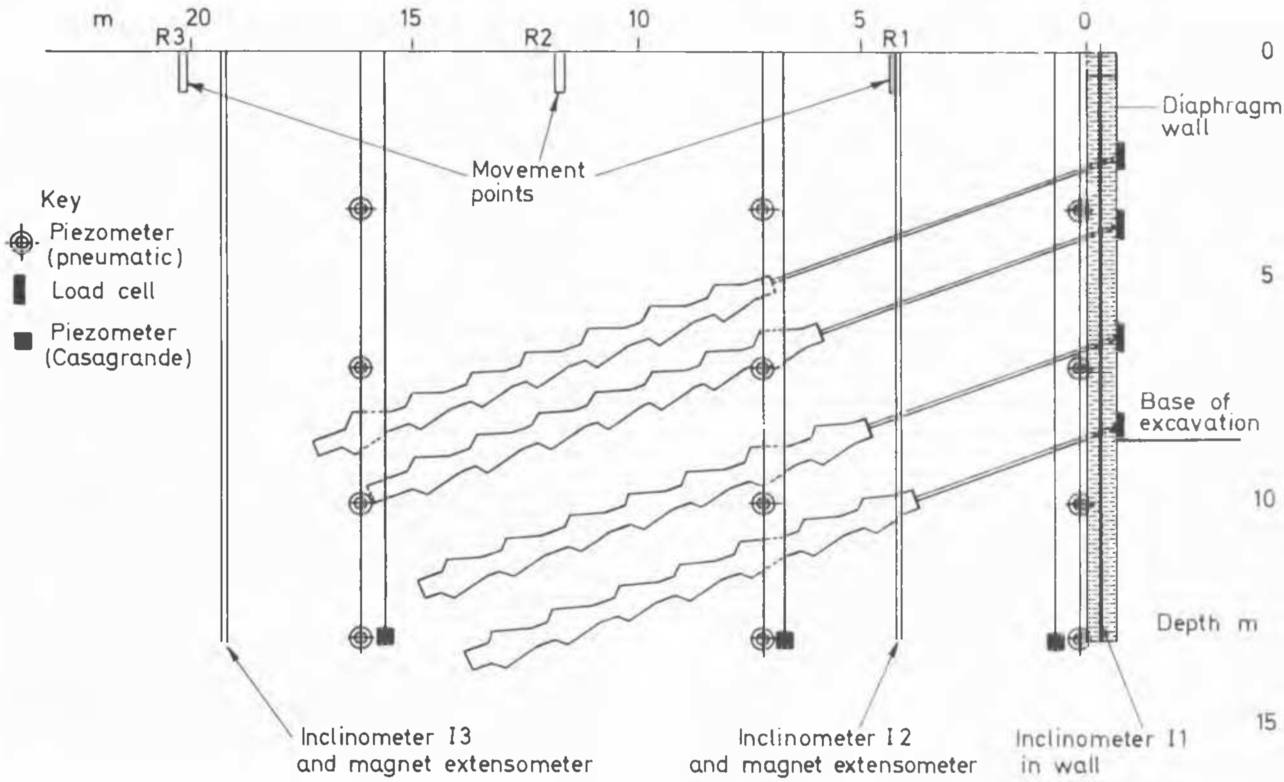

Fig. 3 Section through instrumentation

tube coated with resin to resist chemical action in the ground, down which the instrument is lowered. A strain gauge coupled to a pendulum records the angle at which the inclinometer is held, so that by measuring this angle at intervals equal to the length of inclinometer - in this case, 1 m - a profile of the tube is obtained (Burland and Moore 1973). The orientation of the instrument is maintained by channels in the aluminium tube: the inclination at right angles can be obtained by rotating the inclinometer through 90° before lowering. Three inclinometer guide tubes were installed, the first two in the ground behind the line of the cutting, before the excavation for the wall had begun, while the third one was fastened to the reinforcing cage before lowering the cage into the slurry-filled diaphragm-wall-trench. Each tube was 13 m in length.

The surface movements were obtained using precise surveying invar tapes with theodolite work. The movement points were grouted into the ground at a depth of 2 m and specially designed removable targets were located in the tops of the inclinometer tubes. (Burland and Moore, 1973). Datum points A and B were grouted in at a depth of 4 m to ensure that they were well removed from the zones of seasonal influence. The positions of the survey reference points are shown in the plan view in Fig. 2, and in the cross section Fig. 3.

<u>Pore water pressures</u>

Pore water pressure was monitored during and after the excavation using two types of piezometer. Four pneumatic piezometers were installed at depths of 3½ m, 7 m, 10 m, and 13 m, in each of three boreholes. One of these was just behind the wall, and the others were at distances 7 m and 16 m back from the wall. In addition, Casagrande standpipes were installed at the locations shown in Fig. 3.

<u>Anchor Loads</u>

The anchors in the test panel were inclined at an angle of 20° to the horizontal, with seven underreams giving a design load of 400 kN. Vibrating wire load cells were fixed between pairs of purpose made anchor plates against which the tendons were stressed for each of the eight anchors in the test panel. These recorded the load carried by each anchor.

PROGRESS OF EXCAVATION

The survey reference points, piezometers, magnet extensometers and two of the inclinometer tubes (I2 and I3) were installed towards the end of 1971. The trench for the diaphragm wall in the region of the test panel was excavated through bentonite in January 1972. The diaphragm wall was cast complete with the third inclinometer tube (I1), by the end of that month. The cutting was excavated in a number of steps, with the cut moving from west to east. The depth of cut at one side of the underpass was frequently different from that on the other side. Fig. 4 shows the detailed progress of excavation in the plane normal to the test panel. The initial cut to a depth of about 3 m (Stage I) occurred first on the southern side of the underpass then close to the instrumented wall on the north side of the underpass (IB). The next removal of 2½ m to 3 m (Stage II) occurred first in the mid-third (IIA), followed by the south side (IIB) and then the north side (IIC). The next 2 m was again removed first from the middle, then from the north side and the final trimming of ½m took place all the way across. The figure also shows the installation dates of the rows of anchors.

RESULTS

In this section, the results of the surface surveying, inclinometer readings and magnet extensometer readings are presented in turn, allowing a composite picture of ground movement in three dimensions to be built up. This is then followed by summaries of pore pressures and anchor loads measured over the same period. Discussion of this information is presented in the next section.

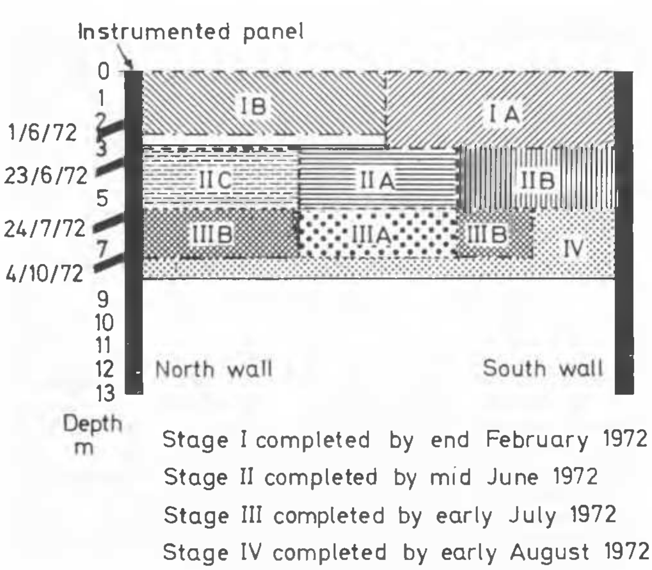

Fig. 4 Progress of excavation

Surface movements

Fig. 5 shows the development of surface movement normal to the wall at the movement points and at the top of the inclinometers at various times during and after excavation. The movement is initially inwards and horizontal, and not until the excavation is complete does much settlement occur. At all points the horizontal movement is greater than the settlement. There is some indication that the points R5 and R4, 38 m and 28 m behind the wall, initially settled, and have since undergone a small amount of heave. Within 14 months of the end of the excavation, the inward and downward movements appear to have ceased, having reached maximum values of about 50 mm and 30 mm respectively. It can be seen that of the order of one third to one half of this total displacement had occurred by the time the excavation was complete (one third settlement, one half of the inward displacement). The difference in movement between R3 and I3, which are within one metre of each other, is due to the 2 m difference in depth between them.

During excavation the top of inclinometer tube I2 moved further towards the cutting than tube I1 in the wall, indicating that a zone of compression developed immediately behind the wall while extension took

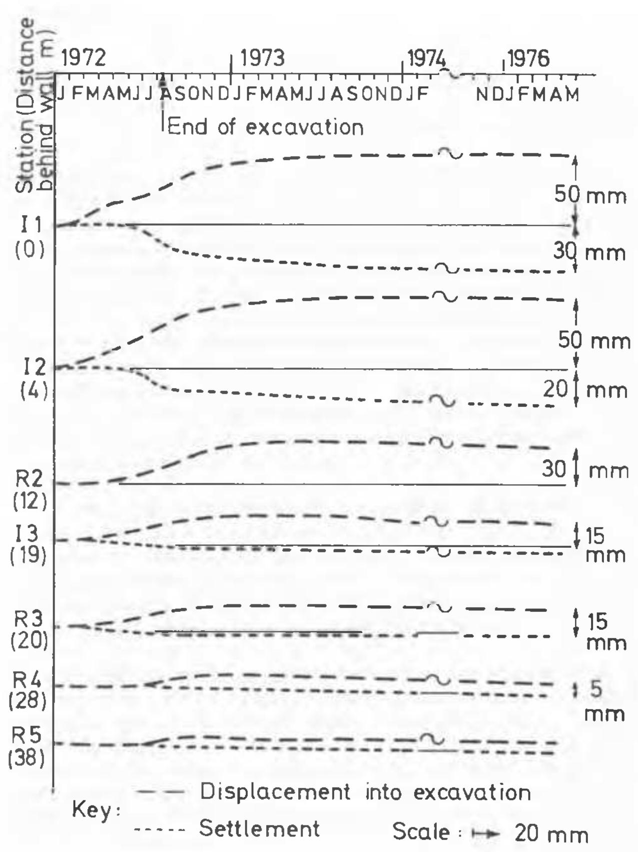

Fig. 5 Surface movements behind the wall

Point	I1	I2	R2	I3	R4	R5
Dist. betw. Adj. points	4	8	7	8.5	11.5	
Strain (per cent) End of excavation	+0.23	-0.18	-0.10	-0.07	-0.02	
14 months after completion	+0.10	-0.30	-0.16	-0.15	-0.02	
44 months after completion	+0.10	-0.34	-0.20	-0.12	-0.00	

TABLE I

place further back. Table I gives horizontal strains near the surface at various times after completion of excavation, (note that compression is indicated by a positive sign). It is evident that during the 14 months following completion of excavation the compression between I1 and I2 reduced from 0.23 per cent to 0.10 per cent, i.e. extension took place. At all other points behind the wall extensions occurred, reaching a maximum of -0.34 per cent approximately 8 m behind the wall. Even as far back as 24 m, three times the depth of the cutting, the strain is appreciable.

Internal displacements

The surface movements have been combined with the inclinometer results to give the total horizontal movements at three locations behind the wall down to a depth of 13 m and the results are given in Fig.6.

The displacement of the wall (inclinometer I1) and the displacement 4 m behind the wall (I2) both follow the same pattern: the movement is largely translational during excavation followed by some rotation after completion of the excavation. Further back from the

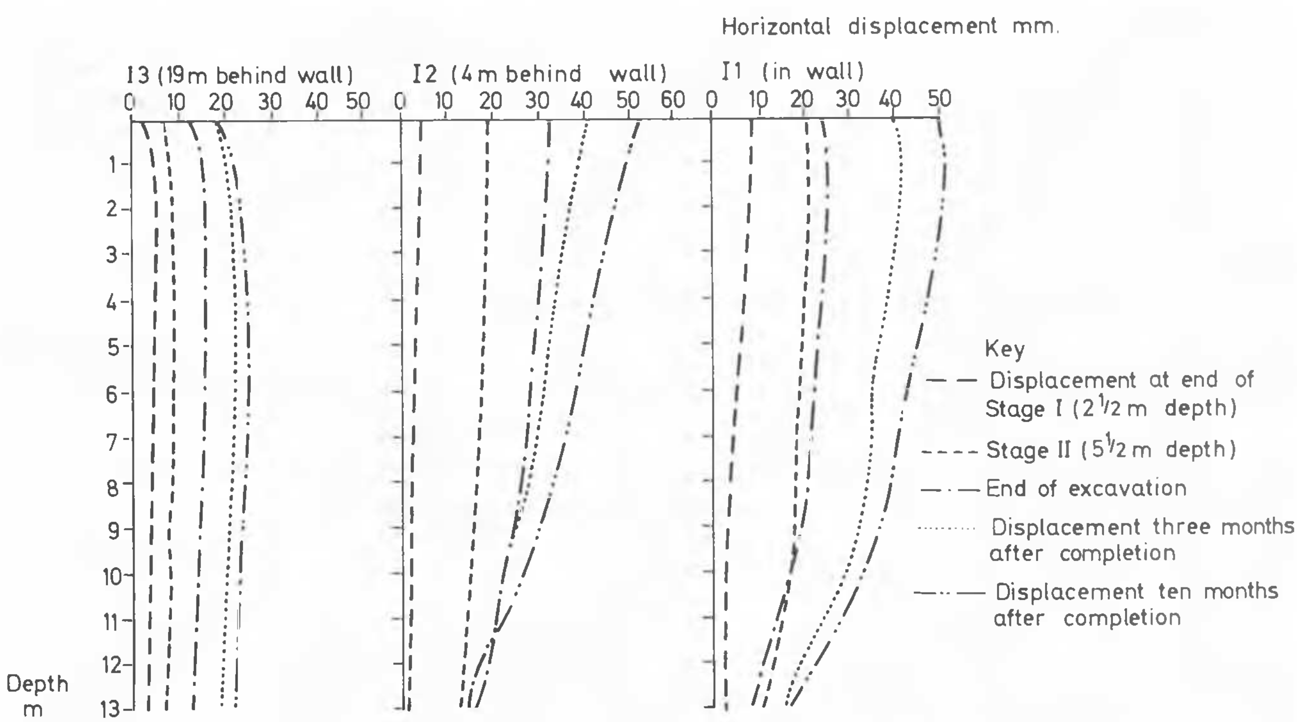

Fig. 6 Horizontal movements of wall and ground

wall at a distance of 19 m (I3) the movement is almost entirely translational.

In the previous section it was noted that compression took place between the tops of I1 and I2 during construction followed by extension thereafter. Fig. 6 shows that this effect extends over the full depth of the wall. At the end of excavation the horizontal compression between I1 and I3 is fairly uniform over most of the depth and equal to about 7 mm. In the first 10 months following excavation a uniform horizontal extension of about 10 mm occurs between I1 and I3 over all except the top metre where the extension was much less.

The readings taken with the inclinometer parallel to the excavation show that the tilt parallel to the cutting was very small.

The magnet extensometers, installed 4 m and 9 m behind the wall, showed that very little differential settlement occurred between the ground level and a depth of 13 m. At the distance 4 m behind the wall, the settlement at a depth of 13 m was 16 mm compared with a surface settlement of 20 mm.

Pore water pressures

Considerable difficulty was experienced with the operation of the piezometers, due mainly to damage caused during construction, so that it has only been possible to draw some general conclusions. Fig. 7 shows the pore pressures recorded by the three sets of piezometers, one immediately behind the wall, one 7 m and one 16 m behind. The pressures are shown separately for the period of excavation and for the period following the end of excavation.

The pore pressures in all three boreholes began to drop at the start of the excavation, and similar behaviour was observed in all of the Casagrande standpipes. Two months after completion of the excavation, the pore pressures were still falling, though more slowly and reached a minimum some 8 to 10 months after the end of excavation. Later readings, mainly obtained from the Casagrande standpipes and not shown in the figure, indicate that subsequently there has been a gradual increase in pore pressure at all the piezometer locations. Nevertheless, 44 months after the excavation had been completed, the values were still considerably lower than the original ones.

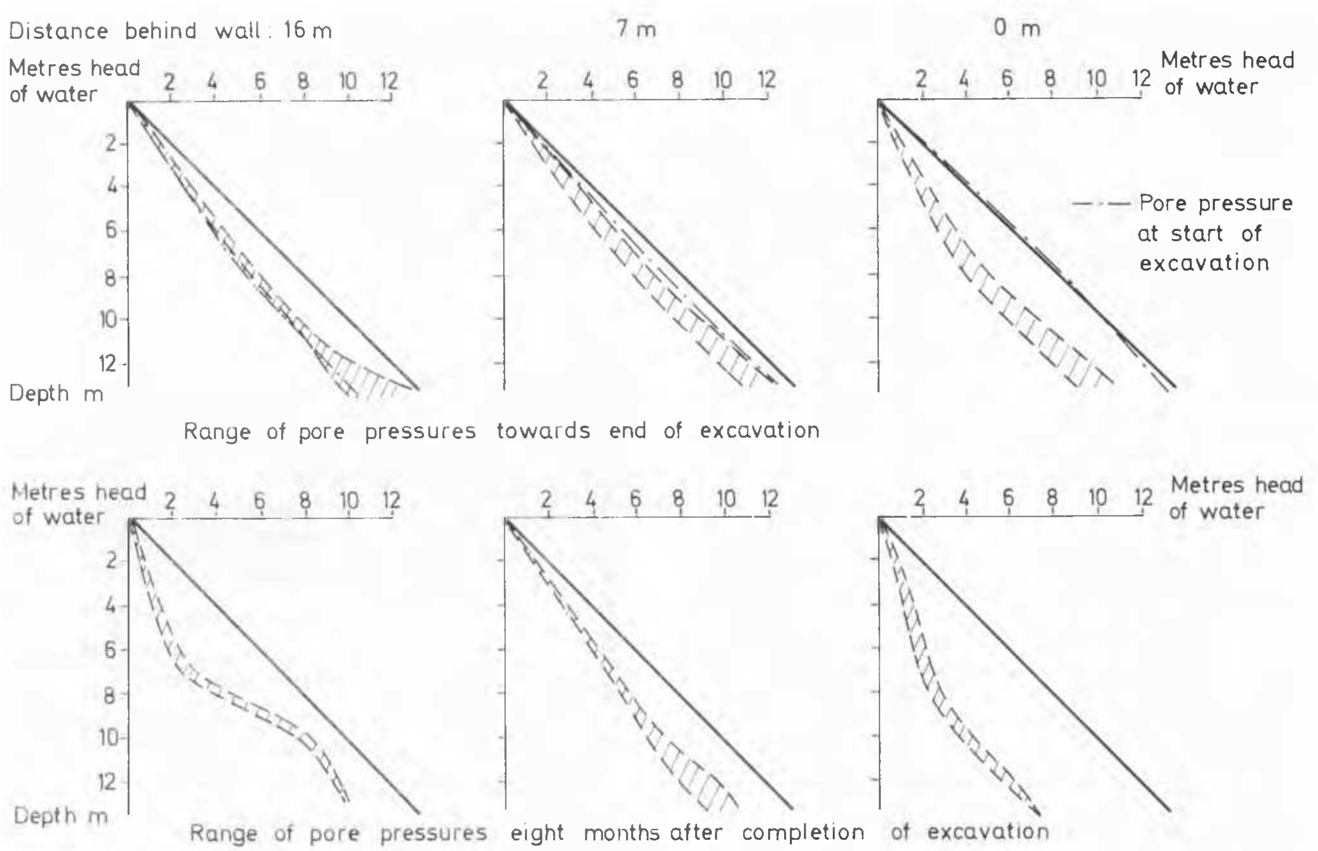

Fig. 7 Development of pore water pressures

Burland and Hancock (1976) have measured similar effects around a deep excavation in London clay at Westminster. Vaughan and Walbancke (1973) have noted that in some clay cuttings it can be 40 to 60 years before pore pressures reach their steady state values.

Anchor stresses

The two top rows of anchors have shown very similar behaviour: a load decrease as the row beneath was stressed, followed by a recovery, and nearly constant maintenance of load (at around 430kN for the top row, and 500kN for the second one). The loads in the third row dropped following completion of excavation, and then also became constant (at about 480kN compared with an initial load of 500kN). The loads in the fourth row continued to drop for about 8 months after completion of excavation, eventually becoming constant at about 370kN compared with an initial load of 440kN.

DISCUSSION OF RESULTS

The magnitude and distribution of the movements that have occurred has been slightly surprising. Fig. 8 shows trajectories of movement obtained by linking together survey movements and those measured with the inclinometer and magnet extensometers.

The movements due to the first 5 m of excavation show that little settlement occurred at this stage, while horizontal displacements are already one third of the total.

By the time the excavation at Neasden had reached its full depth of 8 m (end of stage IV) an appreciable vertical settlement had occurred at and just behind the wall, both at ground level and at a depth of 13 m (level with the bottom of the wall). Ten months after the completion of excavation, when the rate of movements had decreased (later readings suggest that these movements are close to the long-term values), the ratio of horizontal to vertical components of the movements of the top of the wall is about two to one and slightly more than one to one at the bottom of the wall.

Littlejohn and Macfarlane (1974) have studied a 14.5 m deep excavation at Keybridge House, Vauxhall, supported by a diaphragm wall containing three rows of anchors. The site is gravel (to a depth of about 9 m) overlying clay. They found that the crest settlement of the wall was 12.2 mm, compared with a horizontal movement of 22 mm, a similar ratio to that recorded at Neasden. The horizontal deformations of the wall were of the same form as those at Neasden.

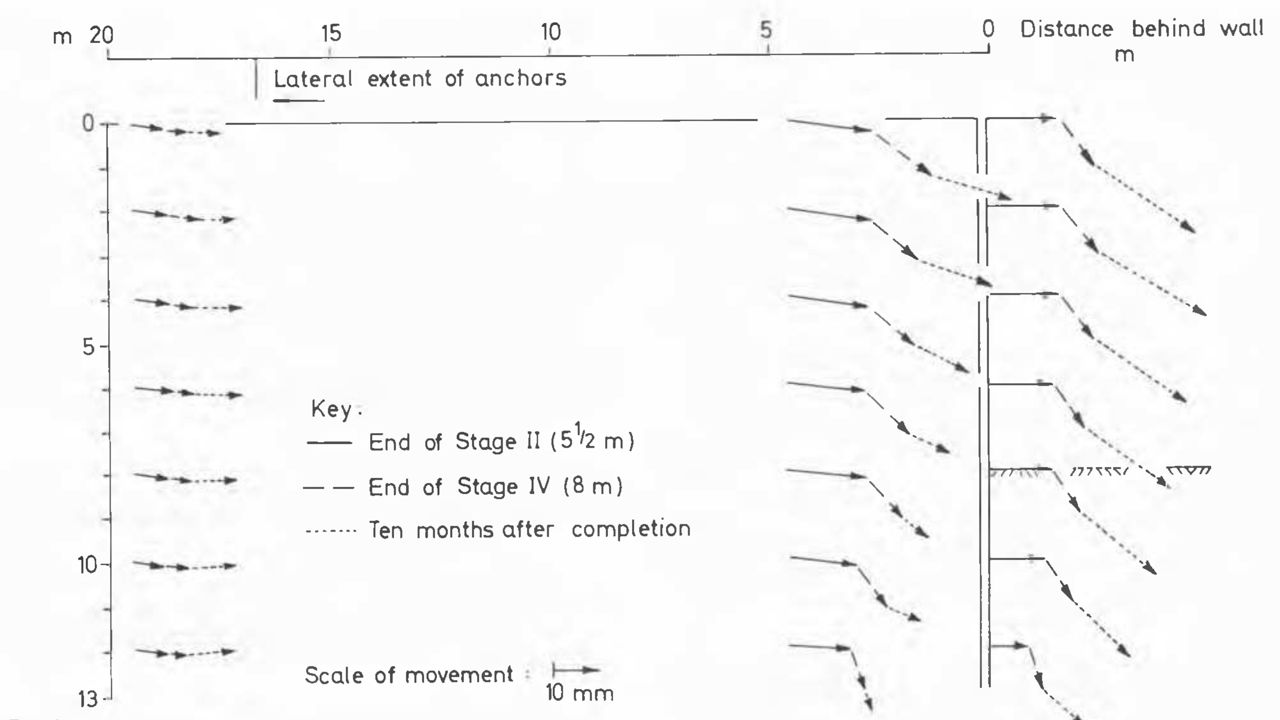

Fig. 8 Vectors of movement

Similar measurements have been made of displacements at two other excavations in London clay, where the diaphragm wall has been supported by struts which act horizontally. In neither of these cases - one the Y.M.C.A. building in London and the other the underground car park at Westminster - has any downward movement of the wall been observed. It would therefore seem that the observed wall settlements are almost certainly due to the downward pull of the anchors.

It was noted in the previous section that, following completion, appreciable horizontal extensions developed in the 4 m behind the wall (between I1 and I2) at all depths. The settlement of I1 was also greater than that of I2. However, if the equivalent extensions along the anchors are calculated (for example from the trajectories in Fig.8) it can be seen that these are of the order of only 2 to 3 mm. The anchor loads in the top three rows have changed very little. The satisfactory performance of these ground anchors is therefore consistent with fairly high horizontal movements.

CONCLUSIONS

1. The soil properties on the site are typical of London clay and the observed behaviour is therefore thought to be representive of this type of tie back wall in London clay.

2. During excavation, surface displacements were initially mainly horizontal and extended back from the wall four to five times the depth of the excavation.

3. Settlements close to and including the wall developed during the later stages of excavation, and can be attributed to the downward pull of the ground anchors. The ratio of vertical to horizontal movements after completion of the excavation was typically of the order of 1:2 at the surface and 1:1 at a depth corresponding to the bottom of the wall.

4. Movement of the wall and surrounding ground continued at an appreciable rate for about one year following completion of excavation. At the surface about one-half the total horizontal movement (50 mm) and one-third the total vertical movement (30 mm) had occurred by the end of construction and the corresponding figures for the bottom of the wall are two thirds of 20 mm and one half of 25 mm. There are indications that, in the long term, the settlements are beginning to decrease.

5. The ground anchor loads showed some variation during excavation but subsequently remained nearly constant. The trend was for a slight increase in load in the upper row and a decrease in the lowest row.

6. The study has provided a useful insight into the mechanism of behaviour of ground anchors. It appears that a block movement of ground has occurred, with translational and tilt components. Within the block, the horizontal movements have become quite high, notwithstanding the satisfactory performance of the anchors.

7. The pore pressures dropped during and after excavation, at least as far back as five times the depth of the cutting. They have recovered only slowly, and 44 months after completion of the excavation, had still not reached their steady state values.

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