Displacements and Strains in Tunnels beneath a Large Excavation in London

Déplacements et déformations dans des tunnels sous une grande excavation à Londres

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Summary

In the course of an excavation, about 680 ft. long by 360 ft. wide and 40 ft. deep, detailed observations were made of the vertical displacements, as well as the diametrical and axial strains in two tunnels, which crossed immediately beneath the site in the London Clay. The development and nature of the movements as the excavation was made are demonstrated by some typical results. The net uplift of the invert of the lower tunnel is used to estimate approximately the average Young's modulus for the lower 65 ft. of the London Clay. The estimated value of 1600 tons/ft.^{2} is larger than many laboratory determinations, but it agrees well with an earlier field estimate of 1200 tons/ft.^{2} obtained from a zone between 35 and 96 feet above the base of the London Clay.

Sommaire

Au cours d'une excavation mesurant environ 207 m de long, 110 m de large et avec une profondeur de 12 m on a fait des observations détaillées sur les déplacements verticaux ainsi que sur les déformations diamétrales et axiales de deux tunnels qui se croisent immédiatement en dessous du chantier dans la London Clay. Le développement et la nature des mouvements qui se sont produits durant l'excavation sont illustrés au moyen de quelques résultats typiques. Au moyen du soulèvement net du radier du tunnel inférieur on détermine approximativement la valeur moyenne du module de Young pour les derniers 20 m de London Clay. La valeur estimée de 1600 kg/cm^2 est plus élevée que plusieurs valeurs déterminées en laboratoire mais s'accorde bien avec une valeur de 1200 kg/cm^2 préalablement estimée sur chantier pour une zone à une profondeur de 11 à 29 m au-dessus de la base de la London Clay.

Introduction

During the construction of the large Shell building at South Bank on the River Thames in London, the Building Research Station has co-operated with the Chief Civil Engineer's Department of the London Transport Executive to make a series of observations of strains and displacements in the two underground railway tunnels of the Bakerloo Line, which traverse the site between the building foundations.

The observations were undertaken, firstly, to assist London Transport in ensuring the safety of the travelling public by detecting any adverse trends of movement at an early stage, secondly to obtain basic information on the distortions of the traditional cast-iron tunnel linings when most of the overburden is removed, and thirdly, to obtain data about the ground movements associated with a very large excavation and the construction of heavy building foundations in London Clay.

Williams (1957) and Skempton and Henkel (1957) have given an account of the ground conditions at the site and of the results of tests on samples from borings made prior to construction. Williams also described the layout of the building, the design of its foundations, and, on the basis of simple elastic theory, he estimated that the railway tunnels would be displaced upwards between 0·8 and 1·5 in. in the central part of the site as a result of the excavation for the large basements.

The observations have covered all stages of excavation and are being continued during and subsequent to erection of the building. This paper will be restricted to a discussion of some of the vertical displacements, the horizontal and vertical diametrical strains, and axial strains in the tunnels arising from the complete bulk excavation.

Site layout, the tunnels and the excavation

An outline plan of the site is given in Fig. 1 and a section along the line of the tunnels is given in Fig. 2. The final excavation for the basement occupies the whole of the site, it is about 680 ft. long by 360 ft. wide and about 40 ft. deep. The material excavated consisted of about 11 ft. of made ground (about 200 years old), about 11 ft. of soft silty clay, about 10 ft. of sandy gravel, and about 8 ft. of London Clay. The excavation reduces the overburden pressure by about 1·9 ton/ft^2.

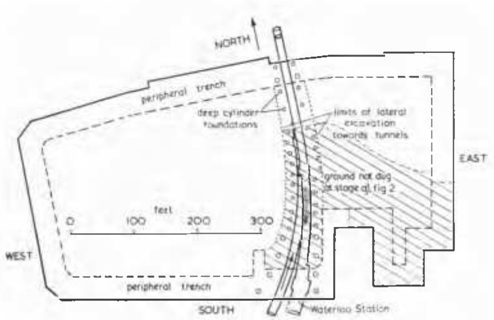

Fig. 1 Plan of site ; the whole area was excavated to a depth of about 40 feet.

Plan du chantier. Le site a été excavé à une profondeur de 12 m environ.

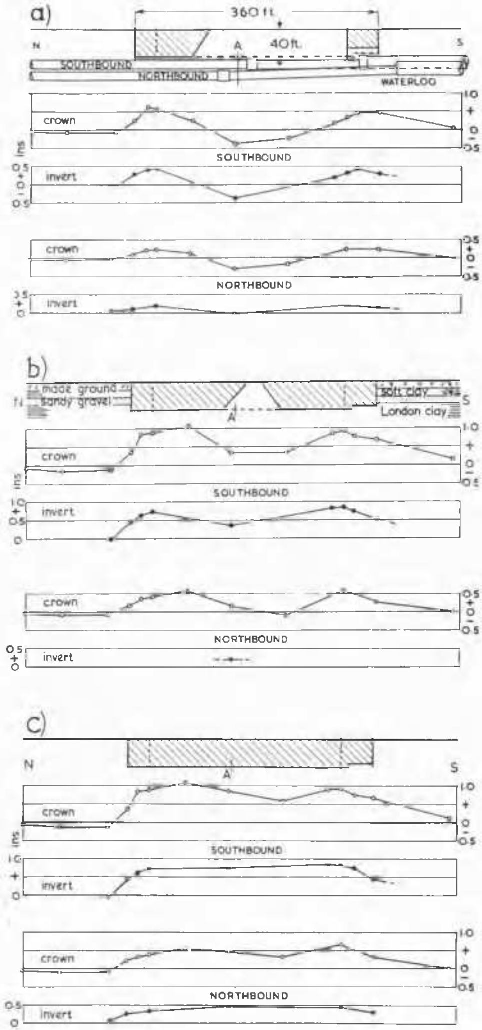

Fig. 2 Sections across the site along the line of the tunnels, showing the state of excavation and the vertical displacements of the crown and invert of both tunnels at three stages a), b) and c).

Sections du chantier le long de la ligne des tunnels, montrant l'état de l'excavation et les déplacements verticaux du sommet et du radier des deux tunnels aux temps a), b) et c).

The tunnels traverse the site in a north-south direction (in the railway sense, but not geographically). Immediately to the north lies the River Thames, and HAIGH (1902) has given an account of the tunnel construction in compressed air beneath the river. Both tunnels were shield driven under the site in a southerly direction, the northbound between January and April 1901, and the southbound between June and August 1902. The shield used for tunnelling under the river was dismantled in the enlargements beneath the centre of the site, see Fig. 2. Under the northern part of the site, the southbound tunnel lies vertically above the northbound tunnel, but towards the southern boundary of the site the northbound rises and moves to one side of the southbound tunnel. The larger tunnels of Waterloo Station adjoin the southern boundaries of the site.

The crown of the southbound tunnel generally lies about 4 ft. below the excavation level, but there is only about 2 ft. of cover at the central and southern enlargements. All the tunnels lie within the London Clay. The running tunnels are 12 ft. internal diameter to the north of the central enlargements and 12 ft. 6 in. diameter to the south.

The tunnel linings are nominally circular and are built from the traditional cast-iron segments, which have been used throughout the London Underground system. The circumferential joints between the rings were packed with soft timber and the longitudinal joints consisted simply of iron bearing on iron. The space, 1 to 2 inches wide, between the lining and the London Clay was filled with lime grout. Measurements on 12 rings, selected at random along both tunnels, showed that the horizontal diameters were larger than the vertical diameters by amounts varying from 7/8 to 3 $\frac{1}{4}$ inches before the present operations commenced; these differences would be due mainly to sagging of the rings during erection.

The excavation for the basements was carried out broadly as follows :

(1) Commencing on the western side, a peripheral trench was excavated in both directions around the whole site between two rows of steel sheet piles, which were driven into the London Clay and strutted apart, see Fig. 1. A retaining wall was built against the outer row of piling and the inner row was removed as bulk excavation of the central dumpling proceeded. The trench crossed the northern end of the tunnels early in 1958 and the southern end in the 1958 summer.

(2) The bulk excavation, which was carried out by dragline excavators, commenced at the western boundary and progressed on a broad front towards the western flank of the tunnels. During this period deep cylinder foundations were excavated, mainly by normal lined-shaft sinking methods, on either side of the tunnels, see Fig. 1, and WILLIAMS (1957).

(3) A long ridge of ground was maintained for the full depth over the line of the tunnels until most of the bulk excavation on either flank had been completed. The crest of this ridge extended for a width of about 25 ft. on either side of the centre lines of the tunnels and it had sides sloping at about 1:1. However, after the bulk excavation had reached the western flank of the tunnels, excavation was commenced from the remaining northern edge on a face moving southwards over the tunnels and extending to the eastern boundary. This face proceeded nearly to the centre of the site, and remained in that position over the tunnels for several months. About this time, the re-entrant portion of the peripheral trench close alongside the southern part of the southbound tunnel was excavated. The extent of the ground remaining at this stage is shown in Fig. 1 and in Fig. 2 *a*. The remaining ridge of ground over the tunnels was excavated on a face moving northwards from the southern edge; the last portion of ground being removed from ever the centre of the tunnels from the end of a narrow ridge of ground running diagonally across to the S.E. corner of the site.

The ridge of ground over the tunnels was taken down in bulk to approximately the London Clay surface, in lengths of about 30 ft. at a time. The remaining clay was removed by pneumatic spades and quickly replaced over the tunnels by a slab of reinforced concrete 5 ft. thick, which was anchored to the tops of the cylinder foundations.

The measurements

In each of the tunnels a series of measurements were made of

(*i*) the strains across horizontal and vertical diameters by means of screw micrometer rods to an accuracy of about $\pm 1{\cdot}5 \times 10^{-5}$ strain;

(*ii*) the longitudinal strains over a succession of lengths equal to the tunnel diameter, by the same method as in (*i*), at two levels in the side of the tunnels to an accuracy of about $\pm 1{\cdot}5 \times 10^{-5}$ strain;

(*iii*) the local circumferential strains in the skin and flanges of the cast-iron segments at about 220 points by means of vibrating-wire strain gauges to an accuracy of about $\pm 2 \times 10^{-6}$ strain;

(*iv*) the changes in the level of the crowns of the tunnels by precision levelling to an accuracy of about $\pm$ 0·02 in. relative to datum points in the tunnels about 200 ft. north and about 300 ft. south of the excavated area.

The measurements (*i*), (*ii*) and (*iii*) were concentrated in the vicinity of the peripheral trench at each end of the disturbed area, and beneath the centre of the excavation. As far as possible the various measurements were made on the same rings and on rings in each tunnel in the same vertical plane.

The (*iii*) measurements could be made at any time, since the gauges were connected by telephone-type selector circuits to a point in Waterloo Station, but the other measurements had to be made during the early hours of the morning when the trains do not operate.

Results of observations

The distribution across the site of the net vertical displacements of the crown and invert of both tunnels at three typical stages of excavation (a), (b) and (c) are shown in Fig. 2. The local displacements caused by driving the steel sheet piling for the peripheral trench close to the tunnels have been eliminated from those results; they were largest at the northern end of the southbound tunnel.

For a distance of at least 150 ft. beyond the northern limits of excavation, where the tunnel construction is quite normal, there was a small settlement of the tunnels at all stages of excavation; this is to be expected from elastic theory. At the northern and southern boundaries of the site, on the lines of the outer piles, the tunnels rose as the excavation progressed and this movement is likely to have been associated with an inward movement of the sheet piling.

Similar movements occurred in the tunnels under the central part of the site. For example, when the excavation was some distance away, stage (a), Fig. 2, the southbound tunnel and the crown of the northbound settled substantially, but as the ground left over the central area was reduced in area, stage (b), the tunnels rose. No settlement of the northbound tunnel was recorded, but it may have occurred.

When the excavation was complete, stage (c), the underlying parts of the tunnels rose above their original level; the southbound by about ¾ inch and the northbound by about ½ inch. Even so, a permanent depression persisted in the crown of both tunnels where the narrow ridge of ground had remained longest over the tunnels. This points to some yield of the ground on account of high shear stresses brought about by the concentrated ridge of ground; otherwise the movements seem to be of an elastic nature.

The persistent small uplift of the crown of the southbound tunnel about 110 ft. beyond the southern limit of excavation is probably associated with the very rigid construction of the twin station tunnels, where concrete and brickwork introduced between the two tunnels form a stiff beam. The normal running tunnels at the northern edge of the site are quite flexible in axial bending and would follow the ground movements.

The time variation of the strains and displacements in both tunnels at the vertical section A (see Fig. 2) near the centre of the site is given in Fig. 3. The axial strains are shown in the upper part of the diagram; these strains are averages measured over two lengths of 12 ft. immediately north and south of section A at levels about one third of a tunnel diameter above the inverts. The net axial strains are compressive, but are much smaller than the diametrical strains on account of the relatively incompressible nature of the tunnel linings in an axial direction. The net axial strains were also shown to be compressive beneath the peripheral trenches and it is likely that the tunnels beneath the excavation are everywhere in axial compression. Axial extension zones were found in the tunnels beyond the limits of excavation.

The diametrical strains and the vertical displacements of the crowns of the tunnels are given in the lower section of the diagram in Fig. 3. It will be seen that the settlement of the crowns of the tunnels beneath the central ridge of ground, between May and September 1958, is accompanied by a compression of the vertical diameters and an extension of

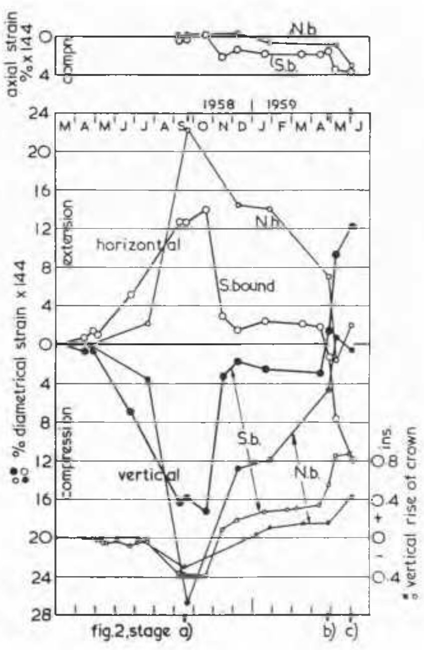

Fig. 3 Movement at the vertical section A in Fig. 2.
Upper diagram. The variation of axial strain in the north and southbound tunnels as excavation proceeded.
Lower diagram. The variations of horizontal and vertical diametrical strains and of vertical displacements of the crown of the north and southbound tunnels as excavations proceeded.

Mouvement suivant la section verticale A de la Fig. 2.
Graphique supérieur. Variation de la contrainte axiale dans les tunnels direction Nord et Sud au cours des travaux d'excavation.
Graphique inférieur. Variations des contraintes et des déformations des diamètres horizontaux et verticaux et des déplacements verticaux du sommet des tunnels en directions Nord et Sud au cours des travaux d'excavation.

the horizontal diameters of the same order of magnitude. Contrariwise, the rise of the crowns between November 1958 and June 1959 is associated with an extension of the vertical diameters, a compression of the horizontal diameters of the same order of magnitude and a much smaller axial compression.

It will be noticed that the net diametrical strains of the northbound tunnel at section A on completion of excavation were practically zero, whereas the southbound tunnel remained elongated in the vertical direction. This result is to be associated with the comparatively shallow cover of ground left over the southbound tunnel.

An estimate of the average value of the Young's modulus of London Clay

On account of the reduction in the depth to diameter ratios of the tunnels to small values and to permanent distortions in their cross-sectional shape, only the vertical displacements of the invert of the northbound tunnel can be used to make a simple calculation of the Young's modulus of London Clay.

In an earlier estimate of Young's modulus from a London excavation SEROTA and JENNINGS (1955) suggested that the elastic deformation of the lower 35 ft. of London Clay and the underlying formations below their datum point was negligible. Checks were made on this datum with an ordinary level and staff to another datum point, but it is unlikely that movements less than about 0·12 in. could have been detected by this method*. The maximum uplift of the northbound tunnel invert is only 0·48 in. and it seems unwise to neglect movements of the order of 0·12 in. It is therefore necessary in the present estimate to make some allowance, at least, for the heave of the Woolwich and Reading Clays, which lie beneath the London Clay, particularly under an excavation covering such a large area as the present one.

Laboratory measurements on a number of carefully-extracted hand specimens of Woolwich and Reading Clays at a depth of 70 ft. below the surface at a site 1 ¼ miles north of the present one gave an average Young's modulus of 3 200 ton/ft^2 for the mottled Reading Clay and 4 400 ton/ft^2 for the Woolwich Clay. An average value of 3 500 ton/ft^2. will be assumed for these beds, which are about 50 ft. thick at the site.

In order to calculate the average Young's modulus of the London Clay the following further assumptions are made :

(1) Poisson's ratio is 0·5 ; this value has not been confirmed and it has been shown that the clay is orthotropic (WARD, SAMUELS and BUTLER (1959)) ;

(2) the movement of the sands and chalk beneath the Woolwich and Readings Beds is negligible ;

(3) the approximate STEINBRENNER (1934) solution for the vertical displacements of a semi-infinite weightless elastic body subjected to a uniform surface loading may be applied ;

(4) the vertical pressure released by the excavation is 1·9 tons/ft.^{2} ;

(5) the thickness of London Clay beneath the excavation is 100 ft.

With these assumptions we first calculated by differences the uplift of the invert of the northbound tunnel due to the 50 ft. of Woolwich and Reading Clays beneath the London Clay for each of the observation points plotted at the bottom of Fig. 2c. These calculated values are deducted from the observed vertical displacements and the differences are used to calculate the Young's modulus of the layer of London Clay below the northbound tunnel. The results of this calculation are given in Table 1, where it will be seen that the average Young's modulus for the whole of the London Clay beneath the northbound tunnel, i.e. the lower 65 ft., is about 1 600 tons/ft.^{2}. This is somewhat larger than the upper limit of 1 200 tons/ft.^{2}, which SKEMPTON (1959) has recently suggested, and it is greater than many laboratory determinations, which are liable to underestimate the modulus on account of sampling disturbance. It is, however, in good agreement with the average value of 1 200 tons/ft.^{2} obtained by SEROTA and JENNINGS (1959), which applies to the zone between 35 and 96 ft. above the base of the London Clay, since it is known that the modulus increases with depth.

Table 1

Calculation of the Young's Modulus of London Clay

	Observed uplift of northbound tunnel invert (ins.)	*Calculated uplift due to 50 feet of Woolwich and Reading Beds* (ins.)	*Uplift associated with London Clay beneath northbound tunnel* (ins.)	*Young's Modulus* (ton/ft.^{2})
North	0·07	− 0·08	0·15	*
	0·26	0·06	0·20	1300
	0·32	0·07	0·25	2300
Point A	0·48	0·13	0·35	1600
	0·44	0·11	0·33	1900
South	0·30	0·04	0·25	1100
			Average	1600

* Solution suggest settlement.

Conclusions

The measured heave of the crown of the southbound tunnel lies within the limits which WILLIAM (1957) estimated for the tunnels. However, the heave of the northbound tunnel and of the invert of the southbound tunnel was smaller, and the tunnels were subjected to several types of movement, including temporary and permanent settlement, which he did not consider.

Detailed examination showed that the movements could be clearly linked with the progress and position of the excavation. Different results would have been obtained if the excavation had been carried out in another way, for example, if a broad trench had been excavated in a series of layers over the tunnels before the adjoining areas had been excavated it is unlikely that the temporary and permanent settlement of the tunnels in the central part of the site would have occurred.

The final upheaval of the ground beneath the excavated area was accompanied by compressive strains in the horizontal plane, and the settlement of the ground beyond the limits of excavation was associated with an extension in the horizontal plane. These horizontal strains may present difficulties in some forms of construction.

The heave of the Woolwich and Reading Clays at a depth of 100 ft. is not likely to be insignificant in an excavation of such a large area and it is estimated from laboratory measurements that it was responsible for about 25 per cent of the heave of the northbound tunnel invert.

The average value of the Young's modulus for the London Clay beneath the northbound tunnel, i.e. the lower 65 ft. of the clay, is estimated to be approximately 1 600 tons/ft.^{2}. This is no more than an estimated value, since the elastic theory involves several assumptions, which are likely to be

* Personal communication from Mr. S. Serota.

unrealistic, particularly in the vicinity of the excavation boundaries.

The distortions of the tunnels were small and the excavation and foundation construction was carried out without interrupting the normal operations of the trains.

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References

[1] HAIGH (A. H.) (1902). Subaqueous tunnelling through the Thames gravel : Baker Street and Waterloo Railway. *Min. Proc. Inst. C.E. 40*, p. 25-42.

[2] SEROTA S. and R. A. J. JENNINGS (1959). The elastic heave of the bottom of excavations. *Geotechnique, 9*, pp. 62-70.

[3] SKEMPTON A. W. and D. J. HENKEL (1957). Tests on London Clay from deep borings at Paddington, Victoria and the South Bank. *Proc. 4th Int. Conf. Soil Mech., 1*, pp. 100-106.

[4] SKEMPTON A. W. (1959). Letter to *Géotechnique, 9*, pp. 145-146.

[5] STEINBRENNER, W. (1934). Tafeln zur Setzungsberechnung, *Die Strasse, 1*, pp. 121-124.

[6] WARD, W. H., S. G. SAMUELS and M. E. BUTLER (1959). Further studies of the properties of London Clay. *Géotechnique, 9*, pp. 33-58.

[7] WILLIAMS G. M. J. (1957). Design of foundations of the Shell Building, London. *Proc. 4th Int. Conf. Soil Mech., 1*, pp. 457-461.