The Development of Earth Loading and Deformation in Tunnel Linings in London Clay

Développement des efforts et des déformations dans les revétements de tunnels sur l'argile de Londres

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SUMMARY

The long-term structural behaviour of three types of segmental tunnel linings in the London Clay is presented. The deformations of each lining are similar; they develop rapidly in the first few months after construction, but continue at a slow rate for at least six years. The vertical diameters decrease and the horizontal ones increase; the circumferential thrust is fairly uniform and approaches a value equivalent to the full overburden pressure acting hydrostatically. A tentative hypothesis explaining the deformation and loading of the lining is given in terms of the existing stress conditions in the clay, its orthotropic properties, and the changes brought about by the excavation.

SOMMAIRE

On examine le comportement structural à long terme de trois types de revêtements segmentés pour les tunnels dans l'argile de Londres. Les déformations de chaque type se présentent de la même façon, elles se développent rapidement au cours des premiers mois suivants la construction mais elles continuent à une allure plus lente pour six ans au moins. Les diamètres verticaux diminuent alors que les diamètres horizontaux augmentent; les efforts circonférentiels sont plutôt uniformes et atteignent une valeur équivalente à la pression hydrostatique des terres superposées. On avance une hypothèse provisoire expliquant la déformation et les efforts dans les revêtements en termes des conditions de contrainte existant dans l'argile, ses caractéristiques orthotropiques et les changements provoqués par les excavations.

PREVIOUS OBSERVATIONS (Ward and Chaplin, 1957) on isolated circular tunnels in London Clay lined with cast-iron segments have shown that the circumferential thrust in the linings 50 or more years after construction corresponds approximately to the full overburden acting hydrostatically. Apart from some short-term observations by Skempton (1943) and by Tattersall, Wakeling, and Ward (1955) no detailed information has been available on the gradual development of the earth loading, of the moments in the segments and the corresponding changes in shape of the linings during the years following construction. In the present paper information about these factors on two tunnels lined with cast-iron segments, and another lined with precast concrete segments is given for periods up to 6 years after construction.

SITES, THE LINING CONSTRUCTION, AND INSTRUMENTATION

Site O

Geotechnical data about this site is given by Ward, Samuels, and Butler (1959). The tunnel lies about 55 ft below the ground surface. The London Clay here is only about 65 ft thick and is overlain by 11 ft of sandy gravel and some 10 ft of filling. The clay at the level of the tunnel has an average shear strength of 3.2 tons/sq.ft. according to compression tests on vertical samples and 4.3 tons/sq.ft. on horizontal samples.

The tunnel, with a 7-ft internal diameter, forms part of the Post Office railway system and was constructed in 1957 with cast-iron segments bolted together and grouted into position in the conventional way. Particulars of the segments are given in Table I and Fig. 1. Each of the six segments in one ring was fitted with vibrating-wire strain gauges of our own design (Ward, 1955a), one on each flange and one in the centre of the iron. The positions of the axes of the wires are shown in Fig. 1; the neutral axis of the section in plane bending lies close to the wire of the central gauge.

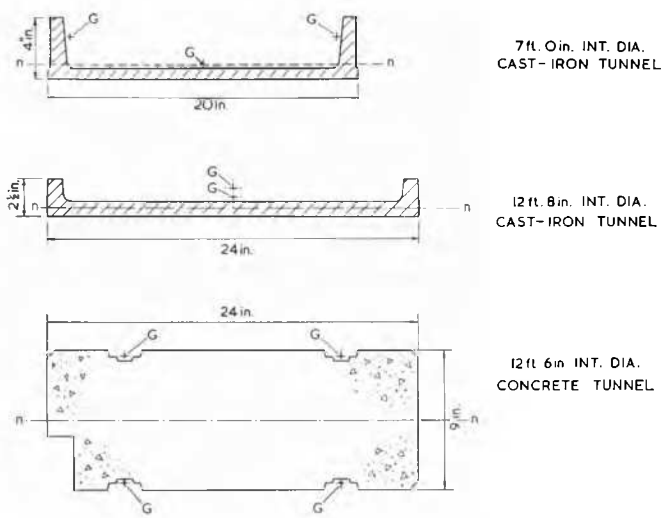

FIG. 1. Radial sections through the lining segments showing positions of gauge wire axes (G) and the neutral surfaces (n n).

Site V

Two tunnels forming experimental portions of the Victoria Line were built in northeast London in 1960. The tunnel linings were novel in design. Two lining rings were instrumented, one, of concrete segments, lay at a depth of about 85 ft and the other of cast iron was at a depth of about 79 ft.

24 m depth

TABLE I. PARTICULARS OF TUNNEL LININGS

Site	Depth (ft)	Internal diameter (ft in.)	Material	Segments in ring	Sectional area of segment (sq. in.)	Second moment of area (in.^{4})	Young's modulus ($\times 10^6$ lb/sq. in.)	Longitudinal joints	Fitting to clay
O	55	7–0	cast iron	6	21	22	14	butt & bolted	grouted
V	79	12–8	cast iron	6	27	6.3	14	knuckle	jacked
	85	12–6	concrete	14	209	1460	5.5	curved butt	wedged

The London Clay in this area extends from the surface to a depth of about 120 ft. The index properties of the clay at a depth of about 80 ft are: water content 28.0; liquid limit 80 to 85; plastic limit 30 per cent of dry weight. The average shear strength is about 3.5 tons/sq.ft. in undrained triaxial compression tests on vertical samples and about 3.8 tons/sq.ft. on horizontal samples, but because there were many fissures in the horizontal samples this latter value must be regarded as low. The strength and Young's modulus of this clay are very similar to those at Site O, and the consolidation and swelling characteristics are also likely to be similar.

One lining, 12 ft 6 in. in internal diameter, consisted of 14 precast unreinforced concrete segments, 9 in. thick. Further particulars of the segments are given in Table I. Each ring was expanded directly against the clay by means of a wedge pushed in by one of the shield jacks at the crown. A circumferential thrust of 18 tons was created by wedging the instrumented ring.

Four vibrating-wire strain gauges of a new type were fitted to each of the 14 segments in one ring in the positions shown in the radial section of the segment in Fig. 1, to measure the circumferential strains. The centre of each gauge lay equidistant from the ends of the segment. Stainless steel components forming the anchorages for the vibrating-wire, its exciting magnet, and a cover plate were cast into the curved surfaces of each segment during its manufacture. The vibrating-wires themselves were inserted and tuned after manufacture.

Another lining examined at Site V consisted of 6 cast-iron segments with knuckle joints, circumferential flanges about half as deep as in the traditional design, and without any of the usual bolts. Further particulars of the segments are given in Table I and a radial section is shown in Fig. 1. The ring of segments is thrust directly against the clay by jacks inserted at the segment joints situated approximately 60° on either side of the invert. When a circumferential thrust of about 12 tons is attained by the jacks, metal wedges are inserted into the joints adjacent to the jacks, which are then removed.

One cast-iron ring was fitted with 12 vibrating-wire strain gauges spaced equally around its circumference. The gauges were fixed on the centre line of the ring at the quarter points of the segments so as to measure the strains in the circumferential direction. The gauges are of a new type and consist of two 0.01-in. diameter high-tensile steel wires stretched one above the other between two posts screwed into the iron. Exciting magnets are mounted between the two wires.

DIAMETER MEASUREMENT

At both sites the changes in vertical and horizontal diameters of each ring were measured with screw-micrometer rods. The measuring rods consisted of aluminium alloy tubes, 2 in. diameter, with one half of a conventional screw-micrometer mounted at one end and its anvil at the other end. A correction was made for the thermal movement of the aluminium alloy. The rod, and a reference bar for checking against accidental damage to the rod, were stored in a box in each tunnel adjacent to the ring under observation. Measurements could be reproduced to ±0.001 in.

LONG-TERM CHANGES IN THE DIAMETER OF THE LININGS

Fig. 2 shows the changes in the horizontal and vertical diameters with time for the three linings, the positive sign representing increases in diameter. As in other published records of tunnels in clay (Ward, 1955b) the horizontal diameter increases and the vertical decreases. Initially the tunnels are not necessarily circular, tape measurements showed that the 12 ft 8 in. iron lining was approximately

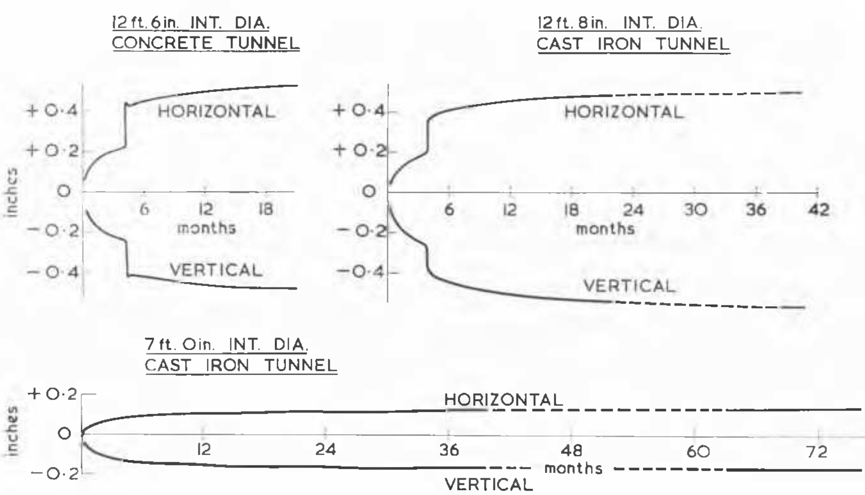

FIG. 2. The changes in horizontal and vertical diameters of the three tunnel linings; the upper two diagrams for Site V and the lower one for Site O.

circular, the 12 ft 6 in. concrete one was about ¾ in. squat, and the 7-ft tunnel about ½ in. squat.

Experiences in a lining with 10 segments to the ring have shown (Tattersall, *et al.*, 1955) that in the approximately horizontally bedded London Clay the greatest changes in diameter take place approximately along the vertical and horizontal diameters and that at 45° to these directions the changes are very small. At Site V, except for the very early stage and the period when the second tunnel was driven alongside, the horizontal and vertical diameter changes are almost continuously equal in magnitude and opposite in sign in the concrete lining with 14 segments and thus the new shape is very close to an ellipse of small eccentricity. In both iron rings, which have only 6 segments, the increase in horizontal diameter is less than the decrease in the vertical diameter. The shape at axis level is modified by the stiffness of the long segments there, so that the horizontal diameter is short.

The rate of change of the diameters in all cases is rapid at first but decreases to a small value except at Site V where the passing of adjacent tunnels caused sudden changes some 4 months after construction. The rates during the second week and between 18 and 21 months after construction are compared in Table II. As was found in the Ashford Common tunnel (Tattersall, *et al.*, 1955), the rates of change of all vertical diameters are greater, at first, than the corresponding horizontal diameters; later the rates for both diameters become practically equal. The rates for the smaller lining decrease more quickly than those for the larger ones but are still measurable after six years.

TABLE II. RATE OF CHANGE OF DIAMETERS AT DIFFERENT TIMES AFTER CONSTRUCTION

			Rate of change of diameters ($\times 10^{-3}$ in./week)	
Site	Lining	Diameter	during second week	between 18 and 21 months
O	7 ft 0 in. iron	*H*	+15	+0.2
		V	−21	−0.2
	12 ft 8 in. iron	*H*	+19	+0.6
V		*V*	−41	−0.6
	12 ft 6 in. concerete	*H*	+21	+0.6
		V	−25	−0.6

DEVELOPMENT OF THRUST IN THE LININGS

The development of average circumferential stress (or strain) with time in each of the linings is plotted in Fig. 3. The stresses generated by the initial jacking, wedging, or grouting are included, and although there is a rapid initial rise at Site O, this occurred after the low-pressure grout was injected. In each lining the average direct circumferential stress in each segment was calculated from the strain-gauge observations using the theory of plane bending and the properties of the segments in Table I.

Site O

In these segments it has been shown in a laboratory test that the theory of plane bending is in considerable error when the radius of curvature of the segment is increased, but is valid when the radius decreases. Hence the circumferential stress plotted in Fig. 3 relates only to the average values in the segments at axis level where the radius of curvature is decreased. After a rapid initial rise in stress, there is a slow increase which continues for at least six years. The stress

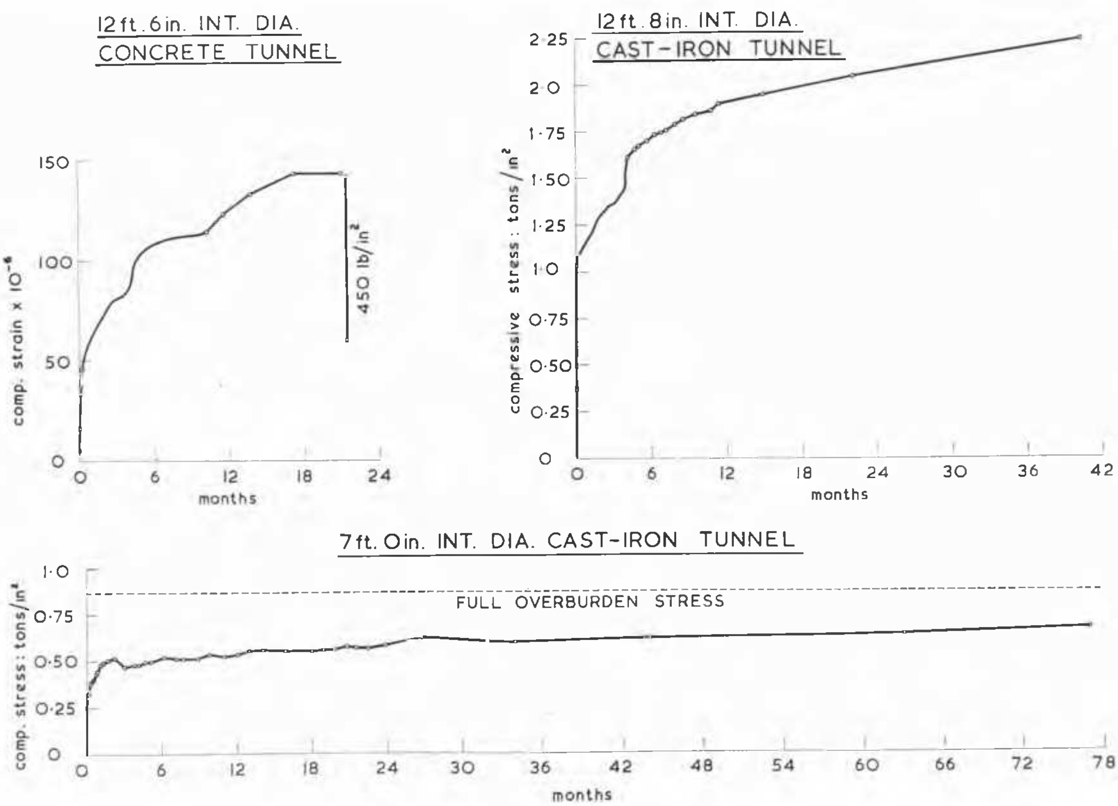

FIG. 3. The development of the average direct stress (or strain) in the three rings with time after construction; the upper two diagrams for Site V and the lower one for Site O.

has reached only about 0.75 of the value to be expected from the overburden acting hydrostatically.

Site V

The curve for the concrete ring in Fig. 3 is plotted in terms of the average strain in all the 14 segments, it includes creep and shrinkage strains. After the effect of jacking, the strain continued to increase rapidly. Three months later the rise was less rapid, but as the adjacent tunnel was constructed alongside the strain suddenly increased. Nine months after construction the strain was increasing slowly. For the following seven months, as a result of ventilation in the tunnel, drying shrinkage occurred on the inner surfaces of the lining and the curve is again steeper. When 21 months had elapsed the segments were removed from the tunnel and the relief of stress, represented by the final, vertical, part of the strain curve, was calculated from Hooke's law. For this purpose the segments were taken to the laboratory and subjected to compression and bending tests, which gave an average value of Young's modulus of 5.5×10^6 lb/sq.in. Hence the average compressive stress in the lining after a lapse of some 21 months proved to be 450 lb/sq.in. and varied little around the ring. This value is equivalent to about 0.65 of the stress to be expected from the full overburden acting hydrostatically.

The development of the average direct stress around the iron ring at Site V with time is given in Fig. 3. The curve follows a similar pattern to the strain curve for the concrete ring, except, of course, that the stage of noticeable drying shrinkage is absent. The average stress 3½ years after construction has risen to 2.2 tons/sq.in. which is close to the full overburden value.

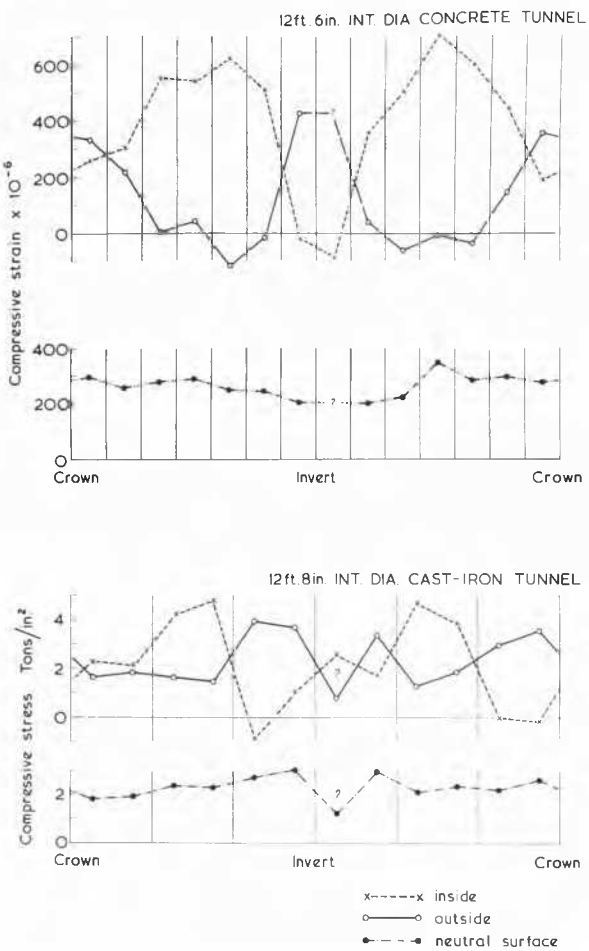

FIG. 4. The distribution of stresses and strains at the inner and outer extremities and at the neutral surface of the segments at Site V.

DEVELOPMENT OF BENDING MOMENTS IN THE LININGS

As a consequence of the shortening of the vertical diameters and the extension of the horizontal diameters all the segments develop bending moments and the stresses at their inner and outer extremities vary from the direct stresses given under the previous heading. The distribution around the ring of the circumferential stresses (or strains) at the inner and outer extremities of the concrete and iron linings at Site V is given in Fig. 4, by the points joined by dashed and full lines respectively. The distance between the two sets of points is proportional to the bending moment in the segments; the moments may be much smaller at the segment joints, represented by the vertical lines in Fig. 4.

The upper diagram gives only the *strain* distribution (including creep and shrinkage effects) in the concrete segments one year after construction. The curvatures of segments on the sides of the tunnel have increased and those in the invert and crown decreased. The most severe bending occurred at axis level on the side adjacent to the second tunnel and the moment released here on dismantling the ring was 65 ton-in.

The next diagram in Fig. 4 shows the corresponding direct strains around the concrete ring. At the time when the ring was dismantled a similar diagram in terms of stress was obtained using the individual elastic moduli measured in each segment, and the distribution was found to be more uniform than Fig. 4 suggests.

The lower two diagrams in Fig. 4 show respectively the distribution of the stresses at the extremities and the neutral surface around the iron ring 3½ years after construction. The two segments at the sides of the tunnel show the expected increase in curvature, and in two other segments the curvature is decreased, but the pattern is somewhat confused by the observations in the remaining two segments.

SOIL MECHANICS OF TUNNEL-LINING ACTION

The present results, and others, show that the diameters of continuously lined circular tunnels in the horizontally bedded London Clay become shorter in the vertical direction and lengthen horizontally, and that a uniform circumferential thrust, equivalent to the full overburden pressure acting hydrostatically, is slowly mobilized, irrespective of the method of construction. The problem is to understand this behaviour in terms of our present knowledge of the London Clay and, in particular, it would be of great value to be able to estimate the bending moments in the segments. The problem is much too complex for analytical treatment and we will only attempt to describe the processes that are likely to occur in the clay surrounding the tunnel.

Our present knowledge of the undisturbed London Clay (Bishop, Webb, and Lewin, 1964; Ward, *et al.*, 1959) suggests that: (*a*) the clay is saturated and has a positive pore-pressure; (*b*) the vertical effective stress lies between the full and the submerged overburden values, and K_0 has a value of about 2 or 3 at the depths which interest us; (*c*) the clay is orthotropic, with a vertical axis of symmetry, in particular with respect to its elastic and consolidation properties.

When a circular tunnel is excavated and *before* a lining is built, the total radial stress at the tunnel surface is reduced to atmospheric pressure. The clay expands elastically towards the hole in the vertical direction and probably moves away from the hole horizontally, and the pore water develops a large suction at the tunnel surface. The total stresses in the ground surrounding the tunnel change substantially for a distance of 1 or 2 diameters away. They may be estimated from the theory of elasticity, taking into account that $K_0 > 1$ and the clay is orthotropic (Savin, 1961). The theory shows that there is a large increase in the total circumferential and longitudinal compressive stresses above and below the unlined tunnel, whilst the corresponding compressive stresses at the sides become low and may become negative.

The large horizontal deviatoric stresses above and below the tunnel will increase the local pore pressure above its original value, hence large water-pressure gradients will exist in the radial directions across the bedding. These large horizontal stresses may cause plastic flow of the clay towards the crown and the invert, which is unlikely to occur at the sides of the tunnel.

Elastic changes occur in the ground as the tunnel excavation approaches, and also subsequently as the excavation proceeds ahead for a distance of 1 or 2 tunnel diameters. They are responsible for the high initial rates of loading and deformation in the ring. The clay near the tunnel boundary also begins to swell on account of the removal of the radial effective stress. The lining, although it receives elastic loading both from the ground and from the method of erection, does not restore the original stresses to the ground. Therefore the clay continues to swell. The swelling and displacement of the clay towards the crown and invert are greater than at the sides, not only on account of the greater pore water pressure but also because the swelling capacity of the clay is greater normal to the bedding. Although there is interaction between the elastic movements and the swelling consolidation movements in the clay, both have the same effect, which is to flatten the tunnel.

A long period of steadily changing stress conditions continues in the disturbed ground which involves swelling in some parts of the region associated with consolidation in others. This is a difficult moving boundary problem which we have not tackled. Final equilibrium is reached when a steady state of seepage becomes established between the undisturbed region and the relatively pervious tunnel lining. This implies an increase in the degree of consolidation towards the lining.

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