Existing Stresses in Several Old London Underground Tunnels

Les Efforts en Peripherie des Revêtements de Quelques Tunnels Anciens du Métro de Londres

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Summary

Measurements were made with the assistance of the London Transport of the existing circumferential stresses in the cast-iron linings of seven old London Underground tunnels at four sites. Vibrating wire gauges were fixed to groups of adjacent tunnel rings and usually the strain was measured when the clay was completely excavated from around the lining. The changes in tunnel diameter were measured approximately.

The average stresses in the 'skin' of the linings are in reasonable agreement with the stresses due to the hydrostatic overburden. In multiple tunnel systems, where adjacent tunnels are less than one diameter apart, the flange stresses in the earlier constructed tunnels can be tensile and are dominated by the effects of the excavation of subsequent tunnels. These effects are completed simultaneously with the excavation and persist for at least 50 years. The changes in diameter are very small and are consistent with the stress changes.

Sommaire

En collaboration avec les autorités du 'London Transport' on a mesuré les efforts en périphérie des revêtements en fonte de sept tunnels anciens du métro de Londres à quatre emplacements différents. On a employé des extensomètres à corde vibrante, fixés à des anneaux adjacents dans les tunnels. Les déformations ont été mesurées généralement après que l'argile entourant le revêtement ait été enlevée. Les changements du diamètre du tunnel ont été mesurés approximativement.

Les efforts moyens à la paroi des revêtements montrent un accord satisfaisant avec ceux qui sont dûs à la couverture hydrostatique. Dans le cas d'un système à tunnels multiples séparés par une distance moindre que leur diamètre, les efforts dans les nervures reliant les anneaux des tunnels creusés en premier lieu sont largement influencés par les effets de l'excavation des tunnels suivants. Ces effets se manifestent dans leur entièreté au cours des travaux d'excavation et persistent pour au moins 50 ans. Les changements dans le diamètre du tunnel sont très petits et en bon accord avec ceux des efforts.

Introduction

During the period September 1954 to March 1956 the Building Research Station in co-operation with the Chief Civil Engineer's Department of London Transport measured the existing circumferential stresses at a large number of points in the segmental cast-iron linings of old underground train tunnels that traverse the over-consolidated clays beneath London. The work was carried out at four sites, called K, R, G and B where two or more tunnels have existed for 50 years and more. At all these sites the construction of new accesses involved the building of new tunnels close to the existing ones and the changes in circumferential stress associated with these operations were measured also. Although these latter observations are of considerable interest and of prime importance for design there is not space to include them in this paper and they will be published elsewhere.

Technique

At sites K, R, and G the new construction involved complete removal of several rings of the existing tunnel lining, but only 3 segments were removed at site B. The technique used to measure the existing circumferential stresses at sites K, R and G was to instal vibrating wire strain gauges (WARD, 1955) on the cast iron and to measure the strain, first when the surrounding clay had been completely removed, and secondly when the lining had been dismantled. In this way it was possible to separate the existing circumferential stresses in the lining due to the earth load from those due to unbolting and dismantling of the segments. The latter stresses were generally small.

At site B the technique was rather different; in ring T (see Fig. 5) separate segments were removed or unloaded and in ring S the local pieces of iron to which the gauges were fixed were cut away by drilling a continuous encircling row of holes. These observations therefore include the bolting and erection stresses.

Four strain gauges were fixed in general to every accessible segment at sites K and R (at site G to segments at axis level only) in groups of 3 adjacent rings in each of two tunnels, 12 ft. 6 in. external diameter. Two of the gauges were fixed to the 'skin' and two fixed to the side of the flanges between the bolts in the positions shown in the cross-section of the iron in the upper part of Fig. 1. At site B, where the two main tunnels

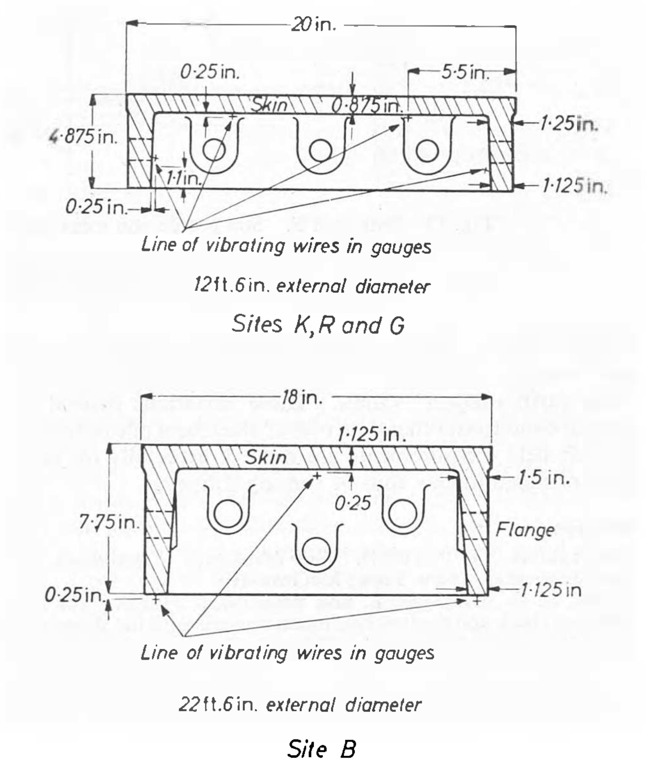

Fig. 1 Cross-sections of the cast-iron tunnel linings showing positions of the vibrating wire gauges

Sections des revêtements en fonte, montrant les positions des extensomètres à corde vibrante are 22 ft. 6 in. external diameter, one gauge was fixed to the centre of the skin and two others were fixed to the tips of the flanges as shown in the lower part of Fig. 1.

The Sites

The general form of the cast-iron linings used in the London Underground is illustrated and described by HEWITT and JOHANNESSON (1942). In the 12 ft. 6 in. tunnel iron at sites K, R and G there are 6 segments and one 10 in. long crown key to one ring, the longitudinal or cross-joints occurring at the sixth points of the circumference, except at the crown key. In

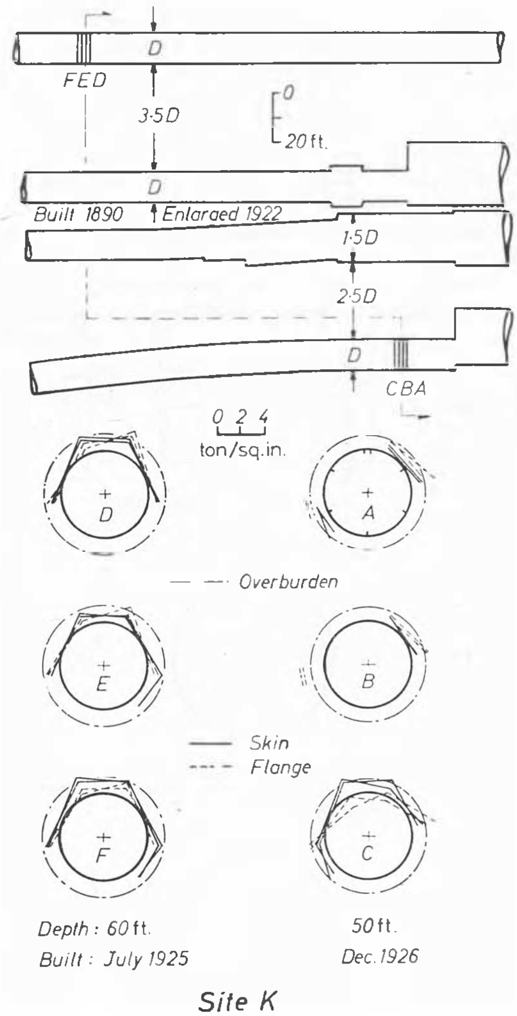

Fig. 2 Tunnel layout and polar diagrams of the circumferential stresses as measured and due to a hydrostatic overburden at site K

Plan du tunnel et graphique des résultats des mesures des efforts en périphérie et du calcul des efforts dus à la couverture hydrostatique à l'emplacement K

the 22 ft. 6 in. iron at site B there are 12 segments to a ring and a crown key as before. The positions of the cross-joints are indicated on one of the tunnel circles in Figs. 2–5.

Plans and cross-sections through the tunnel arrangements as they existed in 1954 are given in the upper parts of Figs. 2–5 for sites K, R, G and B, respectively. The depths of the tunnels and the date and order of their construction are also given on the above figures. The ground surface is generally horizontal above the tunnels, except at site B where the surface slope is about 1 in 18.

The clays surrounding the tunnels have been tested extensively in the laboratory for strength, compressibility and consolidation. The results of these tests can be mentioned only briefly in this paper and will be published elsewhere. At sites K, R and G the undrained compression strengths of the clays are considerably greater than the present full overburden pressure, but the converse is true at site B. All the clays are finely laminated horizontally and are about 1·6 times as compressible in the vertical direction as in the horizontal direction.

There is a water pressure greater than the atmospheric value in the clays at sites K, G and B. At sites K and G the critical swelling pressure of the clays in the vertical direction agrees well with the full overburden pressure, whereas at site B the critical swelling pressure lies nearer to the submerged overburden

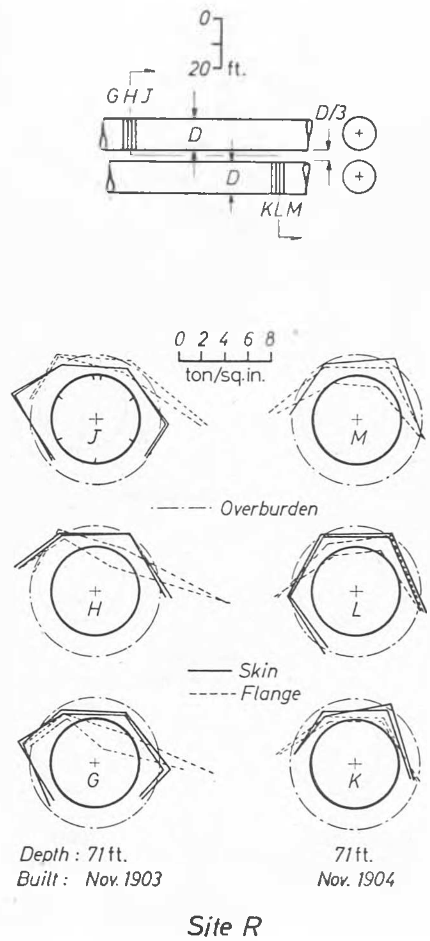

Fig. 3 Tunnel layout and polar diagrams of the circumferential stresses as measured and due to a hydrostatic overburden at site R

Plan du tunnel et graphique des résultats des mesures des efforts en périphérie et du calcul des efforts dus à la couverture hydrostatique à l'emplacement R

pressure. At site R the clays (and associated sand layers) do not yield water and their critical swelling pressure in the vertical direction is greater than the present overburden.

Sites K, G and B are in the London clay proper. At K, R and G several feet of river terrace gravel covers the London clay. The tunnels at K are in the lowest beds of the London clay with saturated sand layers immediately below. At G there is about another 110 ft. of London clay beneath the tunnels. The tunnels at site B lie in the uppermost beds of the London clay which are covered with the Claygate beds and some 45 ft. of fine Bagshot sand. The roofs of the tunnels at site R are situated in the base of the mottled beds of the Reading clay type and the lower parts of the tunnels are surrounded by a very tough sandy clay with a liquid limit of only 40. The clays at R are stronger than those at any of the other sites.

Existing Circumferential Stresses

The existing circumferential stresses are plotted in a series of polar diagrams, ring by ring, in Figs. 2–5. Compressive stresses are plotted radially outwards from the heavily lined circle, that represents the tunnel lining, and tensile stresses are plotted radially inwards. The full straight lines join up the point values of the skin stresses and the straight dashed lines join up the values of the flange stresses. In Fig. 4, where observations were made at two positions only in each ring, the

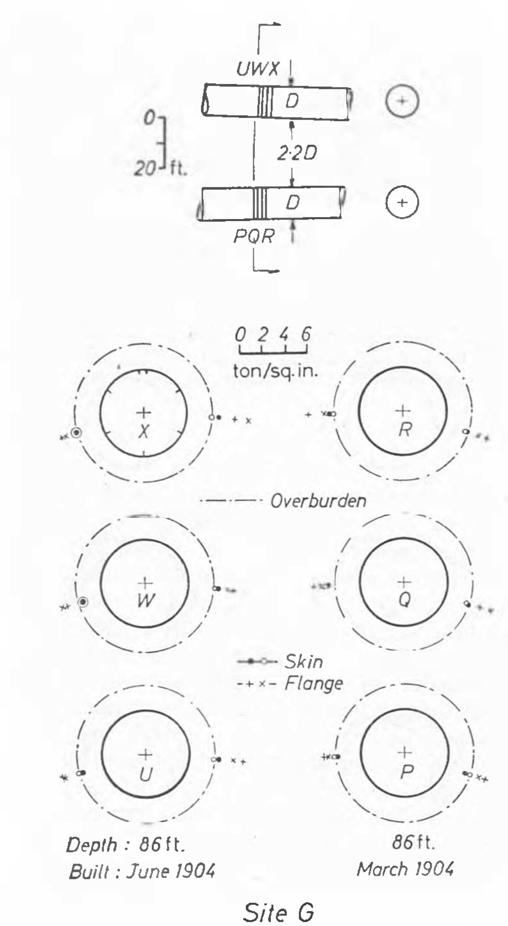

Fig. 4 Tunnel layout and polar diagrams of the circumferential stresses as measured and due to a hydrostatic overburden at site G

Plan du tunnel et graphique des résultats des mesures des efforts en périphérie et du calcul des efforts dus à la couverture hydrostatique à l'emplacement G

point values are plotted. In each polar diagram the dashed-dot circle represents the calculated value of the circumferential stress in the lining when it supports a hydrostatic overburden pressure (including some allowance for the weight of superimposed buildings). In examining the polar diagrams it should be remembered that the following factors influence the magnitude and distribution of the circumferential stresses in a tunnel ring: (a) the depth of the tunnel, (b) the sequence of tunnel excavation, (c) the distance between the tunnels in relation to the tunnel diameter.

Changes in Diameter

Measurements were made of the change in diameter in the vertical and horizontal direction of each of the tunnels at sites K, R and G associated with the removal of the earth load. These measurements were made with a steel tape divided into eighths of an inch and the distance between centre punch marks was estimated to the nearest thirty-second of an inch. The results are given in the table below.

Table

Site	*Ring group*	*Changes in diameter in $\frac{1}{32}$ in.*	
		Horizontal	*Vertical*
K	ABC	+ 0	+ 1
	DEF	+ 1	+ 2
R	GHJ	− 4	+ 4
	KLM	− 2	+ 5
G	PQR	0	− 2
	UWX	+ 1	− 2

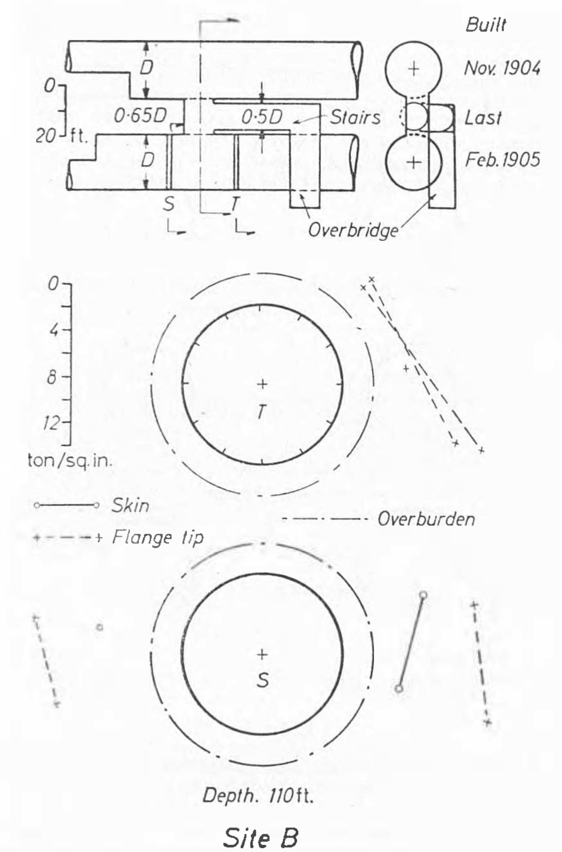

Fig. 5 Tunnel layout and polar diagrams of the circumferential stresses as measured and due to a hydrostatic overburden at site B

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Positive changes are increases in diameter; the technique of measurement is not accurate to more than $\pm \frac{1}{32}$ in. but a more precise method was not possible in the circumstances.

Discussion

The following salient features of the observations will be noted from Figs. 2–5 and the table:

An average value of the skin stresses at sites R and K, where there is a sufficient distribution of measurements around the rings, and at site G, is in reasonable agreement with the hydrostatic overburden pressure. The skin stresses in the roof and invert at site B are presumably low in compression and the stress distribution is probably like that in rings J, H and G at site R.

The values of the flange stresses in relation to the skin stresses indicate considerable bending in some segments, especially where the tunnels are less than one diameter apart and in the first constructed tunnel (site R and B). The flange stresses are large in compression on the radius directed towards the axis of the last constructed tunnel (site R) and can be tensile towards the roof (and presumably towards the invert) in the first constructed tunnel. This latter conclusion is suggested by observations made in Chicago by TERZAGHI (1942), and has been elaborated in detail by our observations of the changes in stress while new tunnels have been constructed alongside, between and above the four sites K, R, G and B. These results show further that the stress changes occur simultaneously and completely with the new excavation and without further change for periods of at least several months. Indeed the sequence of excavation and construction of the tunnels at site R can be established quite clearly from the stress measurements after a lapse of 50 years.

The consistency in the stress distribution in consecutive rings is really quite remarkable and observations on one ring alone would give a good guide to the general situation.

The diameter changes are very small and are consistent with the stress changes on unloading, particularly when the weight of the rings themselves are considered.

The work described in this paper forms part of the research programme of the Building Research Board and is published by permission of the Director of the Building Research Station of the Department of Scientific and Industrial Research. The kind co-operation and interest of the Civil Engineer's Department of London Transport and of their consultants and contractors contributed greatly to the success of these observations and is duly acknowledged.

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