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Ground conditions around an old tunnel in London Clay

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This paper reports the findings of a field study of the ground conditions around an old tunnel in London Clay at a greenfield site in Kennington, South London. Ground conditions were identified from a borehole investigation incorporating a programme of *in situ* pore water pressure monitoring, geotechnical testing and sampling. Additionally, laboratory classification of the samples and a suite of high-quality triaxial tests were carried out. The results of this investigation are presented and discussed in conjunction with published London Clay data. The presence of a tunnel beneath the site allowed the investigation of its influence on the local soil and groundwater conditions.

NOTATION

e	void ratio
G	shear modulus
I_p	plasticity index
k_h	coefficient of horizontal permeability
K_0	*in situ* earth pressure coefficient
q	deviator stress
p	mean normal stress
S_u	undrained shear strength
u	pore water pressure
w	moisture content
ε_{ax}	axial strain
γ	unit weight
σ_a	axial stress
σ_r	radial stress
$'$	denotes parameter in terms of effective stresses

1. INTRODUCTION

The deep aquifer beneath London, comprising the Chalk and the Thanet Sand, is confined over much of the basin by the overlying, relatively impermeable layers of clay that separate the deep aquifer from the perched groundwater in the overlying superficial deposits. The London Clay is up to 150 m thick in areas, but within central London depths between 30 and 100 m are more common. There is a wealth of published information concerning the geotechnical properties of London Clay from the upper and middle levels of the stratum, but only limited data exist concerning the lower deposits—that is, near the base of the stratum (Unit A2)[1].

The principal aim of this study was to investigate the variation of pore pressure in the London Clay with distance from an old tunnel. It is usually assumed that segmental tunnel linings in clays do not provide an impermeable barrier but allow seepage into the tunnel causing permanently reduced pore water pressures in the near vicinity;[2] however, this has not previously been systematically verified by measurement of pore water pressures.

A second aim was to investigate whether the stress changes during construction of the tunnel and in the consolidation period following construction are still evident (in this case nearly 75 years on) in terms of variations in the geotechnical properties of the London Clay with proximity to the tunnel.

2. SITE INVESTIGATION

The site was located within Kennington Park, a greenfield recreational facility, in the Borough of Lambeth in South London. The park is grassed, bounded by mature trees and surrounded along its perimeter by residential housing; the closest dwelling is approximately 60 m from the study area.

A single running tunnel, in service as part of the Northern Line on the London Underground network, runs under the site. The tunnel, constructed in 1924 by shield boring, has an internal diameter of 3·6 m, and is lined with six cast iron segments bolted together and grouted. At the section beneath the study area the tunnel axis lies 21 m beneath ground level (−17·7 mAOD). Fig. 1 shows a plan of the site in relation to the position of the tunnel and location of the ground investigation.

A detailed plan of the ground investigation layout is shown in Fig. 2. Six cable percussion (P1–P6) and two rotary-cored (R1 and R2) boreholes were undertaken. During drilling of borehole P5 standard U100 samples were retrieved at 1 m intervals for laboratory classification, and rotary-cored U100 samples from boreholes R1 and R2 were selected for triaxial testing.

Following drilling, vibrating wire piezometers were installed at a variety of depths in each of the cable percussion and rotary-cored boreholes, to monitor the groundwater regime across the site. Piezometers were also installed from within the tunnel to a distance of approximately 1 m behind the lining, at the same section as the cable percussion (P) boreholes. The remaining boreholes were formed during field testing with self-boring geotechnical instruments. The PM boreholes indicate the position of self-boring permeameter tests undertaken to

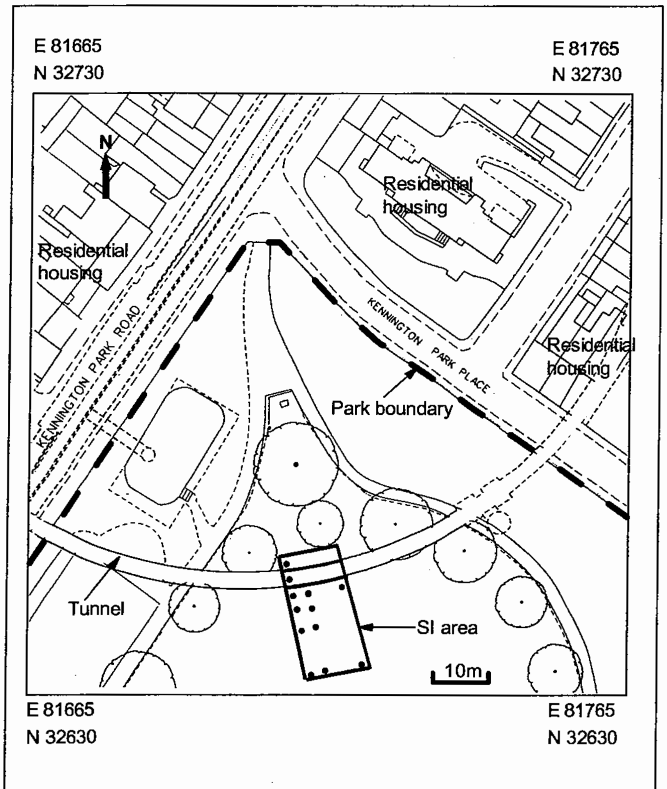

Fig. 1. Plan of site investigation area and surroundings showing the position of the tunnel

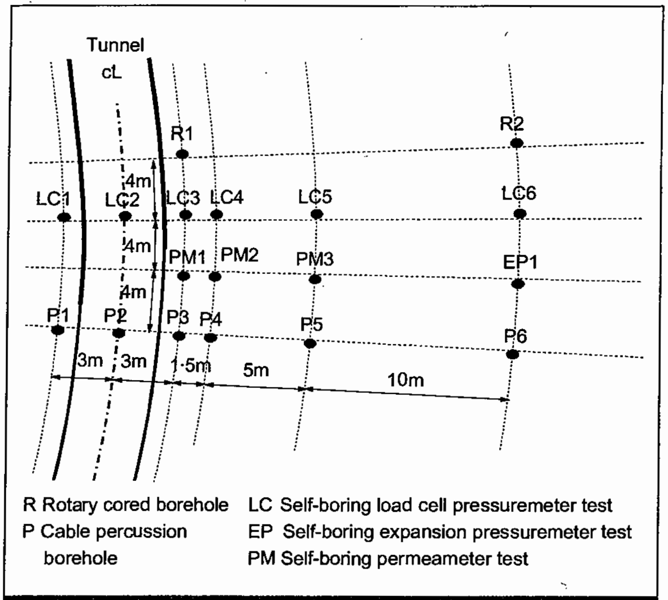

Fig. 2. Site investigation borehole layout with respect to tunnel position

measure *in situ* horizontal permeability. Borehole EP1 was for a series of self-boring expansion pressuremeter tests to evaluate *in situ* horizontal stresses. Self-boring load cell pressuremeter tests were also performed at the locations shown in Fig. 2. Table 1 summarises the type and location of the field and laboratory work carried out.

2.1. Stratigraphy

The borehole records identified the sequence of deposits in the study area as: Made Ground (0–2 m); River Terrace Deposits, sand and gravel (2–7 m); London Clay, stiff fissured clay (7–25 m); Lambeth Group, stiff clay and dense silty sand and gravel (25–40 m); Thanet Sand, dense silty sand (40–50 m); Upper Chalk below 50 m. The drilling records also showed that the River Terrace Deposits were above the water table, groundwater being encountered just above the top of the London Clay stratum. A summary of the stratigraphy encountered is illustrated in Fig. 3.

Borehole records describe the London Clay near the top of the stratum as a stiff dark greyish-brown clay, becoming very stiff at around 10 m below ground level. By around 12 m it was described as being extremely closely fissured becoming very closely fissured, with local occasional pockets and partings of silty fine sand. At depths greater than 16 m the deposit was described generally as very stiff grey/brown fine sandy clay with occasional pockets of light grey silty fine sand. At tunnel axis level, 21 m below ground level and very near its base, the London Clay was described as very stiff dark greyish brown closely fissured fine sandy clay with closely spaced partings of light greyish brown silty fine sand.

The majority of published data relate to London Clay higher within the series than that at Kennington, and hence only limited data exist for comparison. Hight and Jardine[3] and Skempton and Henkel[4] report on lower London Clay sites at Waterloo and on the South Bank respectively, and in both cases an increasing sandiness as the base of the stratum was approached was also observed. This is consistent with the different London Clay sub-units identified by King,[5] as noted by Hight *et al.*[1]

2.2. Groundwater conditions

Groundwater conditions across the site were identified by vibrating wire piezometers installed in each of the R and P boreholes between depths of 7 and 48 m (Fig. 2). In addition, vibrating wire piezometers were installed radially from within the tunnel 1 m behind the tunnel lining at axis level on both sides of the tunnel, and from the knees and the invert. The positions of the piezometers are illustrated in Fig. 4.

During installation of the piezometer from the tunnel invert (T3) rapid water entry into the tunnel took place, a clear indication of the high permeability of the soil strata beneath the tunnel. Although the piezometer was eventually installed, confidence in its reliability could not be assured, and therefore the data are not presented. The piezometers were monitored periodically to ascertain that steady-state conditions were achieved; equilibrium groundwater pressures are presented in Fig. 5.

The data show that the pore water pressures within the clayey strata conform to a slightly subhydrostatic profile, shown as line L, consistent with a water table at approximately 4·5 m below ground level in the River Terrace Deposits and underdrainage into the Thanet Sand. For comparison a theoretical hydrostatic profile with a corresponding water table at 4·5 m depth is shown in Fig. 5, marked as line H1. The data points in the underlying granular strata conform to a hydrostatic profile, shown as line H2, with a piezometric level corresponding to a depth of about 16 m. Although a reduced piezometric level in the Thanet Sand and Chalk aquifer is

	Borehole
Vibrating wire piezometers	R1 and R2; P1-P6; T1-T5
In situ self-boring permeameter tests	PM1-PM3
In situ self-boring expansion pressuremeter tests	EP1
Standard U100 sampling for laboratory classification	P5
Rotary-cored U100 sampling for stress path triaxial testing	R1 and R2

Table 1. Summary of site investigation

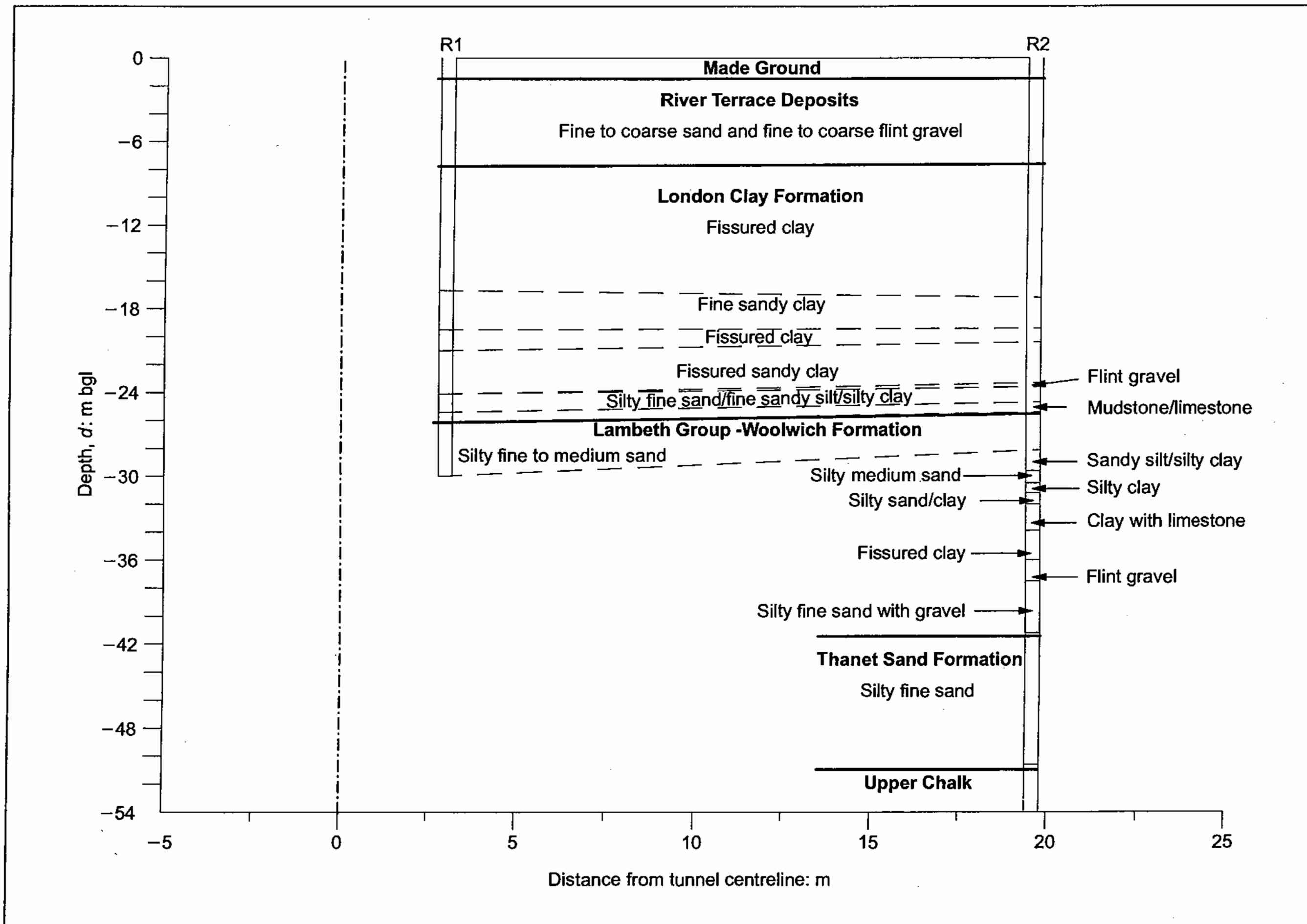

Fig. 3. Stratigraphy beneath case study area. Identified by rotary cores from boreholes R1 and R2 as shown in Fig. 2(b)

clearly evident, the piezometer data indicate a higher water level than expected in this area from the general data summarised in CIRIA Report 69.[6]

It is usually assumed that segmental tunnel linings in clays do not provide an impermeable barrier but allow seepage into the tunnel, causing permanently reduced pore water pressures in the near vicinity.[2] Close inspection of the pore water pressures measured by the piezometers just behind the tunnel lining does indicate slight seepage into the tunnel: Fig. 6 shows that the tunnel piezometer data fall below the regression line, L, derived from the P and R borehole piezometer measurements presented in Fig. 5. This suggests that seepage towards the tunnel is occurring but only very locally, and pore water pressures corresponding to the far field are being reached within 1·5 m from the tunnel (i.e. the distance of boreholes P1 and P3 from the side of the tunnel).

2.3. Soil classification and standard triaxial testing

Standard U100 samples of London Clay between depths of 8 and 25 m were retrieved from borehole P5 (Fig. 2) for classification and testing in the laboratory. Tests to determine particle size distribution, natural moisture content, Atterberg limits and undrained shear strength (on 100 mm specimens) were carried out. Particle size distribution curves from selected depths are shown in Fig. 7, indicating the variability of particle size and a general trend of increasing coarseness as the base of the stratum is approached, as was noted in the borehole drilling records.

The increasing coarseness of the London Clay with depth is reflected in the natural moisture content, plasticity index and undrained shear strength shown in Fig. 8. Despite some scatter in the measured values, a distinct trend of reducing natural moisture content and plasticity index with depth is evident.

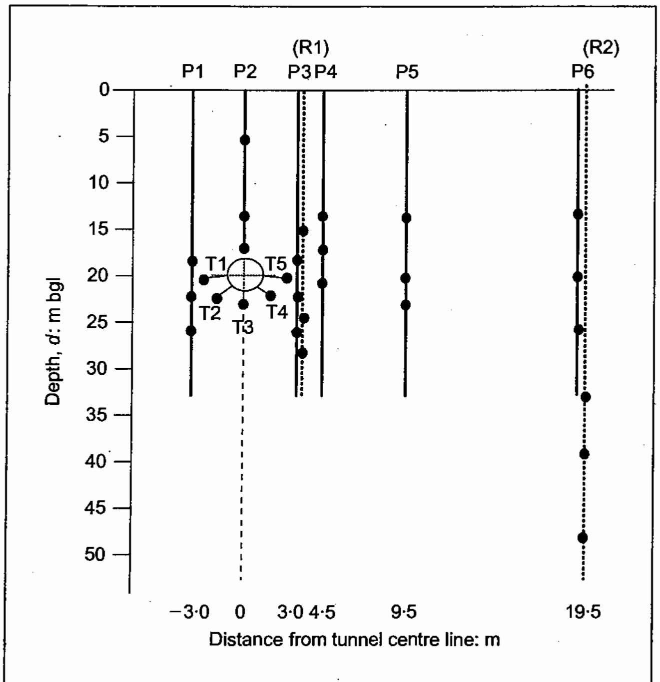

Fig. 4. Position of piezometers. Located in cable percussion boreholes P1–P5, rotary-cored boreholes R1 and R2 (see Fig. 2), and 1 m behind tunnel lining radially at springings, knees and invert (T1–T5)

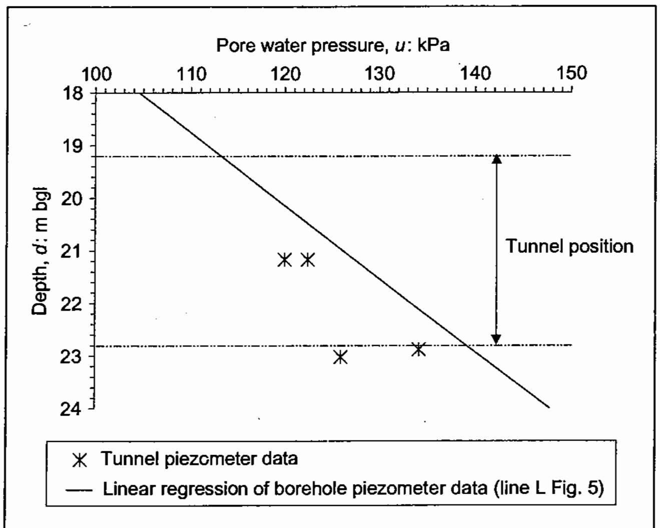

Fig. 6. Pore water pressures around the tunnel. Readings from piezometers installed 1 m behind tunnel lining at springings and knees T1–T5 (refer to Fig. 4 for piezometer locations)

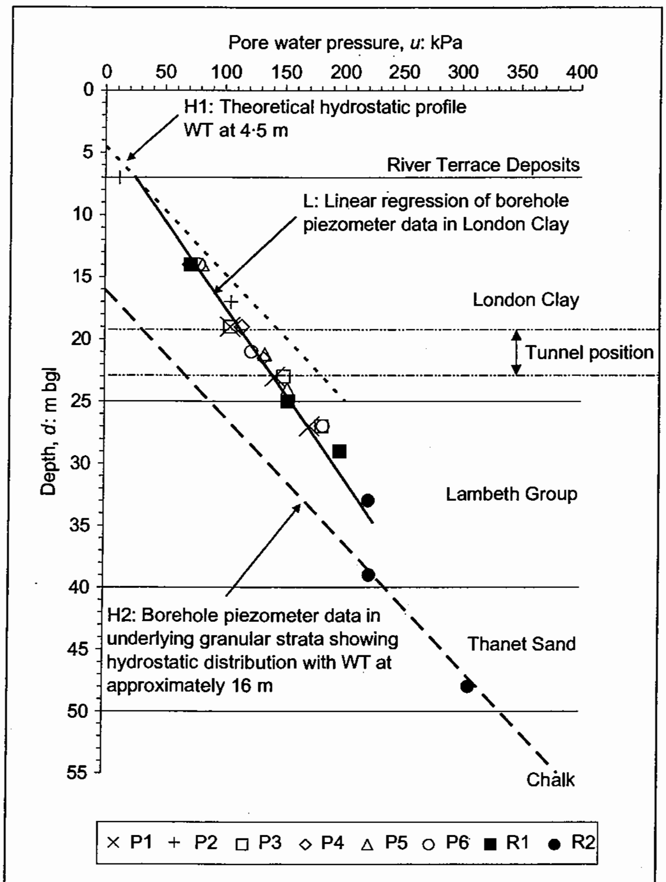

Fig. 5. Equilibrium groundwater pressures from piezometer readings from boreholes P1–P5, R1 and R2 (refer to Fig. 2 and Fig. 4 for piezometer locations)

The observed plasticity index tends towards the upper bound, and the natural moisture content towards the lower bound of values reported of London Clay from similar depths; the undrained shear strength profile is fairly typical.[3]

2.4. *In situ* permeability

Self-boring permeameter tests were carried out between depths of 10 and 23 m in boreholes PM1–PM3 (see Fig. 2). Values of the derived coefficient of horizontal permeability are shown in Fig. 9. A profile of linear regression of the data points from borehole PM1, closest to the tunnel, shows a trend of permeability increasing towards the tunnel. However, this may reflect the influence of the tunnel on the infinite boundary conditions assumed in the interpretation of the *in situ* permeability tests.

Figure 10 compares the *in situ* permeability data from this case study with a selection of reported data from a variety of other London Clay sites.[7–10] With the exception of the two very low measurements at around 20 m depth, the Kennington data show a generally higher permeability than the other reported data, reaching 10^{-8} m/s near the base. This is consistent with the description of the London Clay at this depth containing closely spaced partings of fine sand, as noted earlier.

2.5. Horizontal stress

In-situ horizontal stresses inferred from the self-boring load cell pressuremeter tests exhibited considerable scatter, as reported by Gourvenec *et al.*[11] It was not possible to draw any firm conclusions regarding the variations of in-situ stresses with distance from the tunnel. Fig. 11 shows inferred in-situ stresses interpreted from lift-off pressures from the self-boring expansion pressuremeter tests in borehole EP1 distant from the tunnel (Fig. 2).

3. TRIAXIAL TESTS

The borehole records, soil classification and in-situ permeability data highlight the difference in nature of the London Clay near its base from the higher strata. The implication of these material variations for geotechnical behaviour was investigated in a series of triaxial tests.

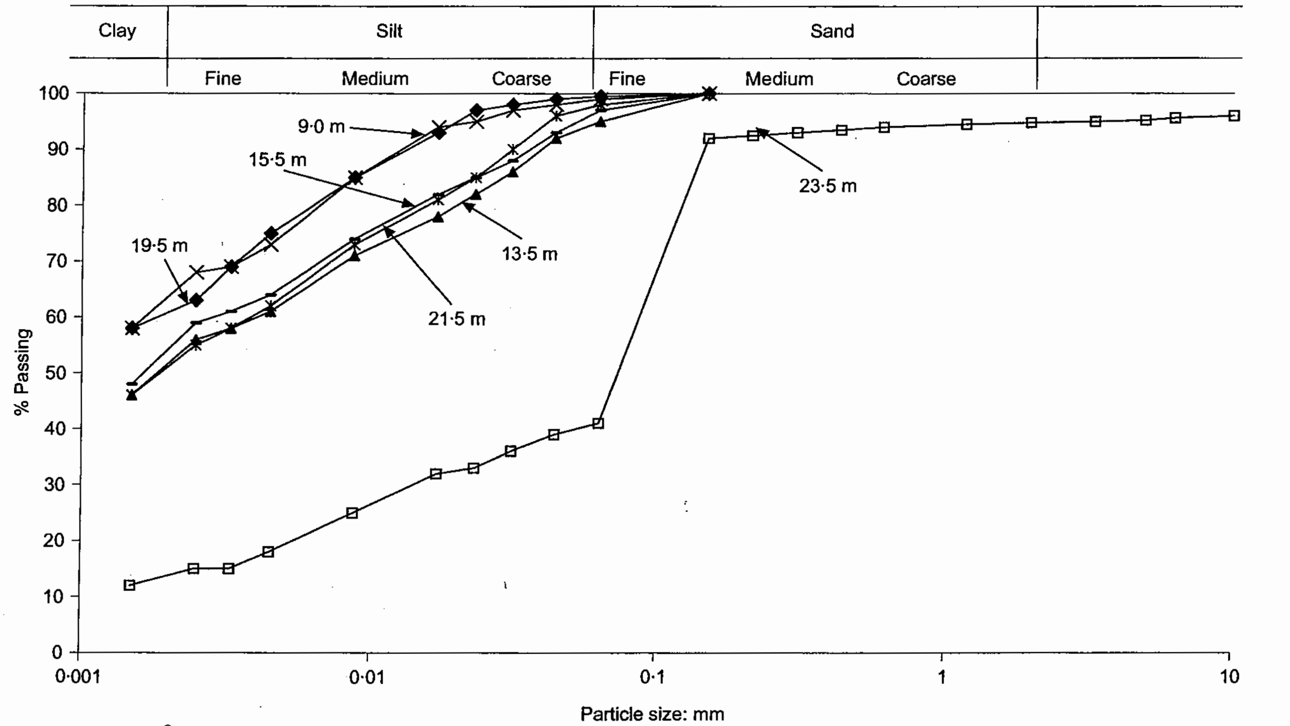

Fig. 7. Particle size distribution curves of London Clay from Kennington site

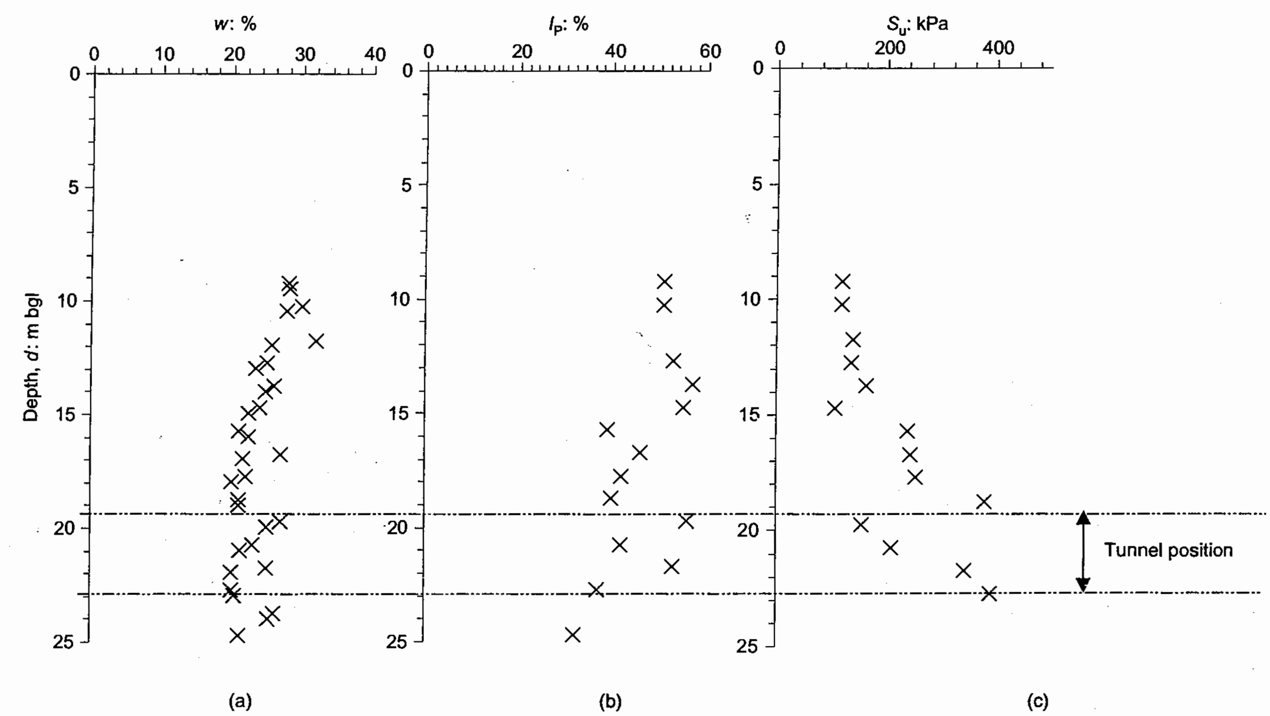

Fig. 8. Index properties of London Clay from Kennington site: (a) natural moisture content, w; (b) plasticity index, I_p (= LL − PL); (c) undrained shear strength, S_u

The programme of triaxial tests was carried out to assess the strength and stiffness characteristics of the London Clay at various depths both close to and remote from the tunnel. Six tests were carried out on 50 mm diameter specimens prepared from rotary U100 cores retrieved from boreholes R1 and R2 (see Fig. 2). The locations of the specimens for triaxial testing are summarised in Fig. 12. In each of the tests the specimens were saturated under a back-pressure, and were consolidated, either isotropically or anisotropically, prior to shear. The appropriate earth pressure coefficient for the initial stress states

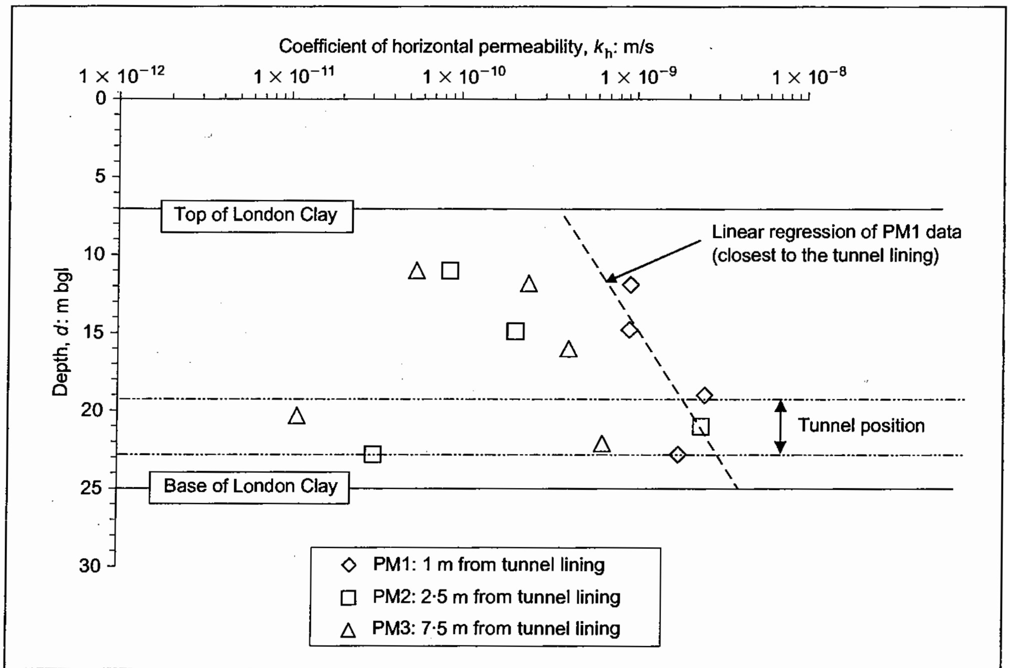

Fig. 9. *In situ* horizontal permeability, measured from self-boring permeameter tests in boreholes PM1, PM2 and PM3 (see Fig. 2 for location of boreholes)

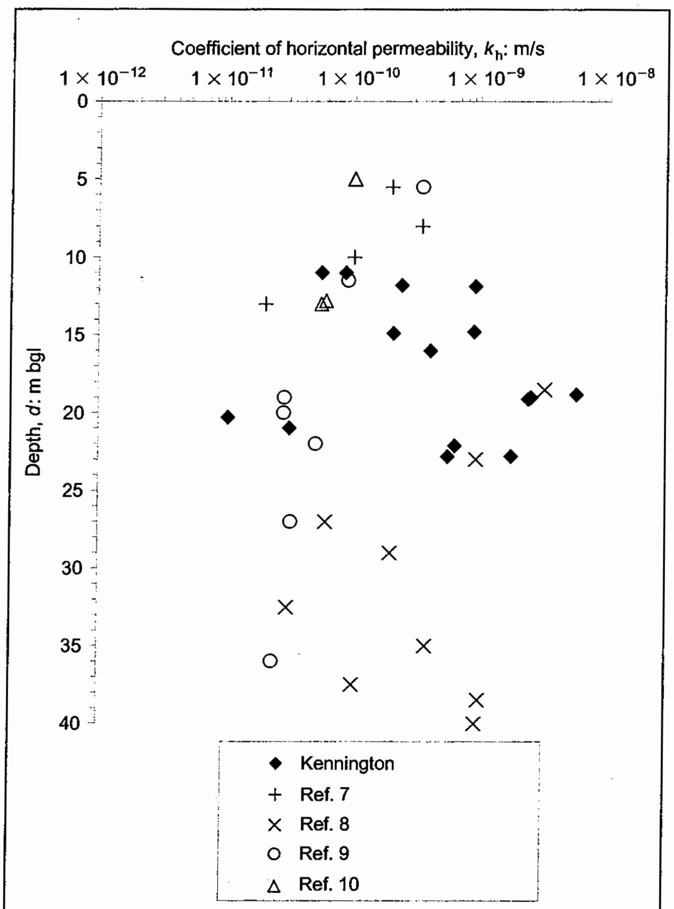

Fig. 10. Comparison of permeability with published sources of other measurements in London Clay

was derived from horizontal stress measurements made *in situ* during the self-boring expansion pressuremeter test in borehole EP1 (Fig. 11). All the specimens were sheared undrained with pore water pressure measurement, in strain controlled triaxial compression to failure (other than Test 4, which was interrupted before failure owing to the development of a fault in the apparatus). All the specimens failed in shear, exhibiting a peak strength prior to development of a rupture zone and softening towards the critical state. Details of the triaxial tests are summarised in Table 2.

3.1. Strength

The effective stress paths followed by each of the specimens during shear are illustrated in terms of mean effective stress p' and deviatoric stress q in Fig. 13.

The results of the tests fall into two groups: Tests 2, 3 and 5 exhibit higher shear strengths than Tests 1, 4 and 6. Reference to Table 2 shows that the division in terms of strength is reflected in the specimen density, with higher strength observed in the denser samples (lower void ratio). The density of the specimens is in turn related to the depth from which they were retrieved, the deeper samples exhibiting higher strengths, consistent with the observed increased sandiness as the base of the London Clay is approached. The results from the tests presented in Fig. 13 suggest that the variation in strength of the London Clay is a function of depth rather than of proximity to the tunnel.

Hight and Jardine[3] present results from triaxial tests on rotary-cored samples from two London Clay sites, both higher in the stratigraphy than at Kennington. One site was situated in Waterloo, 2·4 km north of Kennington, where the base of the London Clay is 40 m below ground level, and the other in Paddington, approximately 7·2 km north-west of Kennington, where the base of the London Clay is 68 m below ground level. Values of peak deviatoric stress observed in these tests are also included in Fig. 13, together with lines of regression of the data points from each of the sites. Comparison of all the data shows that the Kennington strength data lie above the Hight and Jardine results for all the tests except those on the deepest specimens (i.e. 49–62 m). A similar finding is made by Hight *et al.*,[1] who compared the undrained shear strengths of London clay specimens obtained at various locations.

3.2. Stiffness

The stiffness of the Kennington specimens measured in the triaxial tests is presented in Fig. 14 in terms of the secant shear stiffness modulus G against axial strain ε_{ax}. Consideration of the results in conjunction with the index properties of the specimens given in Table 2 shows that higher stiffnesses are exhibited by the denser specimens, consistent with the observed increasing sandiness of the deposit with depth. The distinct division of the results observed in the strength data (presented in Fig. 13) is not reflected in the stiffness data. It is,

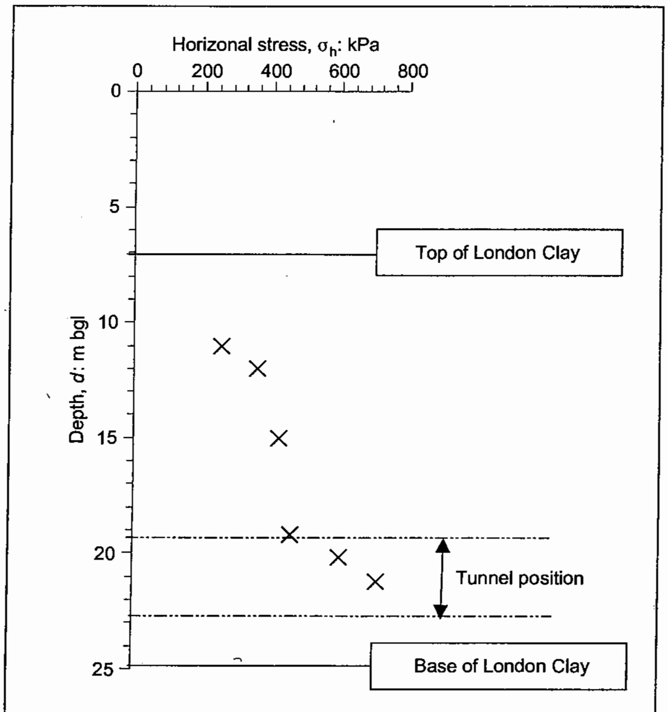

Fig. 11. *In situ* horizontal stress in London Clay inferred from self-boring expansion pressuremeter tests in borehole EP1 (refer to Fig. 2 for location of boreholes)

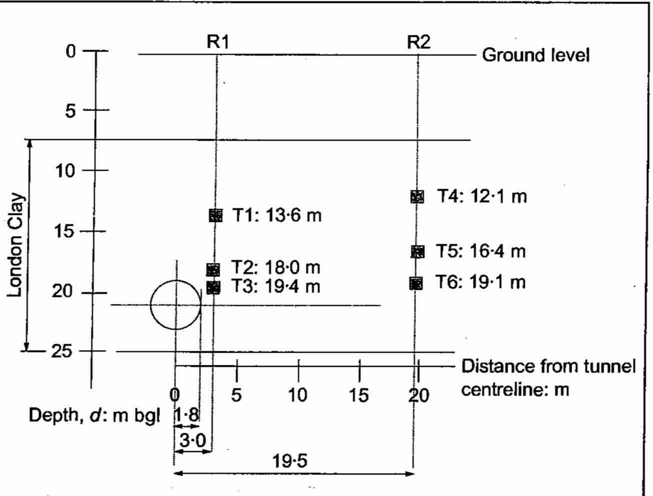

Fig. 12. Location of triaxial test specimens with respect to position of tunnel (see Fig. 2 for location of rotary boreholes R1 and R2)

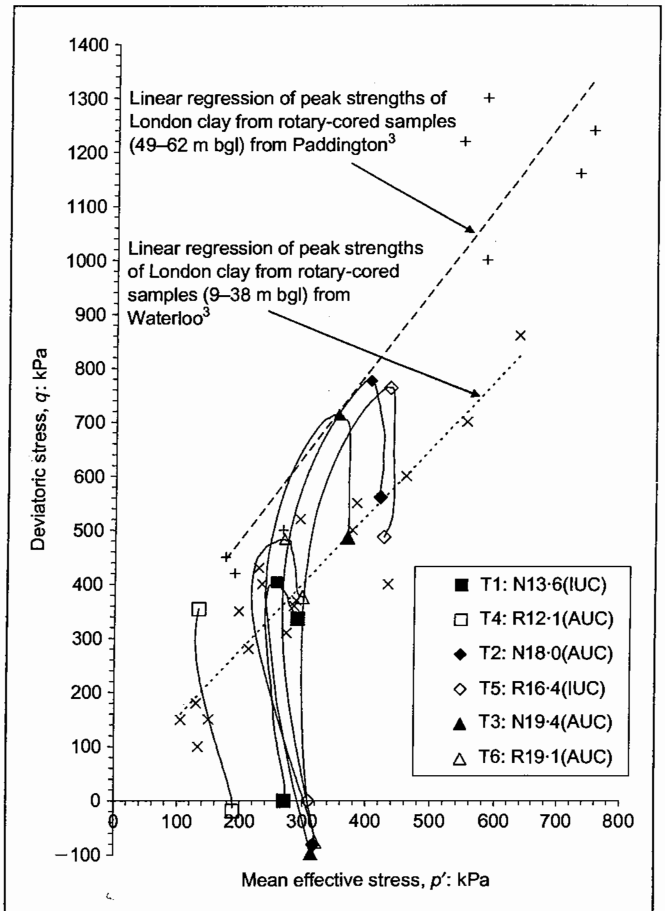

Fig. 13. Effective stress paths from triaxial tests (peak strength data from reference 3)

however, evident from Fig. 14 that the variation in stiffness is related to depth rather than to the presence of the tunnel.

Strain during shear in the triaxial tests was measured using both external and internal displacement measuring devices. The internal sample-mounted device reduced measurement errors due to sample bedding and apparatus compliance. Unfortunately, problems were encountered during data acquisition of the internally measured displacements in Tests 2, 3 and 6, and therefore the stiffness data presented for these tests were calculated from measurements made with the external displacement transducer.

	Test 1: N13·6 IUC	Test 2: N18·0 AUC	Test 3: N19·4 AUC	Test 4: R12·1 AUC	Test 5: R16·4 IUC	Test 6: R19·1 AUC
w_0: %	25	23	22	25	22	25
e_0	0·680	0·614	0·581	0·685	0·590	0·682
p_0': kPa	270	325	325	195	310	325
K_0 assumed	1·0	1·35	1·35	1·11	1·0	1·35

Test reference labels: N indicates that the specimen was prepared from a core retrieved from the borehole near to the tunnel, and R indicates that the specimen was prepared from a core retrieved from the borehole remote from the tunnel. This is followed by the average depth of the tested specimen in metres below ground level. Finally, IUC or AUC indicates that the shear test was carried out on an isotropically or anisotropically consolidated specimen, in undrained conditions following a compression stress path.

Table 2: Summary of stress path triaxial tests

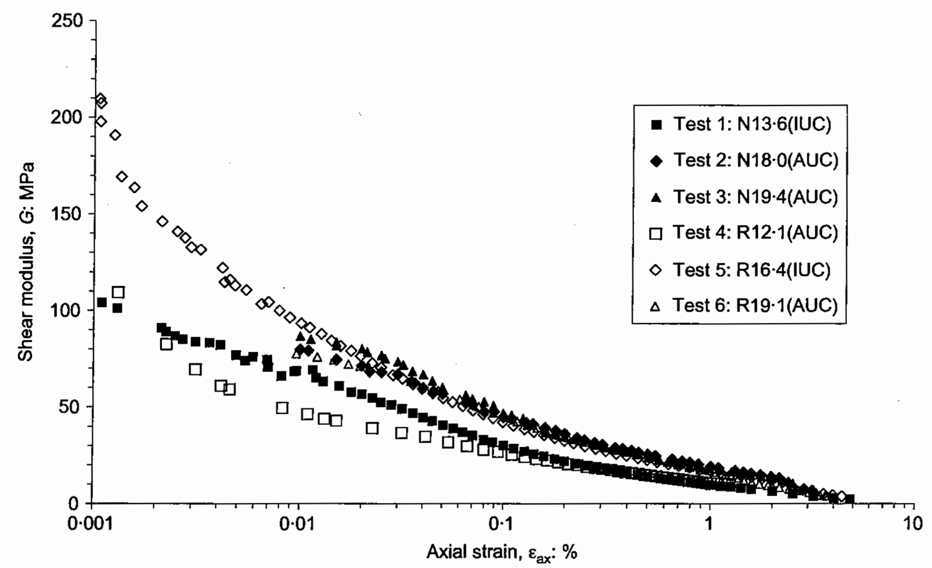

Fig. 14. Shear stiffness modulus from triaxial tests

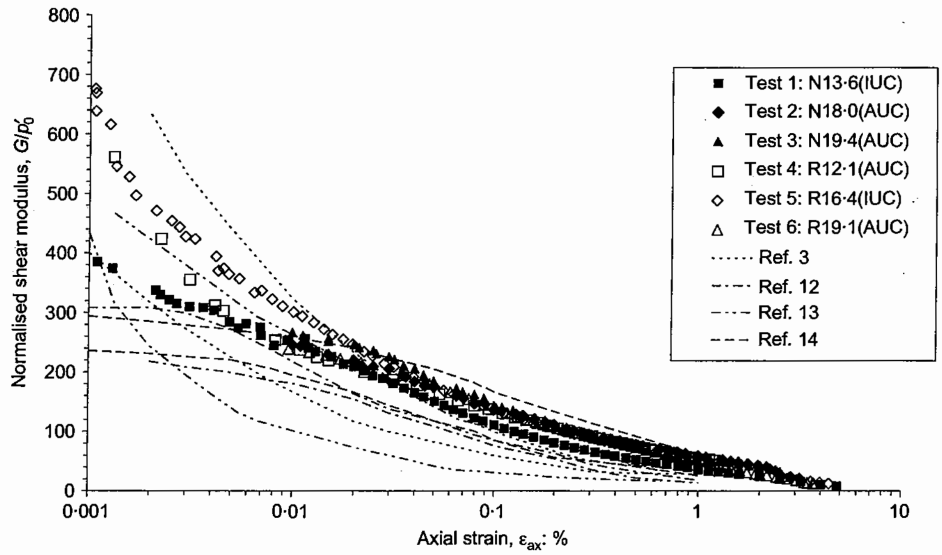

Fig. 15. Comparison of normalised shear stiffness with published data

Figure 15 shows the Kennington data together with a selection of published data from similar tests on specimens from a variety of London Clay sites.[3,12–14] As was the case with the comparative strength data, the published stiffness data reported here relate to London Clay from higher within the series than at Kennington. For the purpose of comparison, the stiffness data in Fig. 15 are presented in terms of the shear modulus G normalised by the mean effective stress at the start of shear, p_0'. The Kennington data lie around the upper bound of the published data.

4. CONCLUSIONS

The geotechnical information derived from the ground investigation at Kennington is of particular interest owing to the low position of the London Clay in the geological series (Unit A2[1,5]). Ground level at the Kennington site was only 25 m from the interface with the underlying Lambeth Group, whereas much existing data about London Clay properties concern material from higher within the series. The following conclusions were obtained from the investigation:

(*a*) The nature and engineering properties of Lower London Clay can differ considerably from those encountered higher in the series. Comparison of the data with other London Clay data from similar depths, but from higher within the series, showed that the London Clay at Kennington exhibited coefficients of permeability and shear strength and stiffness towards the higher end of reported data from other London Clay sites.

(*b*) The borehole investigation provided visual evidence of the changing nature of the London Clay with depth, identifying an increasing portion of silt and sand, particularly as its base was approached. The increased sandiness of the clay was reflected in the results of the field and laboratory tests, which identified a reducing natural moisture content, reducing plasticity, higher permeability, and higher shear strength and stiffness with depth.

(c) The variation in soil properties was more noticeably related to depth, and to the increasing sandiness of the clay, than to proximity to the tunnel. The presence of the tunnel appeared to have no discernible effect on the strength and stiffness characteristics. There was possibly some evidence that permeability was higher close to the tunnel.

(d) The presence of the tunnel also appeared to have an influence on the local pore water pressure regime. Although little evidence of groundwater seepage towards the tunnel was evident from the borehole piezometer data across the site, there was a slight reduction in pore water pressures recorded by the piezometers installed just behind the lining, suggesting that far-field conditions are reached within about 1·5 m of the tunnel.

(e) The high pore pressures observed close to the tunnel lining at Kennington were surprising, as it is usually assumed that segmental tunnel linings in clays act as a drain, causing permanently reduced pore water pressures close to the tunnel. The conditions at Kennington probably result from the higher permeability associated with the sandiness of the clay, leading to the tunnel being less permeable relative to the London Clay than usual. Whereas tunnels running through very low-permeability London Clay found higher in the series may well act as drains, those such as at Kennington in the basal London Clay deposits appear to be effectively impermeable. Further site investigation around other tunnels in London Clay would be necessary to confirm this.

5. ACKNOWLEDGEMENTS

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base was approached. The increased sandiness of the clay was reflected in the results of the field and laboratory tests, which identified a reducing natural moisture content, reducing plasticity, higher permeability, and higher shear strength and stiffness with depth.

(c) The variation in soil properties was more noticeably related to depth, and to the increasing sandiness of the clay, than to proximity to the tunnel. The presence of the tunnel appeared to have no discernible effect on the strength and stiffness characteristics. There was possibly some evidence that permeability was higher close to the tunnel.

(*d*) The presence of the tunnel also appeared to have an influence on the local pore water pressure regime. Although little evidence of groundwater seepage towards the tunnel was evident from the borehole piezometer data across the site, there was a slight reduction in pore water pressures recorded by the piezometers installed just behind the lining, suggesting that far-field conditions are reached within about 1·5 m of the tunnel.

(e) The high pore pressures observed close to the tunnel lining at Kennington were surprising, as it is usually assumed that segmental tunnel linings in clays act as a drain, causing permanently reduced pore water pressures close to the tunnel. The conditions at Kennington probably result from the higher permeability associated with the sandiness of the clay, leading to the tunnel being less permeable relative to the London Clay than usual. Whereas tunnels running through very low-permeability London Clay found higher in the series may well act as drains, those such as at Kennington in the basal London Clay deposits appear to be effectively impermeable. Further site investigation around other tunnels in London Clay would be necessary to confirm this.

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