Field investigations of long term ground loading on an old tunnel in London Clay

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ABSTRACT: This paper presents the results of a field study carried out early in 1998 to investigate the current ground conditions around an old cast iron lined tunnel in London Clay. The eventual loading carried by these tunnel linings is unknown, but concern exists that there may be a gradual increase in loading with time. The considerable lengths of the London Underground network run through London Clay in tunnels constructed with cast iron segmental linings. The investigation therefore provides information vital to the estimation of the remaining design life of London’s underground transport infrastructure.

1 INTRODUCTION

London Underground Limited (LUL) is currently undertaking a project to evaluate the long term durability and capacity of segmental cast iron tunnel linings in service on the London Underground network. The project runs in parallel with an EPSRC grant awarded to Cambridge University Engineering Department (CUEED).

For the purpose of this collaborative investigation, a case study a section of a single running tunnel of significant age (constructed in 1924) with a cast iron segmental lining. From historical records and geological maps the tunnel is known to lie within a substantial thickness of London Clay. The tunnel is selected to conduct a site investigation. In December 1997 LUL contracted Soil Mechanics Limited (SML) to carry out a site investigation of the study area and Geotechnical Consulting Group (GCG) were appointed as the consulting engineers. The fieldwork was carried out between January and May 1998. The field study which is presented in this paper included comprehensive monitoring of ground water pressures with vibrating wire piezometers installed bored holes at various depths and distances from the tunnel and from within the tunnel. The piezometer data was complemented by a programme of self-boring load cell pressuremeter, expansion pressuremeter and permeameter field tests to determine the in situ stress state and permeability of the clay both adjacent to and remote from the tunnel.

2 BACKGROUND

It is usually assumed that segmental tunnel linings in low permeability clays do not provide an impermeable barrier but cause permanently reduced pore water pressures in the near vicinity and seepage into the tunnel, i.e. the tunnel acts as a drain (Ward & Pender, 1981). However, this has never been systematically verified by measurement of pore water pressures.

The mechanisms of pore water pressure dissipation and equilibration following construction of a tunnel in clay cause swelling and consolidation of the clay around the tunnel, leading to a time dependent increase in loads carried by the lining. Knowledge of the eventual ground loading acting on tunnel linings is very limited and the nature and extent of the gradual increase in loading with time is poorly understood.

Investigations to identify the development of load carried by old cast iron tunnel linings in London Clay with time have been undertaken in the past using methods of direct measurement, for example with strain gauges mounted on lining segments or pressure cells inserted between the segments (e.g. Ward & Thomas 1965; Barratt et al., 1994). These studies suggest equilibrium vertical loads acting on tunnel linings between 60 and 100% of the full overburden pressure. Further to the difficulties in interpreting these data to quantify the loading applied to the tunnel lining by the ground, much of the data refers to multiple closely spaced tunnels, the development of load around which would be
expected to be very different from that around a single tunnel.
The key to understanding the long term ground loading on tunnel linings in clay is the measurement of the ground water pressure regime, close to and remote from the tunnel, and very few such measurements exist around old tunnel linings in London Clay.

3 SITE DETAILS

A plan of the case study area is shown in Figure 1. The tunnel section chosen for the investigation forms part of the Kennington Loop on the Northern Line of the London Underground network. Kennington is situated in the Borough of Lambeth in South London.
The site is grassed, bounded on its northern side by several mature trees, and is used solely as a recreational facility. Residential housing bounds all sides of the park, the closest dwellings to the study area being within 60m on the north side of Kennington Park Place.

According to the geological map of the area the site is underlain by River Terrace Deposits resting on London Clay followed by the Lambeth Group (Woolwich and Reading Beds), the Thanet Sand Formation and the Upper Chalk.

The tunnel has an internal diameter of approximately 3.6m (11 feet 8 ¼ inches), lined with six cast iron segments bolted together and grouted into position. At the tunnel section chosen for study the tunnel axis is located approximately 21m below ground level. The ground is reasonably level over the entire study area so for clarity throughout this paper depths are stated in metres below ground level.

4 SITE INVESTIGATION

The fieldwork for the site investigation comprised eighteen exploratory holes located in a 12m east-west zone extending 3.0m to the north of the tunnel centreline and 19.5m to the south. A plan of all the site investigation boreholes with respect to the position of the tunnel is shown in Figure 2. The two R boreholes located along the eastern boundary of the study area were formed by rotary coring, the six P boreholes located along the western boundary of the study area were formed by cable percussion and the remaining 10 holes (LC, PM and EP) were commenced by cable percussion and completed with in situ self-boring devices.

4.1 Stratigraphy and soil classification

Records of the materials encountered during formation of the R and P boreholes identified the sequence of deposits at the study area as: Made Ground (0.1-8.0m); River Terrace Deposits - sand and gravel (1.8-7.5m); London Clay - stiff fissured clay (7.5-15.0m) inter-laminated with silt and sand (15.0-25.5m); Lambeth Group - very stiff clays, dense silty sands and gravels (25.5-50.0m); Thanet Sand - dense silty sand (40.0-50.0m); Chalk (below 50m). The drilling records also showed that the River Terrace Deposits were above the watertable, ground water being encountered at the top of the London Clay stratum.

In situ lateral earth pressures and horizontal permeability of the London Clay were derived from tests with self-boring instruments at depths between 10 and 23m and distances from the tunnel centreline between 3 and 19.5m. The lateral earth pressure tests were carried out in boreholes LC1-LC6 and the permeability tests in boreholes PM1-PM3.

A summary of the geotechnical parameters of the London Clay is presented in Figure 4.

In situ lateral stress measurements were made with a self-boring load cell pressurometer (LCPM), measuring total stress in the surrounding soil with six independent load cells distributed evenly around the circumference of the instrument sleeve. The LCPM is a new instrument, developed by the Transport Research Laboratory (TRL) and CI for the assessment of Ko (Darley et al. 1996), and is designed to minimise soil disturbance during installation. Previous experience with the instrument is very limited, and so the field lateral stress conditions measured in borehole LC2 were verified against results from control tests carried out in borehole EP1 with a conventional self-boring expansion pressurometer.

The arithmetic mean of the six independent total horizontal stress measurements from each of the LCPM tests are shown against depth in Figure 5. Considerable scatter is apparent indicating that averaging the individual load cell readings provides an inappropriate representation of the stress state.
Figure 5. Summary of total horizontal soil stresses

Figure 6. Variation in total horizontal stress measurements with orientation

Figure 7. Summary of permeameter tests

Figure 8. Position of piezometers

Figure 9. Summary of piezometer readings

5 CONCLUSIONS

A comprehensive investigation of the ground conditions around a 75 year old tunnel has been undertaken. The London Clay was found to be a varied material, generally a stiff fissured over-consolidated clay, with a comparatively high proportion of sand and silt as well as bands of mudstone and limestone, especially near its base.

The mean horizontal stresses measured by the
Compensation grouting to control tilt of Big Ben Clock Tower

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ABSTRACT: Big Ben Clock Tower is the most famous of many historic and important structures affected by ground movements associated with construction of the Jubilee Line Extension Project in London. The construction works for the new Westminster Station are outlined. Compensation grouting undertaken to control the tilt of the Tower is described, drawing particular attention to the instrumentation used to monitor tilt and the precision to which the tilt could be controlled.

1 INTRODUCTION

The construction of Westminster Station on London Underground Limited’s (JUL’s) new Jubilee Line Extension (JLE) project in London was predicted to produce significant movements of the Big Ben Clock Tower and the adjoining Palace of Westminster (Fig. 1) as a result of excavation of two 7.4m OD (outer diameter) tunnels and the 39m deep station escalator box. These activities produce two components of movement: an initial, immediate movement directly associated with the progress of excavation and a time related component due to drainage and consolidation of the London Clay. Protective measures, primarily in the form of compensation grouting below the Clock Tower, have been implemented during the construction period to control settlement and tilt of the structure.

This paper describes the compensation grouting and monitoring procedures undertaken over a 21 month period to control the tilt of the Clock Tower during construction of the tunnels and the deep excavation for the station box.

2 JLE WESTMINSTER STATION

The layout of the new Westminster Station on the JLE is shown in plan on Figure 2 and in section on Figure 3. The station comprises bored 7.4m OD platform tunnels in a vertically stacked arrangement below Bridge Street with a 39m deep diaphragm wall box to the north. Access to the platforms is provided by four shafts between the tunnels and the box at both tunnel levels. Escalators to the ticket hall and Bridge Street with interchange facilities to the new District and Circle station are provided within the station box. Design of the station is described by Carter et al. (1996).

Prior to any substantial excavation within the station escalator box, the running tunnels were driven from east to west as pilot tunnels. The lower, westbound (WB) tunnel was constructed in March 1995 and the upper, eastbound (EB) tunnel in October 1995 at depths of 30m and 21m below ground level respectively. The running tunnels are 4.85m OD and were built in expanded concrete segmental linings, each of which was 1.0m in length. A Howden open face shield with a backactor was used for both drives.