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Site investigation for the tunnels and stations of the Jubilee Line Extension, London

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ABSTRACT: This paper describes the site investigation undertaken for the design and construction of the underground sections of the Jubilee Line Extension in London. It provides the background to other papers on this major project presented at this symposium.

1 INTRODUCTION

The Jubilee Line Extension to the London Underground system (hereinafter referred to as JLE), which is at present under construction, runs from the existing Green Park station in central London, to Stratford in east London, a distance of 15.5km (see Figure 1).

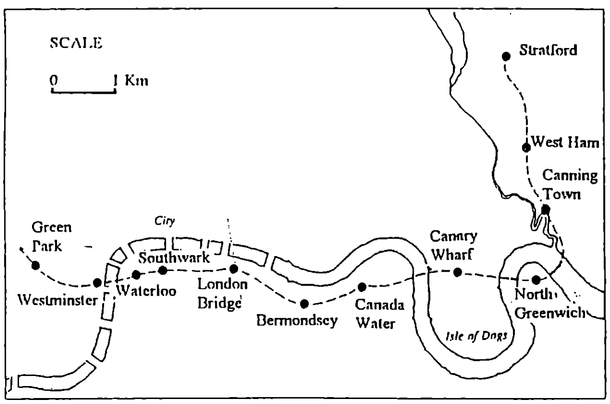

Figure 1 Route plan.

The route from Green Park to Canning Town, approximately 11.5km, is in twin 4.4m internal diameter bored tunnels at depths from 20m to 30m below existing ground level. The remainder of the route to Stratford is at grade.

There will be eleven stations along the route, four of which are being constructed as large open cut boxes, five are either enlarged tunnels or a combination of enlarged tunnels and open cut, and two are surface constructions.

This paper deals with the site investigation for the tunnels and deep excavations.

2 DESCRIPTION OF THE ROUTE

The JLE tunnels pass beneath a variety of types of urban land use. At the western end, the step plate junction with the existing tunnel is being constructed beneath high quality buildings, some of which date from the turn of the century, or earlier, and many of which are listed by English Heritage as being of outstanding architectural importance.

From this area , known as St James's, the tunnels pass south east under St James's Park, past the government Treasury Building and Big Ben clock tower, and beneath the River Thames just downstream of Westminster Bridge.

From this highly prestigious tourist area of London, the tunnels pass beneath County Hall, the former home of the Greater London Council, and then beneath a more prosaic ten storey office block (Elizabeth House), before reaching the complex underground construction beneath Waterloo station.

East of Waterloo, the tunnels run beneath a British Rail Viaduct for some 3km, including London Bridge Station.

Further east, the tunnels pass beneath residential public and private housing of varying quality and then beneath the backfilled Surrey Docks complex, before crossing the river again to the Isle of Dogs. At this location the disused West India Dock forms the site of the new Canary Wharf Station.

From the Isle of Dogs the tunnels pass beneath the river again to the North Greenwich Peninsular, where the new North Greenwich Station occupies the derelict former site of a gas works, which was demolished in the 1960's.

From North Greenwich station the tunnels cross the river for the last time and surface just before reaching Canning Town Station.

3 GEOLOGY

The geology of the route comprises Cretaceous and Tertiary sedimentary deposits, which have been gently folded into a shallow structural dome, lying just south of the axis of the London Basin syncline. The Tertiary sediments are overlain by a blanket of Pleistocene gravel and sand, which, in turn, is overlain by recent alluvium and made ground.

A geological section along the JLE route is shown in Figure 2.

The youngest of the Tertiary sediments is the London Clay, which occupies the periphery of the dome, outcropping at the east and west ends of the JLE route. This is a stiff to very stiff, fissured, silty clay, which has been heavily overconsolidated by past geological activity. Along the JLE route it reaches a maximum thickness of some 45m.

Beneath the London Clay is some 15m of silts, sands, clays and pebble beds, which are known collectively as the Woolwich and Reading Beds. During the course of the JLE site investigation, a classification of these soils was developed, resulting in seven stratigraphic sub units, which are described in detail later in the text.

The Woolwich and Reading Beds overlie the Thanet Beds, which consist of approximately 20m of fine to medium silty sand, which becomes more silty and clayey with depth.

The Thanet Beds are separated from the underlying Chalk, by a thin band of claybound gravel known as the Bullhead Beds.

3.1 *Groundwater*

Groundwater is present within the superficial deposits (gravels, alluvium and made ground), and within the permeable Tertiary deposits beneath the London Clay (Thanet Sands and granular sub units of the Woolwich and Reading Beds). These two water bearing zones are commonly referred to as the upper and lower aquifers respectively.

The water table in the upper aquifer is generally at approximately zero ordnance datum (ie. 5m to 6m below ground level), whilst the piezometric surface in the lower aquifer was found to be between -1m O.D. and -10m O.D. in the area of South London traversed by the JLE.

Extraction of water from the lower aquifer for industrial water supply during the past 150 years has resulted in a piezometric surface depressed by the order of 50m in Central London. Since the mid 1960's, however, extraction has virtually ceased and the piezometric surface has been rising at a rate of approximately 1m/year. The rise in water level and its effect upon civil engineering structures has been described in a CIRIA report (Simpson et al 1989) and

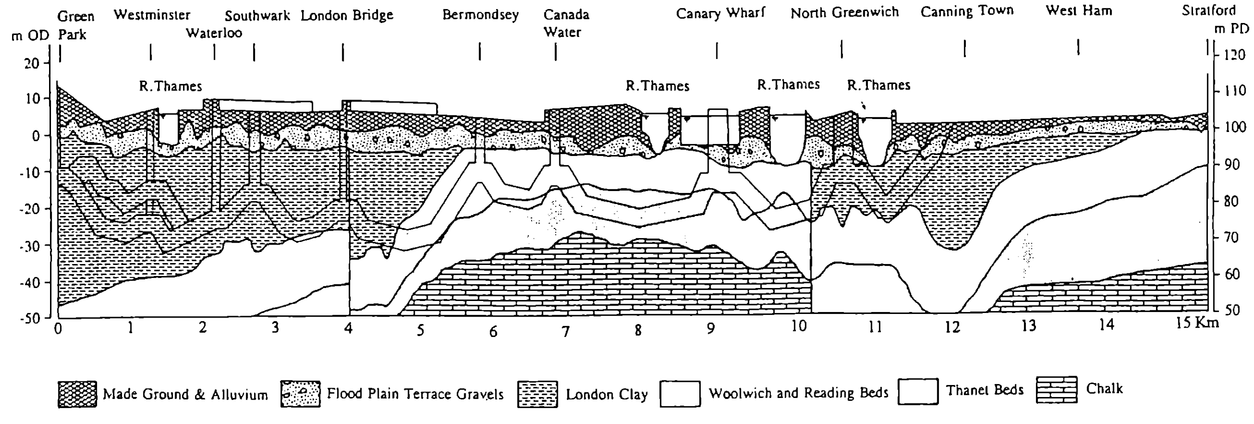

Figure 2 Schematic geological section along the JLE route.

is being monitored by the National Rivers Authority. Based on a consideration of all the available evidence and having regard for the 120 year design life of the JLE a long term piezometric surface of 2.5m O.D. was considered appropriate for the design of underground structures on the JLE.

4 SITE INVESTIGATION

4.1 *Background*

The design of the JLE was divided into eleven distinct contracts. In view of the relatively tight programme for the design it was decided to provide interpretive geotechnical reports to the designers which would provide a full appraisal of the ground conditions and recommend geotechnical design parameters based upon this appraisal. In this way it was hoped to relieve the designers of having to digest a very large volume of information in a very short time. These interpretive reports were later made available to the main works tenderers.

The responsibility for planning and reporting on the site investigation was divided into three. The western part, from Green Park to Canada Water, the eastern part from Canada Water to Stratford, and the central part (the Isle of Dogs).

The site investigation itself was divided into nine packages. The organisation of the site investigation works is shown in Table 1.

4.2 *Desk Studies*

Extensive desk studies were undertaken during the year preceeding the start of fieldwork. A database of over two hundred pre-existing boreholes was compiled along the route, for which logs of varying quality were available. These ranged from old wells dating back to the early nineteenth century, to high quality site investigation boreholes carried out for the development of London's docklands. These data were used, together with old maps and publications, to prepare tentative geological sections and geotechnical interpretations of the route, which were used to plan the succeeding field work programme.

Table 1 Organisation of JLE Site Investigation

Package No	**Area**	**Contractor**	**Engineer**
1 & 2	Green Park to Ewer St	Soil Mechanics Ltd	Mott MacDonald
3 & 4	Ewer St to Canada Water	Soil Mechanics Ltd	Mott MacDonald
5	River Crossings	Fugro Mc Clelland Ltd	Fieldwork Supervision: G Maunsell & Partners Reporting: Geotechnical Consulting Group
6	Canada Water to Durands Wharf	Exploration Associates	Fieldwork Supervision: G Maunsell & Partners Reporting: Geotechnical Consulting Group
7	Canary Wharf	Foundation & Exploration Services Ltd	Ove Arup & Partners
8	North Greenwich Peninsula	Foundation & Exploration Services Ltd	Fieldwork Supervision: G Maunsell & Partners Reporting: Geotechnical Consulting Group
9	Thames Wharf to Stratford	Soil Mechanics Ltd	Fieldwork Supervision: G Maunsell & Partners Reporting: Geotechnical Consulting Group

4.3 *Fieldwork*

The fieldwork was carried out over a five month period from August to December, 1990. The primary objectives of the investigation were:-

(i) To define the geological boundaries between strata at a representative number of locations in order to be able to prepare geological sections.

(ii) To define the material and engineering properties of the individual strata throughout the route.

(iii) To define the groundwater conditions throughout the route.

(iv) To identify geological hazards.

As a major part of the fieldwork, approximately 150 boreholes were sunk by cable percussion techniques, forty of which were extended below the superficial deposits by rotary coring. Ten of these boreholes were located in the River Thames at the site of tunnel crossings, these being constructed from a jack up barge.

The average spacing between the boreholes on land was of the order of 150m, rotary coring being undertaken at the sites of major shafts, stations and river crossings to enable detailed lithology and stratigraphy to be established.

Where rotary coring was employed the borehole was pre-bored by cable percussion through the superficial alluvium and Terrace Gravel to the top of the 'solid' geological stratum. Rotary coring was then employed using the wireline technique with polymer drilling fluids to produce high core recoveries (almost 100% in most boreholes), and high quality core. A rigid plastic liner was used within the core barrel to enable the core to be removed intact. The liner was then cut longitudinally, split, photographed and logged. Core lengths required for testing were cut from the core run, wrapped in cling film and then dipped in molten wax. This process was then repeated to ensure complete protection for the sample during transit to the laboratory.

Downhole geophysical logging was employed in selected core holes to assist in the identification of variations in geotechnical properties, correlation of laboratory test results and to provide transit times for interpretation of boomer seismic reflection profiling of the river crossings. Three arm caliper, sonic, natural gamma and gamma backscatter logging was undertaken within the mud filled corehole after removal of the outer corebarrel.

At some locations where high quality undisturbed samples of London Clay were required for small strain triaxial testing, pushed in thin walled tube sampling was employed in cable percussion boreholes. The samples were taken by jacking a thin walled (2mm) stainless steel tube against a reaction frame bolted to a concrete base encased against casing clamps. The sampling tubes (either 1150mm long or 600mm for stiffer soils to avoid buckling), were lightly greased inside and outside and then jacked into the soil at a rate of approximately 10mm per second. High quality samples approximately 800mm long or 400mm in the case of the shorter tubes, were generally obtained. This sampling method has been described by Harrison (1990).

Pressuremeter tests, using the Cambridge self boring pressuremeter, were carried out in 9 boreholes in London Clay and 3 boreholes in the Woolwich and Reading Beds/Thanet Sands. These tests were performed principally to determine the in-situ horizontal stress and shear modulus of the various soil types at sites where large excavations were to be made for station construction.

Determination of in-situ stress based on 'lift-off' pressures was not always successful in the mixed soils of the Woolwich and Reading Beds, which can contain varying amounts of granular material in the form of gravel and shells, leading to disturbance in the side of the hole and damage to the membrane. Variation in lift off pressure between the three strain arms sometimes occurred and/or cavity strains in excess of 0.2%, which were taken to invalidate the method.

In the Thanet Sands an oversize cutting shoe was fitted to the pressuremeter and the cutting shoe was replaced by a tricone bit. Values of shear modulus obtained for both the Thanet Sand and the sandy layers of the Woolwich and Reading Beds showed a considerable scatter.

In addition to the boring and sampling, the following field investigations were undertaken:-

(i) Pumping tests at Canary Wharf and Canada Water Station sites in the Thanet Beds and the Chalk, to determine permeabilities and groundwater flow characteristics of these strata.

(ii) Over water geophysical survey using seismic reflection techniques at river crossings, to confirm the continuity of the main stratigraphic boundaries, identify discontinuities and scour hollows, and provide a detailed bathymetric survey.

(iii) Standpipe piezometers were installed at regular intervals along the route to provide long term data on groundwater conditions.

(iv) An extensive programme of trial pitting was undertaken, to provide details of foundations to structures overlying the route and as part of the investigation for contaminated ground at the open excavation sites.

An important requirement of the fieldwork was considered to be a detailed analysis of the stratigraphy of the extremely variable Woolwich and Reading Beds. The British Geological Survey was commissioned to carry out this work, which involved detailed logging. correlation between boreholes and identification of marker zones. This work, which was carried out by Ellison (1991), resulted in the classification of seven lithostratigraphic sub units of the Woolwich and Reading Beds, which was adopted by the Project (Fig 3). A number of 'teach ins' were held for the Contractor's and Supervising Engineer's field staff in order to ensure uniformity of strata description on the borehole logs.

A detailed description of the lithology of the Woolwich and Reading Beds is given in Table 2.

4.4 *Laboratory Testing*

Laboratory tests were carried out on soil and water samples obtained from boreholes and trial pits. The testing programme comprised standard tests (ie. those described in BS 1377 : 1990), and specialised testing, which included the most recent advances in mechanical testing of soils.

Standard tests were carried out on disturbed and undisturbed soil samples to determine:-

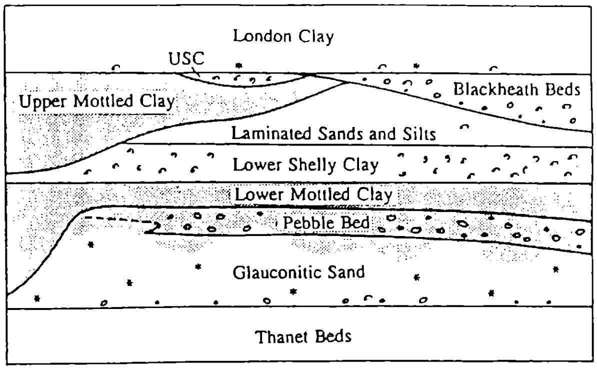

Figure 3 Generalised stratigraphical relationships within the Woolwich and Reading Beds in Central London. Key: USC, Upper Shelly Clay; o , flint pebbles; ↶ , shells; ░, colour mottling; * , glauconite

(i) Material properties - Atterberg Limits, particle size distribution, moisture content and specific gravity.
(ii) Mechanical properties - undrained and drained shear strength and compressibility.
(iii) Chemical content - sulphates, chlorides and organic content.

Specialised testing was carried out on thin walled tube samples and rotary cored samples to determine:-
(i) Insitu mean effective stress from instrumented triaxial tests and soil suction tests.
(ii) Small strain stiffness characteristics from instrumented isotopically and ansiotopically consolidated triaxial compression tests.

Table 2 Lithology of the Woolwich and Reading Beds

Sub Unit	**Description**
Upper Shelly Clay (USC)	stiff thinly laminated dark grey and grey brown, very silty clay, or very clayey silt with locally fine sand, sporadic shell fragments and rounded flints. Impersistent bands of limestone
Upper Mottled Clay (UMC)	very stiff, extremely closely fissured, mottled brown, red brown, and blue grey silty clay with some pockets of light brown fine sand and silt.
Laminated Sands and Silts (LSS)	stiff thinly interbedded and laminated silty clay, clayey silt and dense fine to medium sand. Shells may be sparse. Carbonaceous plant debris may occur.
Lower Shelly Clay (LSC)	very stiff, dark grey clay with many shell fragments often weakly cemented.
Lower Mottled Clay (LMC)	very stiff, mottled, calcareous silty clay. Calcareous concretions are common especially towards the top where they may form very thick limestone beds. To the east this unit becomes a dense fine sand.
Pebble Bed (PB)	very dense blue green and grey, fine to coarse flint gravel with occasion cobbles with a matrix of clay, silty clay, fine to medium sand or no matrix at all. May be clast supported or matrix supported.
Glauconitic Sand (GS)	dominantly green grey clayey, very silty fine to medium sand, with laminae, and thin beds of clay or flint gravel.

(iii) Clay minerology using X-ray diffraction techniques.
(iv) Chemical testing of contaminated man-made and natural ground for selected organic and inorganic contaminants.

Specialised triaxial testing was carried out on samples from locations where large excavations were to be formed, to assist in the design of temporary and permanent support systems and for use in numerical modelling of the behaviour of the soil surrounding excavations and the resultant effect on nearby structures. Such analyses were performed for the Westminster site, where a 45m deep excavation is being made just 35m from the Big Ben clocktower, and at Canada Water, where a 20m deep excavation is being carried out approximately 20m away from a 20 storey tower block.

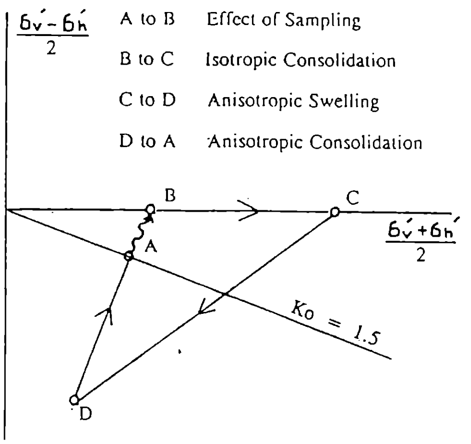

Figure 4 Stress path prior to undrained shearing in the triaxial test.

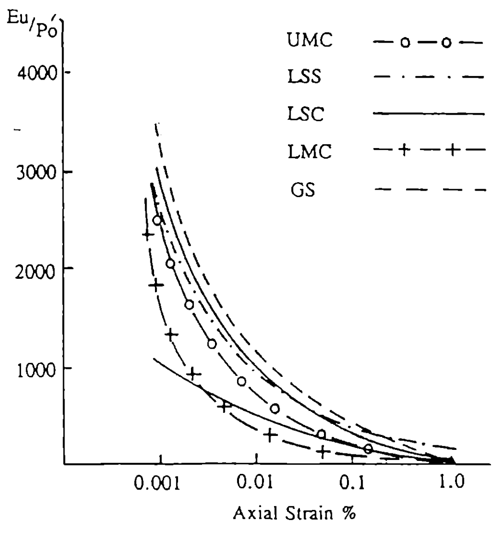

Figure 5 Strain/stiffness relationship for various sub units of the Woolwich and Reading Beds.

In order to ensure that the correct stiffness values were being determined, the soil samples were brought to the appropriate insitu stress state by following the three stage consolidation stress path shown on Figure 4. The stages were chosen to represent the cycle of deposition, erosion and re-deposition considered to be appropriate for the soil at the selected sites.

The small strain stiffness characteristics of some sub units of the Woolwich and Reading Beds, expressed in terms of undrained Young's modulus (Eu), normalised by the mean in-situ effective stress P'o, are shown in Figure 5.

5 CONCLUSIONS

The site investigation for the JLE employed some of the most advanced techniques of boring, sampling, in-situ and laboratory testing available to the geotechnical industry. Extremely high quality cores were obtained of the variable and, therefore, difficult to sample, soils of the Woolwich and Reading series. This made it possible for the British Geological Survey to develop a classification of sub units which is rapidly gaining wide acceptance, and which greatly assisted the geological interpretation on the JLE. A core sample from one of the JLE boreholes is kept by the BGS as the type sequence for these strata.

The high quality cores of the Woolwich and Reading Beds and the London Clay, together with undisturbed samples obtained by pushed thin walled tube sampling made possible the use of advanced laboratory techniques to measure the small strain stiffness characteristics of these soils. The soil properties obtained were, in turn, used in the most advanced numerical methods available to model the behaviour of the soils around the JLE works.

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