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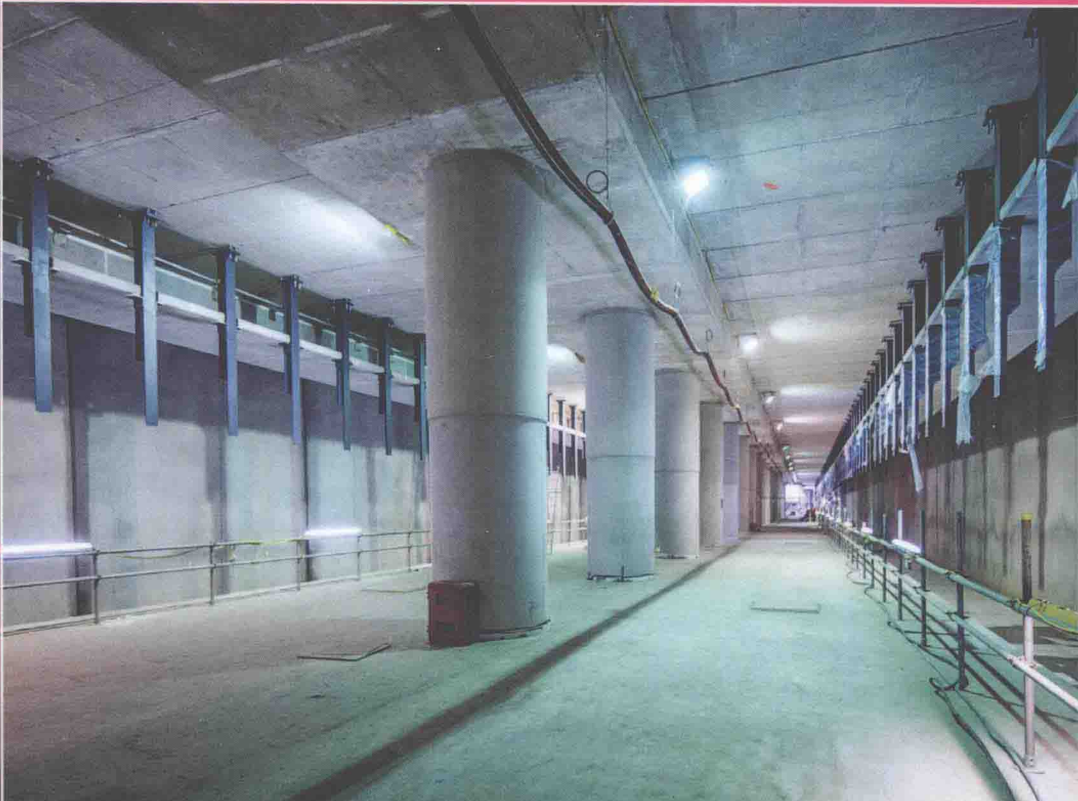
Crossrail Project
Infrastructure design and construction
Volume 3



Edited by Mike Black

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Foreword

This is the third in a series of volumes that will chart the technical progress of the Crossrail project.

Now in its fourth year, the Crossrail Technical Papers Competition continues to grow and is becoming the primary method of capturing some of the technical and innovative achievements made on the project. This publication contains the best of the papers submitted in 2015, which record, in detail and with transparency, achievements and best practice made by the project teams during the design and delivery of this project.

This annual competition has been extremely successful in attracting high quality contributions from authors across the programme, including personnel from the Crossrail delivery team, consultants, contractors, suppliers and third party stakeholders. It provides an outlet whereby they can pass on their experiences and best practice to the rest of the project and the wider technical community.

The Technical Papers Competition has continued as the programme has progressed through construction into fit-out and eventually into trial operations. Subsequent volumes will evolve to contain papers that reflect the technical disciplines active at each stage of construction up to the railway becoming fully operational in 2019. It offers a unique opportunity to pass on invaluable learning to others planning, designing and delivering underground construction and urban metro projects throughout the world.

On behalf of Crossrail Ltd, we take great pride in the publication of this book which records the technical challenges and achievements of the teams delivering the Crossrail project. I hope you enjoy reading about this fascinating project and find its content both interesting and informative.

Mike Black
Crossrail Head of Geotechnics

An Introduction to the Crossrail Project

The concept of rail tunnels crossing central London to link Paddington and Liverpool Street stations dates back to the 19th century when the Regent's Canal Company were granted permission to build a railway that would link Paddington with London's docks. Although this was aborted, the idea re-appeared in the 1940s and is alluded to in Sir Patrick Abercrombie's County of London Plan and Greater London Plan.

The idea has had many variations since then, but the principles of having twin-bore tunnels large enough to handle main line rolling stock, yet providing a metro-tube service without the need for passengers changing between main line stations and tube stations, remains the purpose to this day.

The construction of the Crossrail project began at North Dock in Canary Wharf in May 2009. Seven years on, it is the biggest railway construction project in Europe and is one of the largest single infrastructure investments undertaken in the UK. It consists of 21 kilometres of new twin-bore tunnels under central London and 10 new world-class stations constructed under the largest city in the European Union. The route will link existing Network Rail services from Reading and Heathrow in the west, and Shenfield and Abbey Wood in the east connecting new stations at Paddington, Bond Street, Tottenham Court Road, Farringdon, Liverpool Street, Whitechapel, Canary Wharf, Custom House, Woolwich and Abbey Wood.

The Crossrail tunnels are being constructed using eight tunnel boring machines (TBMs) beneath the busy streets of London. These running tunnels, linking the stations, are constructed with precast reinforced concrete segments. Of the 10 new, ticket halls for the eight underground stations, five portals, plus the various ventilation and access points along the route, are constructed using secant and diaphragm walls boxes and shafts. The station tunnels and caverns are being constructed using fibre reinforced sprayed concrete lining (SCL). In addition to this, there is a multitude of grouting shafts used to mitigate the effects of ground movement on London's existing infrastructure.

Currently, over 44 million hours have been worked, with the project employing over 10,000 people across more than 40 worksites throughout London and the South East. However, Crossrail is more than a civil engineering project. As the tunnelling and underground construction phase nears completion, the project is embarking on the next big challenge involving the mechanical, electrical and architectural disciplines related to rolling stock, rail systems and station fit outs.

Crossrail has relied on tried and tested technology and engineering principles throughout its design and construction programme while recognising its duty to embrace new technologies and innovation wherever practical.

As part of Crossrail's legacy, it is incumbent upon the organisation to share its experiences and best practices with the rest of the industry and to showcase the skills of the personnel involved and the successful delivery of each phase of works. This publication is the culmination of that experience and best practice celebrated by the Crossrail Technical Papers Competition and is presented here.

Contents

Crossrail Project: Infrastructure design and construction – Volume 3
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Design of the Deep Cut and Cover Crossrail Paddington Station Using Finite Element Method

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Abstract

The flagship Crossrail Paddington Station is generally located within London Clay and takes the shape of a deep cut and cover underground box structure approximately 264 m long, 24 m wide and 24 m deep framed with diaphragm walls and constructed top down using plunge columns connected to 1.8 m diameter bored piles. It is located at the heart of one of London's most significant existing transport hubs, directly beneath Departures Road and Eastbourne Terrace and is adjacent to the Grade I listed Paddington mainline station.

The geotechnical design of the deep cut and cover underground box structure was undertaken using two-dimensional finite element method and in accordance with the Crossrail Civil Engineering Design Standards.

Monitoring data from inclinometers located within and behind the main box diaphragm walls has provided valuable information throughout the construction process and on completion has allowed the geotechnical approach to the design of these walls to be assessed.

The deep excavation of the station is mainly influenced by the undrained behaviour of London Clay, which can be assessed either in terms of effective (Undrained (A) and (B) analyses) or total (Undrained (C) analysis) stresses.

Three constitutive soil models have been adopted for the undrained analysis of London Clay. These are the Mohr-Coulomb model (MC), Hardening soil model (HS) and Hardening soil model with small strain stiffness (HSS), the results of which are compared to the diaphragm walls deformations measured during construction to assess the performance.

The deflections obtained from the Undrained (A) HSS model were found to match the measured wall deflections reasonably well, especially for the final excavation stages. Generally, the predictions of all FE models gave a narrow range within which the field data is enclosed.

This paper provides insight into the mechanism of soil-structure interaction of this deep excavation as well as into the appropriateness of the design approach, using advanced finite element analysis that was calibrated against field data.

Nomenclature

CAU	Anisotropically consolidated undrained triaxial compression and extension tests with mid-height and base pore pressure and local axial and radial strain measurement
CIU	Isotropically consolidated undrained triaxial compression and extension tests with mid-height and base pore pressure and local axial strain measurement
c_{incr}	Cohesion increase with depth
c_{ref}	Cohesion (constant)
d_{inter}	Equivalent thickness of the interface elements
DR	Departures Road
EA	Normal stiffness of the plate element
EBT	Eastbourne Terrace Road
EI	Flexural rigidity of the plate element
E_{50}^{ref}	Elastic modulus based on triaxial tests (secant stiffness) used in Hardening soil model and defined for a reference stress level
E_{inc}	Elastic modulus increasing with depth used in Mohr Coulomb soil model
E_{oed}^{ref}	Elastic modulus based on oedometer tests (tangent stiffness) used in Hardening soil model and defined for a reference stress level
E'	Elastic modulus used in Mohr Coulomb soil model and defined for a reference elevation level
E_{o}^{ref}	The initial elastic modulus at very small strain and defined for a reference elevation level
E_{ur}^{ref}	Elastic modulus for unloading and re-loading conditions used in Hardening soil model and defined for a reference stress level
FE	Finite Element
G_{o}^{ref}	Reference shear modulus at very small strain
HS	Hardening soil model
HSS	Hardening soil model with small strain stiffness
K_{0nc}	Coefficient of lateral pressure at rest for normally consolidated soils
k_x	Permeability in horizontal direction
k_y	Permeability in vertical direction
m	Value used to identify the variation of elastic modulus with depth for the Hardening soil model

MC	Mohr-Coulomb model
p_{ref}	Confined reference stress value corresponding to elastic modulus.
R_f	Percentage defining the failure asymptote for stress-strain curve
R_{inter}	Reduction factor for reducing the shear strength parameters of the soil in contact with structures.
s	Bored Pile Spacing
$T_{Strength}$	Tension stress in the material.
UUP	Unconsolidated undrained triaxial compression tests with mid-height pore pressure and local axial strain measurement
CAU	Anisotropically consolidated undrained triaxial compression and extension tests with mid-height and base pore pressure and local axial and radial strain measurement
CIU	Isotropically consolidated undrained triaxial compression and extension tests with mid-height and base pore pressure and local axial strain measurement
W	Weight
y_{ref}	Depth reference to where material (strength) parameters increases with depth for Mohr-Coulomb model
ϕ	Friction angle
σ_t	Tensile cut off
$\gamma_{0.7}$	Shear strain magnitude at $0.722G_0$
γ_{sat}	Saturated bulk density
γ_{unsat}	Unsaturated bulk density
ν	Poisson's ratio
ν_{ur}	Poisson's ratio of the material for unloading-reloading
ψ	Angle of dilatancy of the material

Introduction

The deep cut and cover Crossrail Paddington Station is constructed in one of London's most significant existing transport hubs, primarily through London Clay. The two-dimensional finite element software Plaxis 2D was used for the design, which was undertaken in accordance with Crossrail Civil Engineering Design Standards Part 3 CEDS-3[8] .

The undrained behaviour needs to be considered for London Clay. Using the software Plaxis, this behaviour can be assessed in two ways; in terms of effective and total stresses. There are three constitutive ground models commonly used for such analyses; Mohr-Coulomb model, Hardening soil model and Hardening soil model with small strain stiffness. A comparison of the results of the FE models with the measured wall deflections, derived from inclinometers located within and behind the main box diaphragm walls, can give a useful insight on the performance of the geotechnical design.

It should be noted that each of these models requires different input parameters, the influence of which on the outcome of the analysis is of interest.

The evaluation of the performance of the diaphragm wall modelling is expected to be helpful to engineers and researchers that need to perform similar analyses, allowing them to use these models with more confidence.

The Site

The Crossrail Paddington Station is the most westerly underground station of Crossrail, located directly beneath Departures Road and Eastbourne Terrace, aligned with the existing Grade I listed Paddington mainline station. The location of the new station and the constraints from the surrounding buildings, among which are the Grade 1 Mainline Station, Macmillian House and the Hilton Hotel, are presented in Figure 1.

The station is a deep cut and cover underground box structure approximately 264 m long, 24 m wide and 24 m deep, framed with 40 m long diaphragm walls of 1200 and 1000 mm thickness installed along the box perimeter down to 85.5 m ATD. The general excavation depth is around 21 m below Departures Road and 24 m below Eastbourne Terrace. A top-down construction has been adopted, using plunge columns that are connected to 1800 mm diameter and 40m long bored piles along the centreline of the box. These piles initially carry the temporary construction loads from the upper floors on the plunge columns and subsequently support the permanent columns and resist the long term uplift forces. Four permanent slabs prop the diaphragm wall panels during construction and in the permanent case. Figure 2 shows a typical cross section through the station.

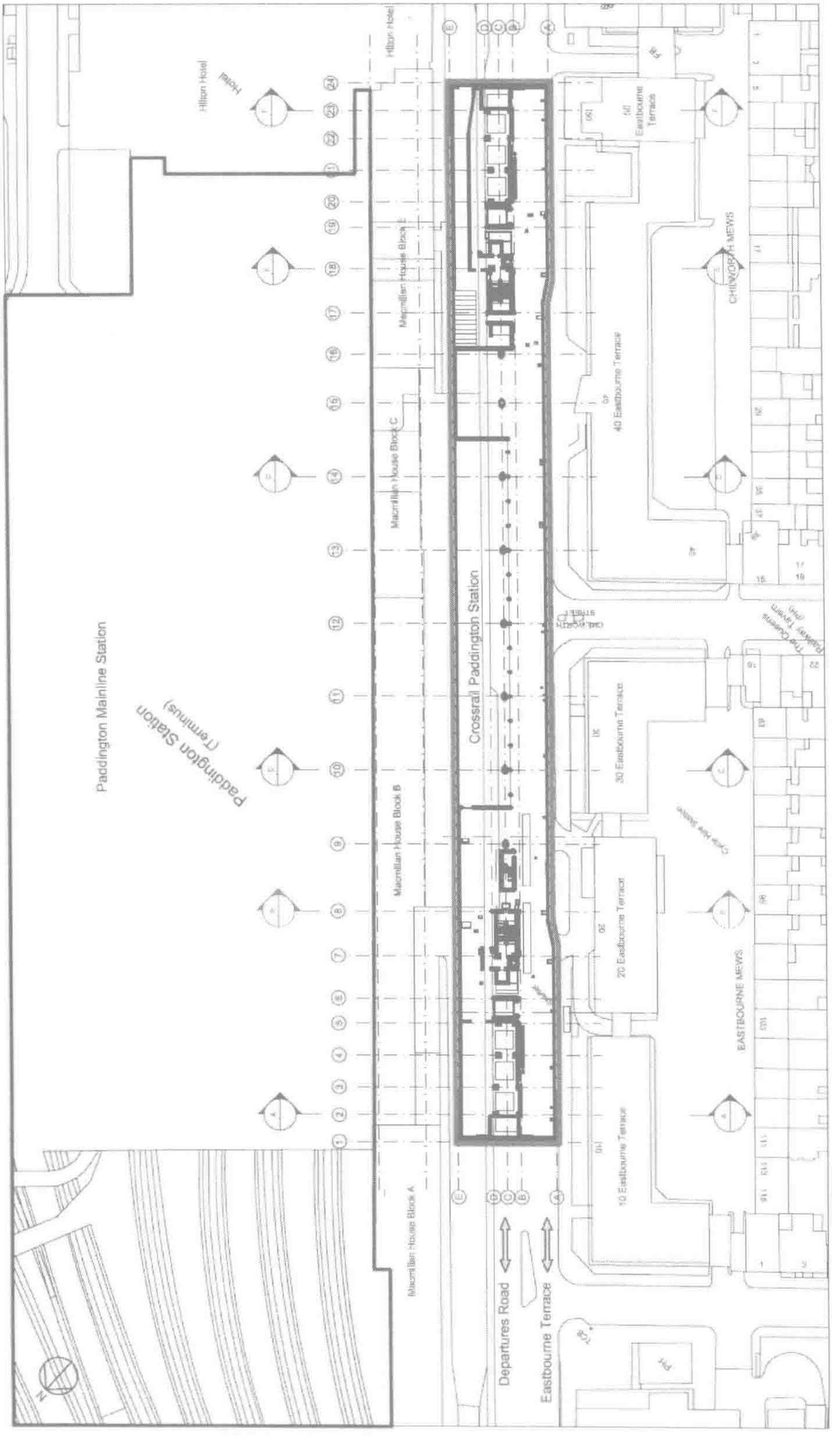

Figure 1 Location Plan view of Crossrail Paddington Station

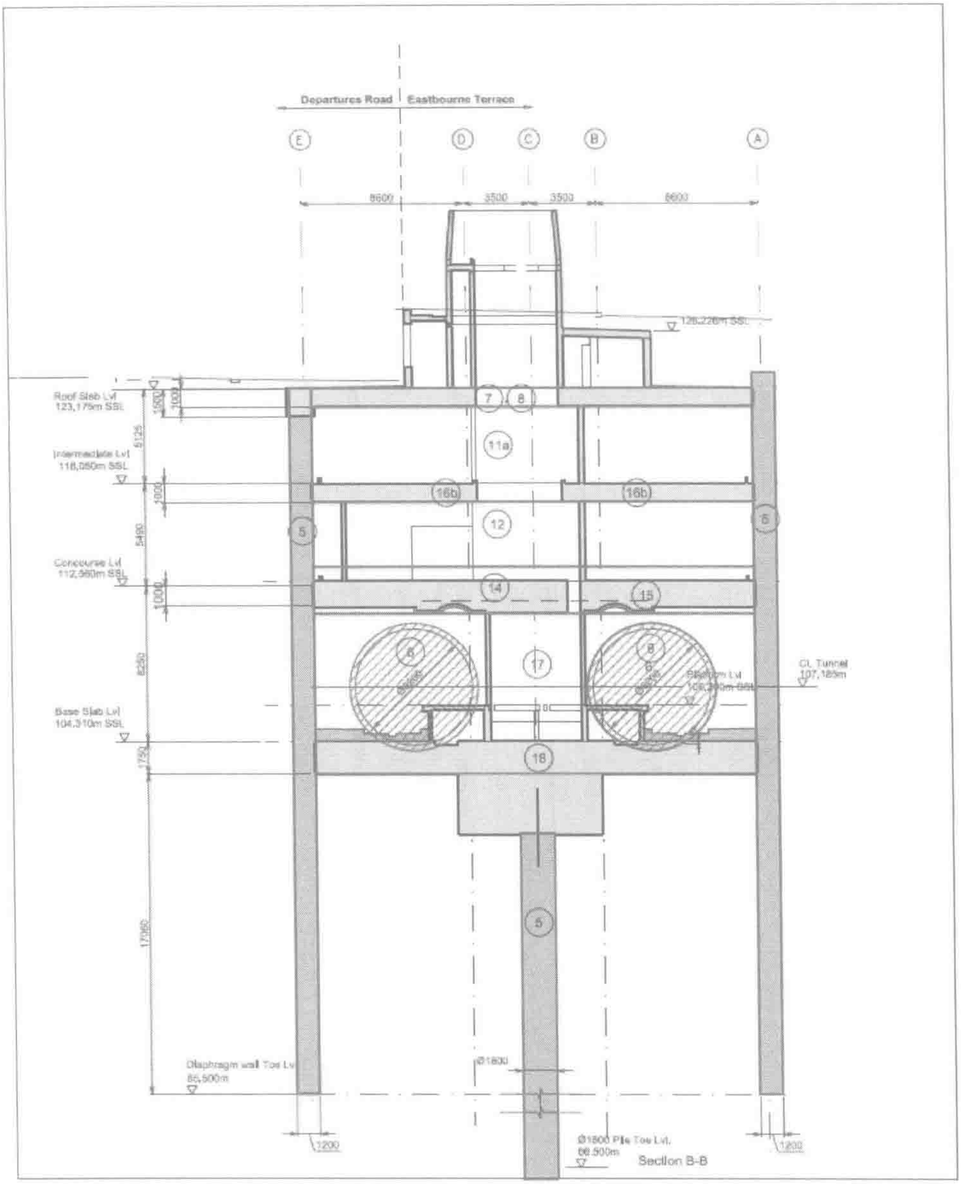

Figure 2 Typical Cross section of Paddington Station

Geological Profile
The site is underlain by Made Ground, and occasionally Langley Silt, overlying in turn by River Terrace Deposits and London Clay of significant thickness, over the Lambeth Group, followed by the Upnor Formation, Thanet Sand and Chalk. The entire Paddington Crossrail construction does not penetrate the base of the London Clay. There are two aquifers beneath the site; a shallow upper aquifer in the River Terrace Deposits and a lower deep aquifer in the Chalk, Thanet Sand and Upnor Formation.

Analysis and Results

Design Approach
Plane strain finite element analysis of the Paddington main station box has been performed using the FE package Plaxis 2D (version 9.02), with 15 node elements and medium mesh coarseness with local mesh refinement.

Due to variation in the station box layout and adjacent existing structures, six different sections have been identified for the analysis. The location of these sections, named Sections A to F, along the box is shown on Figure 1. This paper focuses solely on Section B, which is adjacent to 20 Eastbourne Terrace and MacMillan House Block B. The rigidity of both these existing structures was accounted for by modelling fixed end anchor props with high stiffness at the top of the basement levels. A typical FE model section is shown in Figure 3.

The analysis has been carried out in accordance with CEDS-3[8] for the modelling of the initial and long-term conditions, thus assuming drained conditions when simulating the initial conditions and the design life situation of the station box accordingly. For the modelling of the excavation and the construction stages of the box a different approach from the original analysis has been adopted. The original analysis was modelled with drained conditions on the active and undrained conditions on the passive side, in line with the CEDS-3. However, fully undrained conditions throughout the model have also been considered for the design analysis. A comparison between the two different approaches is discussed later.

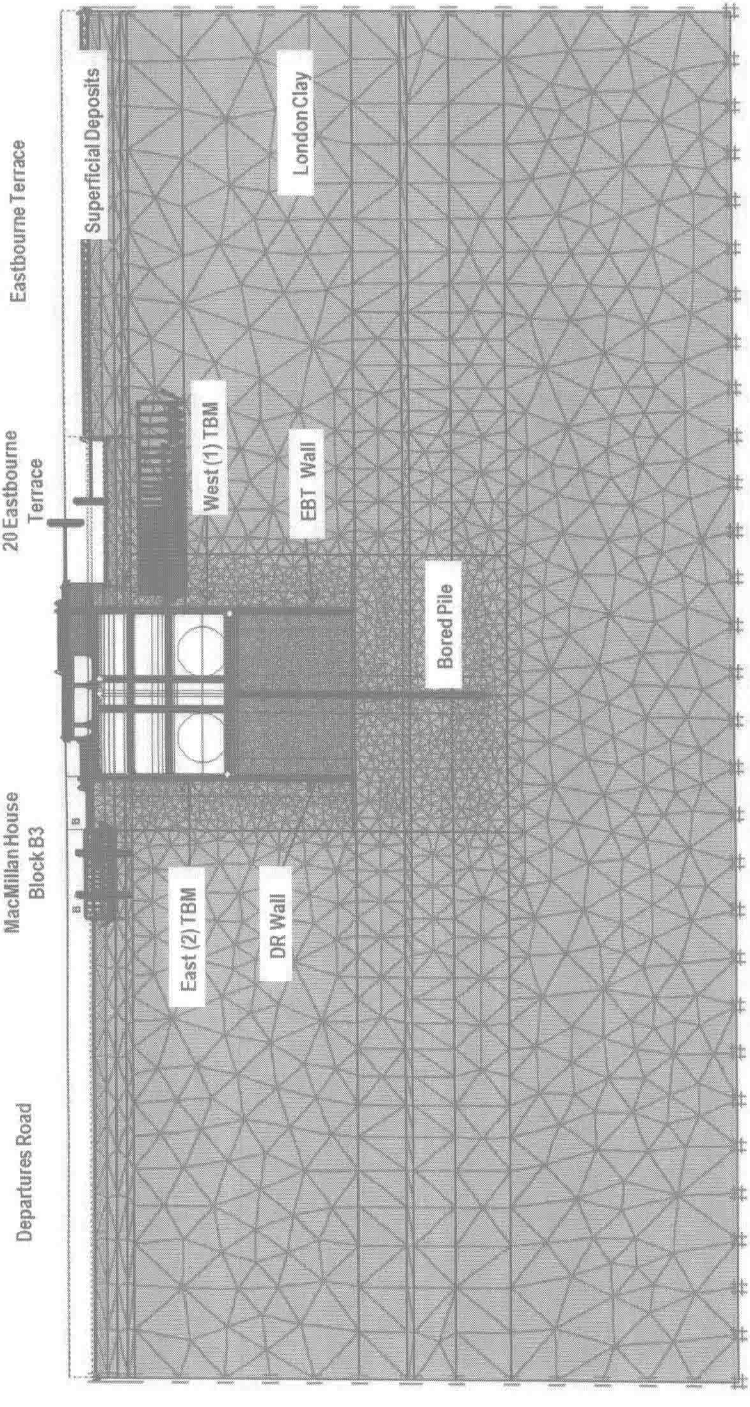

Figure 3 Typical FEA Cross section

The Ground Constituent Models

The Mohr-Coulomb, Hardening Soil and Hardening Soil with Small Strain Stiffness models can be simulated as either drained or undrained. The excavation problem is mainly influenced from the undrained behaviour of London Clay and therefore the three constitutive soil models were adopted to simulate the undrained conditions in order to evaluate their performance in predicting the wall deflections.

The soil models are merely an approximation of the real soil behaviour and thus it is important to consider their inherent assumptions and limitations when applied [3]. An example of incorrect use of the soil models is best illustrated in the Nicoll Highway collapse [9].

Mohr Coulomb model (MC)

The Mohr-Coulomb model represents a first order approximation of soil and rock behaviour, assuming the stress-strain relation to be linear elastic-perfectly plastic. The slope of the linear elastic section of the stress-strain curve is defined as the Young's modulus of soil (E'), and the perfectly plastic section is obtained when the stress states reach the Mohr-Coulomb's failure criterion.

An increase in soil stiffness with depth can be modelled. However, the model does not account for stress dependency, stress-path dependency of stiffness or anisotropic stiffness [4].

The MC model involves six input parameters ($c, \varphi, E', v, \psi, \sigma_t$). The effective friction angle (φ) for London Clay was directly obtained from laboratory tests. Effective cohesion (c) was assumed to be zero, but to aid computation in the calculations of PLAXIS, a very small value c = 1 kPa was adopted. The drained Poisson' ratio was assumed to be 0.2.

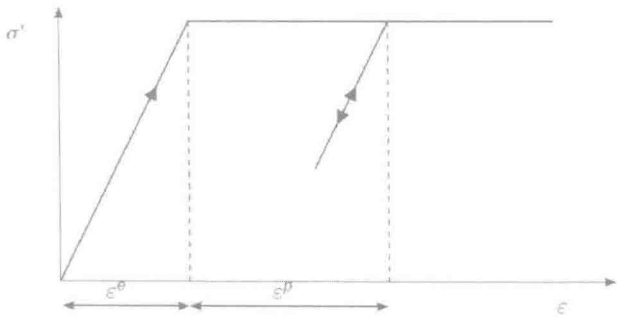

Figure 4 Mohr-Coulomb Soil Model[4]

Hardening Soil Model (HS)

The Hardening Soil model is an advanced soil model that has a hyperbolic stress-strain relationship and uses the same failure criterion as the MC model. The hyperbolic stress-strain relation between the axial strain ε_1 and deviatoric stress q for primary loading is presented in Figure 5 and defined by Equations (1) and (2) [4].

$$\varepsilon_1 = \frac{1}{2E_{50}} \frac{q}{1 - {}^{q}/_{q_a}} \tag{1}$$

$$q_a = \frac{q_f}{R_f} \tag{2}$$