Tunnelling and Underground Space Technology 74 (2018) 167–177

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Comparative study of the effects of three tunneling methods on ground movements in stiff clay

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ARTICLE INFO

Keywords:
Tunneling methods
Cavity deformations
EPB
TBM
NATM
Open-face

ABSTRACT

This paper interprets ground movements induced by tunnel construction, by comparing monitoring data with analytical and numerical predictions based on an assumed set of deformation parameters at the cavity boundary. By minimizing differences between the computed and measured ground movements, optimal cavity deformation parameters can then be used to characterize the performance of the tunneling process. We compare the performance of three tunnel construction methods in stiff clay: (i) closed-face excavation using an Earth Pressure Balance (EPB) tunnel boring machine; (ii) open-face shield excavation; and (iii) sequential construction using the New Austrian Tunneling Method (NATM). The measured data were obtained from three projects in London each involving different tunnel size and depth, but all excavated through deep units of stiff London clay. The measured performance in each case is evaluated using analytical solutions, that assume linear elastic properties for an elastic half-space, and numerical simulations that use an effective stress soil model, MIT-S1, with input parameters calibrated to elemental behavior of the London Clay. Although the numerical analyses achieve better agreement with the measured data, the analytical solutions perform well and could be used in future studies. The results indicate that the closed-face tunneling provided the best control of volume loss, while open-face shield excavation caused the largest ovalization of the tunnel cavity. The proposed methodology offers a practical framework for cataloging and comparing tunnel performance in future projects.

1. Introduction

Construction-induced ground movements and their effects on overlying structures often represent a key constraint in the selection of urban tunneling methods. These projects usually impose strict limits of allowable ground movements, and include instrumentation along the tunnel alignment to monitor ground and structure displacements. Choosing the appropriate tunneling method depends on the project timeline, expected excavation process and control of the allowable ground displacements.

Tunnel-induced ground displacements can be interpreted by empirical relations, analytical, or numerical solutions. Based on empirical methods (Peck, 1969), the ground volume loss caused by tunneling ($\Delta V_L/V_0$) is usually related to a transversal surface settlement trough corresponding to a Gaussian distribution (Fig. 1a). The centerline settlement, u_y^0, and inflection point, x_i, are fitted to measured data (e.g. Mair and Taylor, 1997). For undrained conditions in low permeability soils, the surface ground volume loss is equal to the volume of ground moving into the tunnel cavity. Analytical solutions (Whittle and Sagaseta, 2003; Pinto and Whittle, 2014) relate the surface and subsurface ground displacements for a linear elastic half-space to two independent tunnel cavity shape modes, the uniform convergence (u_ε) and the distortion (u_δ), and a third dependent parameter, the uniform vertical translation, (Δu_y) (Fig. 1b). Δu_y is dependent on both the convergence and ovalization modes in the analytical solutions to compensate parasitic vertical displacements generated by the superposition method assumed in the analytical solutions. However, Δu_y is an independent parameter when considering non-linear deformation properties (as done in the current paper for the numerical analyses). It should be noted that in practice these three parameters are difficult to measure in the field and are rarely reported.

The volume loss, ΔV_L is uniquely defined by the uniform convergence component, as $\Delta V_L = -2u_\varepsilon/\pi r$ (where r is the tunnel radius). The analytical solutions provide a complete framework for describing the far-field ground displacements, but do not represent non-linear or inelastic properties of the soil mass in the near field (close to tunnel cavity) or effects associated with finite depths of deformable soil. These limitations can be addressed by using numerical analyses using a 2D finite element model with a non-linear elasto-plastic soil model that is

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https://doi.org/10.1016/j.tust.2018.01.005
Received 20 March 2017; Received in revised form 2 January 2018; Accepted 5 January 2018

Nomenclature

List of symbols

c'	soil cohesion
C_b	small strain stiffness of the soil (dimensionless)
e_0	in situ void ratio of the soil
E'_v	vertical effective stiffness of the soil
E_u	undrained stiffness of the soil
H	depth of the tunnel axis
k_v	vertical permeability of the soil
K_0	coefficient of lateral stress at rest
$K_{0,NC}$	coefficient of lateral stress at rest corresponding to the K_0-LCC regime
m	parameter describing slenderness of the bounding surface
n	number of ground displacement data points
p	parameter describing change of bounding surface shape as a function of current void ratio
p'_{ref}	reference effective stress at unity void ratio
p_α	atmospheric pressure
r	tunnel radius
u_y	vertical free-field ground displacement
u_y^o	maximum vertical free-field ground displacement
u_ε	uniform convergence of the tunnel cavity
u_δ	ovalization of the tunnel cavity
V_o	initial volume of the tunnel cavity per unit length
x_i	horizontal distance to the inflection point in the free-field settlement trough
y	depth of interest in the ground
γ	soil unit weight
ΔV_L	volume Loss at the tunnel cavity
Δu_y	uniform vertical translation of the tunnel
θ	parameter describing transitional regime from OC to NC soils
ν'	Poisson's ratio
ρ	relative distortion at the tunnel cavity $= -u_\delta/u_\varepsilon$
ρ_c	soil compressibility in the LCC regime
φ'	soil friction angle
φ'_{cs}	critical state friction angle of the soil
φ'_{mr}	maximum friction angle of the soil
ψ	rate of evolution of anisotropy for MIT-S1 soil model
ω	parameter describing variable Poisson's ratio
ω_s	parameter controlling small strain non-linearity in shear

calibrated to the local soil conditions (Ieronymaki et al., 2016). The tunnel deformations are simulated using the three cavity deformation modes (Fig. 1b), but considering the translation mode, Δu_y as an independent parameter. Best estimates of the cavity deformations modes are then obtained through an optimization process using monitored ground deformation data.

This paper compares measured greenfield ground movements (i.e. field without the presence of any other structures) with tunnel cavity deformations (from analytical and numerical analyses) from three reported case studies in London Clay: (i) closed-face EPB construction of a 6.8 m diameter Crossrail tunnel (C300; Ieronymaki et al., 2016); (ii) the open-face shield construction of a 4.85 m tunnel for the Jubilee Line Extension (JLE; Nyren, 1998) and (iii) sequential excavation (i.e., NATM) construction of ~9 m diameter trial tunnel for the Heathrow Express (HEX, Deane and Bassett, 1995). Although the three cases involve tunnels of different diameters and depths they all have been excavated within the stiff London Clay, at sites with similar soil stratigraphy, and include data from well-instrumented greenfield test sections. Given the low permeability of London Clay, undrained conditions are assumed despite the different drainage boundaries of the three types of construction.

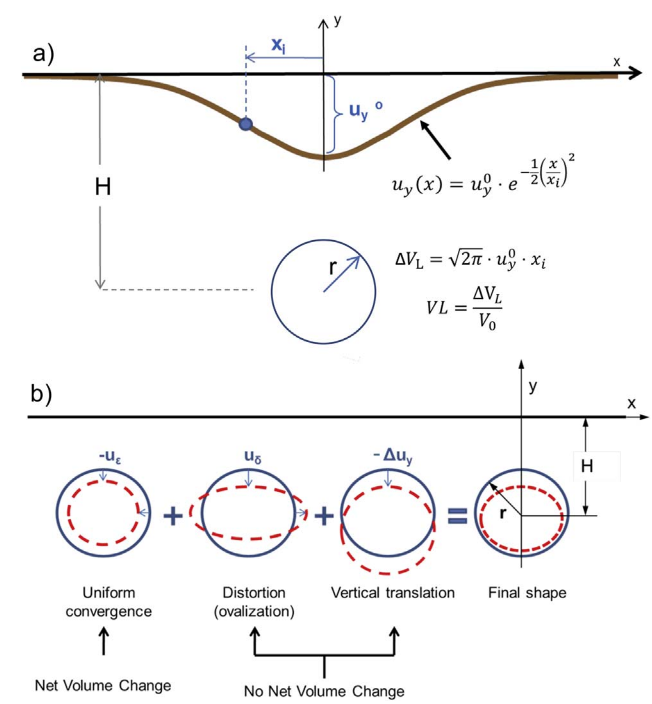

Fig. 1. Interpretation of ground movements; (a) by empirical methods (after Peck, 1969), (b) deformation modes around tunnel cavity (after Whittle and Sagaseta, 2003).

2. Site characteristics

2.1. Crossrail tunnel

Crossrail contract C300 consists of the construction of twin 6.8 m outside diameter (OD) tunnels from the western portal at Royal Oak portal eastwards to Farrington station. The tunnels were bored using Earth Pressure Balance (EPB) machines (with 7.1 m diameter cutterhead). Greenfield data were gathered as the tunnels advanced beneath Hyde Park (Fig. 2). Surface vertical and horizontal displacements were measured at several sections, using Precise Leveling Points (PLPs) and geodetic prisms, that measure the displacement vector (vertical and two orthogonal horizontal displacement components). Subsurface deformation data were obtained from extensometers and inclinometers at one section (F in Fig. 2; Ieronymaki et al., 2016).

The current paper focuses on the first bore for the Westbound (WB)

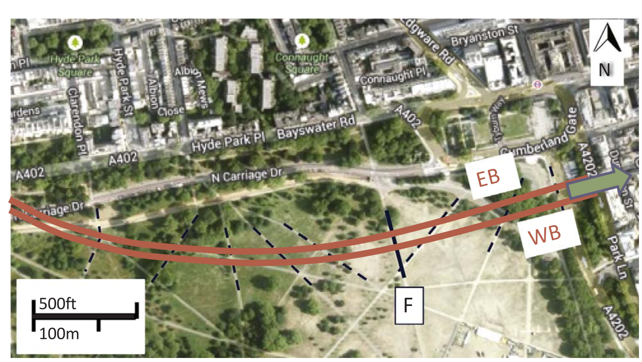

Fig. 2. Alignment of Crossrail tunnels beneath Hyde Park and location of Section F with surface and subsurface instrumentation (aerial photo courtesy of Google maps).