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Building response to tunnelling[☆]

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Abstract

Understanding how buildings respond to tunnelling-induced ground movements is an area of great importance for urban tunnelling projects, particularly for risk management. In this paper, observations of building response to tunnelling, from both centrifuge modelling and a field study in Bologna, are used to identify mechanisms governing the soil–structure interaction. Centrifuge modelling was carried out on an 8-m-diameter beam centrifuge at Cambridge University, with buildings being modelled as highly simplified elastic and inelastic beams of varying stiffness and geometry. The Bologna case study presents the response of two different buildings to the construction of a sprayed concrete lining (SCL) tunnel, 12 m in diameter, with jet grouting and face reinforcement.

In both studies, a comparison of the building settlement and horizontal displacement profiles, with the greenfield ground movements, enables the soil structure interaction to be quantified. Encouraging agreement between the modification to the greenfield settlement profile, displayed by the buildings, and estimates made from existing predictive tools is observed. Similarly, both studies indicate that the horizontal strains, induced in the buildings, are typically at least an order of magnitude smaller than the greenfield values. This is consistent with observations in the literature. The potential modification to the settlement distortions is shown to have significant implications on the estimated level of damage. Potential issues for infrastructures connected to buildings, arising from the embedment of rigid buildings into the soil, are also highlighted.

Keywords: Soil–structure interaction; Tunnels; Building response; Centrifuge modeling; Case history; Settlements

1. Introduction

While relatively accurate predictions of the 'greenfield' ground movements due to tunnelling, in both vertical and horizontal planes, can be made (Mair and Taylor, 1997), the presence of a structure may alter these movements by what is termed 'soil–structure interaction'. The estimation of the risk of damage to buildings, however, typically involves assuming that the structure deforms according to the greenfield ground movements, i.e., fully flexibly, and ignoring the stiffness of the building (e.g., Mair et al., 1996). Estimates of the damage using this assumption can be highly conservative.

[☆] Geotechnical classification categories: E12 Soil–structure interaction. H05 Tunnels and underground openings.

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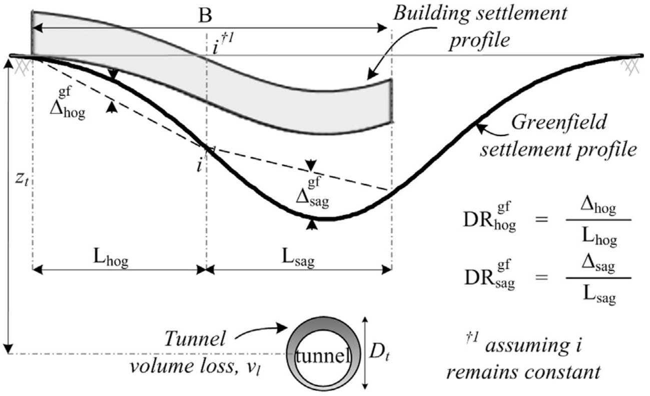

Fig. 1. Influence of soil–structure interaction on settlement distortions Aerial view of site and tunnelling works.

Potts and Addenbrooke (1997) conducted a parametric finite element analysis to investigate the response of buildings to tunnelling. Two parameters were defined to characterise the modification to the settlement and the axial response of buildings; they were the relative bending stiffness (ρ^*) and the relative axial stiffness (α^*). ρ^* and α^* were later modified by Franzius et al. (2006), the former to be dimensionless. Expressions for ρ^*_{mod} and α^*_{mod}, defined by Franzius et al. (2006), are presented in Eqs. 1 and 2, respectively.

$$\rho^*_{\mathrm{mod}} = \frac{EI}{E_s B^2 z_0 L} \tag{1}$$

$$\alpha^*_{\mathrm{mod}} = \frac{EA}{E_s BL} \tag{2}$$

where EI and EA are the bending stiffness and the axial stiffness of the structure, respectively. E_s is the secant stiffness of the soil at an axial strain of 0.01% and at a depth of $z=z_0/2$. B is the building width and L is the length parallel to the tunnel heading. The dimensions are illustrated in Fig. 1.

Settlement distortions to buildings are typically measured in both hogging and sagging modes of deformation using the deflection ratio (Δ/L or DR, defined in Fig. 1). The hogging and sagging regions are partitioned by the point of inflexion (i) of the settlement trough, assuming that each building responds fully flexibly. Potts and Addenbrooke (1997) quantified the modification to settlement distortions in terms of the ratio of the measured deflection ratio to the equivalent greenfield value, as presented in Eq. (3). This ratio is given the term 'modification factor' (M^{DRhog} and M^{DRsag}).

$$M^{DR} = \frac{DR^{str}}{DR^{GF}} \tag{3}$$

where DR^{GF} is the greenfield deflection ratio and DR^{str} is the deflection ratio displayed by the building; both are defined separately in hogging and sagging.

Modification factors to the greenfield settlement distortions are highly dependent on ρ^*_{mod} (Franzius et al., 2006). Similarly, the modification to tensile and compressive horizontal strains, in the hogging and sagging regions, respectively, are highly dependent on α^*_{mod} (Franzius et al., 2006).

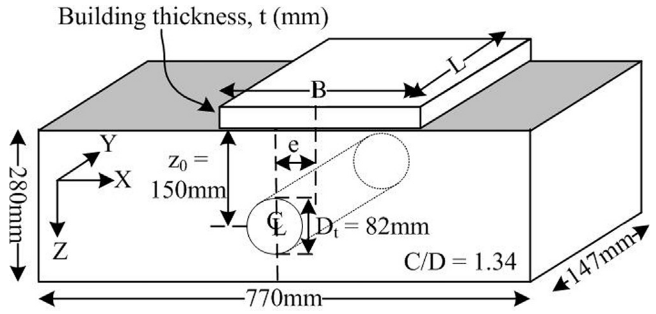

Fig. 2. Model dimensions (in model scale).

This paper presents the results of a series of centrifuge tests in which idealised model buildings in the form of beam structures, of varying stiffness and geometry, are subjected to tunnelling-induced ground movements. Mechanisms governing the effects of the soil–structure interaction are identified and compared with observations from a case study of a tunnelling project in Bologna, in which the response of two buildings, of significantly different stiffness, were extensively monitored. Based on these observations, methods commonly used to assess the risk of damage to buildings from tunnelling are discussed.

2. Centrifuge modelling

The following section presents the results from the centrifuge modelling of the building response to tunnelling.

2.1. Experimental setup

A series of centrifuge tests was carried out on the 8-m-diameter centrifuge at the University of Cambridge to investigate the response of buildings to tunnelling in sand. Centrifuge tests were carried out under plane strain conditions at 75*g* (Farrell, 2011). Using common scaling laws (Taylor, 1995), the model was designed to represent a tunnel with a diameter (D) of 6.15 m with a cover (C) of 8.25 m (at prototype scale), in fraction E silica sand. The model dimensions are shown in Fig. 2.

Sand was poured into the model to a relative density of 90% using an automatic sand pourer which enabled a high level of repeatability between tests. The model tunnel was formed using a brass mandrill with an outer latex rubber lining. The resulting annulus between the two was filled with water until an 82-mm-diameter cylinder was obtained. This model tunnel was then placed in a recess in the front Perspex face and the back aluminium plate to achieve plane strain conditions. During the test, volume losses were imposed by withdrawing the fluid from the tunnel using a piston and motor driven actuator system. Soil and building displacements at the Perspex face of the model were measured at incremental volume losses of 0.1%, using particle image velocimetry (PIV) (White et al., 2003). Physical displacement measurement instruments were also utilised to validate the PIV readings. Similar modelling techniques have been adopted by Taylor and