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# A simplified elastic analysis of tunnel-piled structure interaction

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ABSTRACT

In urban areas, engineers often need to assess tunnelling-induced displacements of piled structures and the resulting potential for damage. This paper presents an elastic study of tunnel-pile-structure interaction through Winkler-based Two-Stage Analysis Methods (TSAMs), focusing on structural displacements resulting from tunnel excavation beneath piled frames or simple equivalent beams. Comparison of results with 3D finite element analyses shows that the simple TSAM models are able to provide a good assessment of tunnelling-induced building displacements. Parametric analyses highlight the role of tunnel-pile interaction and the superstructure (stiffness, configuration, and pile-structure connections) in the global response of the tunnel-soil-building system. In particular, the effect that key parameters have on deflection ratios and horizontal strains are investigated. Results illustrate how piled foundations increase the risk of structural damage compared to shallow foundations, whereas structural stiffness can reduce building deformations. Flexural deformations are predominately induced by tunnel excavations beneath piles whereas horizontal strains at the ground level are negligible when a continuous foundation is included. Furthermore, it is illustrated that results based on buildings modelled as equivalent beams can differ considerably compared to when they are modelled as framed structures. Simple design charts are provided to estimate horizontal strains and deflection ratio modification factors based on newly defined relative axial and bending stiffness parameters which account for the presence of the piles.

## 1. Introduction

In urban areas, the increasing demand for infrastructure and development of services has resulted in tunnel construction and deep excavations taking place in close proximity to buried infrastructure and building foundations. To avoid possible damage to structures, engineers need to be able to accurately assess excavation-induced deformations of the buildings. However, although various studies have considered the effect of excavations on either a building with shallow foundations or piles connected by a rigid cap, the understanding of how the tunnel-pile interaction affects the response of buildings is still not well understood.

Various studies have considered the case of tunnel construction beneath buildings with shallow foundations. It has been recognised that the building stiffness should be taken into account in the assessment of tunnel-structure interaction since it generally tends to decrease the structural distortions and risk of damage with respect to the greenfield case (Franzius et al., 2006; Dimmock and Mair, 2008; Maleki et al., 2011; Farrell et al., 2014; Giardina et al., 2015). On the other hand, the tunnel-single pile and pile group interaction problems have been widely analysed using field trials, physical modelling, and numerical simulations, leading to some confidence in the assessment of pile group displacements (Jacobsz et al., 2004; Kaalberg et al., 2005; Selemetas, 2005; Devriendt and Williamson, 2011; Marshall and Mair, 2011; Dias and Bezuijen, 2015), internal forces (Kitiyodom et al., 2005; Huang et al., 2009; Ng et al., 2012; Soomro et al., 2015), and pile failure due to tunnel excavation (Marshall and Haji, 2015). However, as indicated by Mair and Williamson (2014), studies have focused predominately on tunnelling adjacent to piles, for which the induced building distortions are expected to be minimal. In these cases, tunnelling mainly causes lateral bending in piles rather than settlements along the pile axis. In contrast, tunnelling beneath piles induces vertical pile movements, which leads to structural deformations. Moreover, it is important to note that only

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a few studies have considered the effects of structural configuration on building deformations induced by excavations. Goh and Mair (2014) highlighted the importance of structural configuration in the global interaction based on an extensive set of numerical analyses which evaluated the response of framed buildings to deep excavations. Fargnoli et al. (2015) suggested that the use of an equivalent plate and beam model for the superstructure may lead to an erroneous evaluation of the structural response to tunnelling-induced movements. The work of Losacco et al. (2014) suggested that, in order to obtain satisfactory results, more advanced simplified structural models of the building, rather than a simple beam/-plate, could be incorporated into the global interaction analysis.

In a preliminary risk assessment of building damage caused by tunnelling, it is important to be able to predict, with reasonable simplicity and reliability, the induced structural deformations. However, for tunnelling beneath buildings on piled foundations, there is a limited amount of information and guidance available to inform such a risk assessment. In practice, engineers typically evaluate the tunnelling-induced deformations empirically, assuming that pile heads settle according to a subsurface greenfield settlement profile. The depth of the selected settlement trough is usually taken at some distance between the surface and the pile tip in order to account for the piles being dragged down by subsurface soil movements (Devriendt and Williamson, 2011). For tunnels, several relationships between surface greenfield soil displacements and pile head settlements have been proposed depending on pile tip position. For instance, Kaalberg et al. (2005) and Selemetas (2005) suggested three zones where pile head settlements may be larger than (zone A), equal to (zone B) or smaller than (zone C) the greenfield surface settlements (see Fig. 1). These also agree qualitatively with results obtained by other researchers who used centrifuge testing to study the problem (Jacobsz et al., 2004; Marshall and Mair, 2011).

However, despite the general agreement, a comparison of previous studies carried out by Dias and Bezuijen (2015) demonstrated that the relationship between pile head and greenfield surface settlements is not a unique function of the relative tunnel-pile tip position; it also depends on working loads, tunnel volume loss, and distribution of working load between pile base and shaft. As shown in Fig. 2, Dias and Bezuijen (2015) indicated that the regions A-B-C defining the relative pile/surface settlements do not capture the full complexity of the problem. The authors suggested an upper limit of the normalised pile head settlement depending on the normalised horizontal pile offset to the tunnel centreline. However, use of this upper limit would lead to an over-conservative assessment of tunnelling-induced deformation in piled buildings.

The previous studies indicate that piles with their tips directly above the tunnel (i.e. within a horizontal offset of one tunnel radius from the tunnel axis) are likely to settle more than the surface, whereas piles outside this area generally settle less than the surface. This causes a narrowing of the pile head settlement profile with respect to the greenfield surface settlement trough, leading to an increased potential for building damage. Moreover, assessing tunnelling-induced deformations in buildings using a tunnel-pile interaction analysis (i.e. assuming that the building follows the settlement curve obtained from a tunnel-pile or tunnel-pile group analysis) does not allow inclusion of the influence of the building on the global interaction; this may be overly conservative in the cases of relatively stiff structures, as illustrated by a case study reported by Goh and Mair (2014).

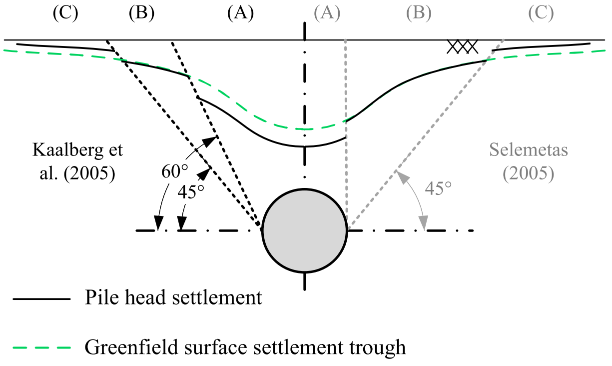

**Fig. 1.** Proposed relationships between pile head and greenfield surface settlements depending on pile tip location.

In the first part of this paper, the complete tunnel-pile-structure interaction is investigated through a Winkler-based Two-Stage Analysis Method (TSAM), focusing on structural displacements that result from the tunnel excavation. Since displacements are damage related quantities, their prediction can be used to evaluate building serviceability state. The TSAM method is able to capture the main interaction mechanisms and the effects of structural configuration on the global response of the system to tunnelling. In the second part of the paper, effects of structure stiffness on the building deformations, both axial and flexural, are investigated, with emphasis on the role played by the piled foundations. Two simple design charts for evaluating the piled building deflection ratios and horizontal strains are proposed.

## 2. Background

### 2.1. Two-stage analysis method (TSAM)

Soil-structure interaction systems are characteristically complex due to the effects of interfaces, soil non-linearity, and plasticity. However, despite this, simplified elastic methods are common in structural and geotechnical engineering. In particular, many useful tools for tunnel-pile interaction analysis have been developed using the elastic framework. These are based on a two-stage procedure: (1) the greenfield soil displacements caused by tunnel excavation are estimated analytically, through closed-form expressions (Loganathan and Poulos, 1998; González and Sagaseta, 2001; Franza and Marshall, 2015), or numerically using software based on the finite element (FE) or finite difference (FD) methods; (2) the analysis of the full system, including soil, foundation and superstructure, is carried out considering the foundation subjected to a system of external loads that would, in the absence of the included structure, reproduce the greenfield soil movements.

Two-staged analyses of tunnel-pile interaction problems have incorporated continuum or Winkler-based analyses in order to study tunnel-single pile and tunnel-pile group interactions. Chen et al. (1999) and Loganathan et al. (2001) used a boundary element method (BEM) to analyse pile groups. Basile (2014) extended previous works to include the non-linear soil behaviour within the BEM. The main conclusion of previous works is that the group effect is beneficial, resulting in a reduction of foundation displacements and internal pile forces compared to isolated piles. Moreover, the work of Basile (2014) indicated that soil non-linearity leads to a remarkable reduction of axial forces within the piles. Kitiyodom et al. (2005) and Huang et al. (2009) considered a beam on a Winkler elastic foundation to study the problem of tunnel-pile group interaction, confirming the beneficial effects of pile-soil-pile interaction. Zhang et al. (2011a,b) and Zhang et al. (2013) improved the soil model to account for soil nonlinearities and pile-soil interface characteristics in order to assess the influence of working loads. It was shown that existing working loads have an influence on the pile-tunnel interaction; the increase of pile working loads results in an increase of excavation-induced pile