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Elastic analysis of tunnelling beneath capped pile groups

Analyse élastique d'un tunnellement en dessous de groupes de pieux sous semelle

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ABSTRACT: The response of pile groups to ground movements caused by tunnelling has received little attention by researchers for cases involving capped pile groups and tunnel-pile clashes. In this paper, tunnel-pile group interaction (TPGI) is studied using a linear elastic continuum-based finite element model. In the analysis, piles are modelled as Euler-Bernoulli beams that are either constrained by an elevated cap or have a free-head condition; the soil is modelled as an elastic continuum. In the first part of the paper, two pile groups with a 2 x 2 and a 3 x 3 configuration, respectively, are considered for both the cases of tunnelling adjacent to and beneath the piles. The displacements and internal forces of the piles are evaluated, as well as the foundation response in terms of cap movement for varying tunnel-pile group horizontal offset. The effects of increasing the tunnel depth on the TPGI are also evaluated. In the second part of the paper, the impact of tunnel-pile clash on pile settlements and post-tunnelling forces along the trimmed piles is studied for varying cap stiffness. It is shown that the outcomes of the proposed model compare well with more rigorous numerical analyses, hence suggesting the viability of the model as a reliable preliminary design tool.

RÉSUMÉ: Les chercheurs ont peu attiré l'attention sur les réactions des groupes de pieux aux mouvements du sol causés par les tunnels, notamment dans les cas impliquant des groupes de pieux avec semelle et des pénétrations pieux-tunnel. Dans cet article, l'interaction TPGI (tunnel - groupe de pieux) est étudiée à l'aide d'un modèle éléments finis linéaire et élastique. Dans cet analyse, les pieux sont modélisés comme des poutres d'Euler-Bernoulli qui sont soit contraintes par un plafond surélevé, soit ont un état de tête libre; le sol est modélisé comme un continuum élastique. Dans la première partie du document, deux groupes de pieux de configuration 2 x 2 et 3 x 3, respectivement, sont pris en compte dans les cas de creusement de tunnels adjacents et sous les pieux. Les déplacements et les forces internes des pieux sont évalués, ainsi que la réponse de la fondation en termes de mouvement de la semelle pour différentes excentricités horizontales entre les groupes de pieux et le tunnel. Les effets de l'augmentation de la profondeur du tunnel sur le TPGI sont également évalués. Dans la deuxième partie du document, l'impact de la pénétration pieu-tunnel sur les tassements de pieux et les forces post-tunneling le long des pieux taillés sont étudiés en fonction de la rigidité de la semelle. Il est montré que les résultats du modèle proposé se comparent bien avec des analyses numériques plus rigoureuses, ce qui confirme la fiabilité du modèle en tant qu'outil de conception préliminaire.

Keywords: Tunnelling; pile group, tunnel-pile clash, soil-structure-interaction.

1 INTRODUCTION

There is an increasing demand for tunnelling in urban areas that leads to underground excavations and tunnelling in close proximity to existing deep foundations. This can result in the deformation and damage to the foundation, the superstructure, or both (Dias & Bezuijen 2015, Jacobsz et al. 2004).

Recent works have highlighted that there is potential for pile differential settlements and, thus, for superstructure damage when tunnelling beneath piles (i.e. tunnel axis below the pile tip level) (Franza & Marshall 2018, Franza & Marshall 2019, Soomro et al 2015, Soomro et al. 2017, Williamson et al. 2017). On the other hand, pile response to tunnel excavation is mostly characterised by pile deflection for the scenario of tunnelling adjacent to pile groups (i.e. tunnel axis above the pile tip level) (Basile 2014, Loganathan et al. 2001). Notably, there is a lack of preliminary design tools that consider a tunnel-pile clash scenario (Dubasaru et al. 2015), a phenomenon that is occurring with increased frequency in practice (among others, Geilen & Taylor 2001) and that can have a significant impact on a structure.

This paper presents a continuum-based Finite Element Method (FEM) model for the linear elastic analysis of the response of a capped pile group to excavation-induced ground movements. In particular, the case of tunnel construction is considered to highlight [i] the effect of varying the tunnel-pile group relative location and [ii] the impact of a tunnel-pile clash.

2 PROPOSED MODEL

For tunnelling, two-stage analysis methods (TSAMs) are common in structural and geotechnical engineering for both piles (Basile 2014, Franza et al. 2017, Loganathan et al. 2001) and shallow foundations (Deck & Singh 2012, Elkayam & Klar 2018). For preliminary risk assessments relating to deep foundations, linear elastic soil models can be used for a quick evaluation of the soil-structure interaction and its effects on the structure (Franza et al. 2017, Loganathan et al. 2001, Mu et al. 2012). However, refined models accounting for non-linear or inelastic soil-pile load transfer mechanisms might be needed for more accurate predictions that consider the complex aspects of the soil behaviour (e.g. Basile 2014, Zhang et al. 2013). Despite the risks associated with tunnelling beneath piles, most research using TSAMs has focused on the scenario of tunnelling adjacent to pile groups (Basile 2014, Loganathan et al. 2001, Mu et al. 2012) whereas, to the authors' knowledge, TSAMs have not been used to deal with tunnelling beneath capped pile groups.

In this paper, a linear elastic soil model is used to investigate the scenarios of tunnelling near to a capped pile group and a tunnel-pile clash. Future work by the authors will deal with non-linear load transfer mechanisms.

The applied TSAM consists of the following steps. For tunnelling near to a pile group: (0) the external loads due to the superstructure are applied at the pile heads and/or the cap; then, the foundation-soil system is solved to obtain the pre-tunnelling pile internal forces; (1) the greenfield soil displacements caused by tunnelling are estimated using empirical methods, semi-analytical solutions, or numerical analyses; (2) the analysis of the full system, including soil and foundation (capped pile group), subjected to a system of external loads (that would result in the soil movements estimated from step (1) in the absence of the structure) is carried out in order to evaluate the tunnelling-induced effects. For a tunnel-pile clash: steps (0) and (1) are as detailed above but there are some changes in step (2); in step (2.1), to obtain the capped pile group stiffness matrix, the finite elements corresponding to the trimmed portion of the pile are deactivated; in step (2.2), the foundation-soil system with the trimmed pile is subjected to the system of forces equivalent to tunnelling. Finally, for both cases, the post-tunnelling foundation conditions are evaluated by superposing the displacements and internal forces obtained from stages (0) and (2).

2.1 Greenfield ground movements

In this paper, the semi-analytical formulas proposed by Loganathan and Poulos (1998) were adopted in step (1) to evaluate tunnelling-induced vertical and horizontal greenfield soil displacements. Importantly, the use of these formulas allows for comparison with previous works.

2.2 Finite element method

The numerical solution used the FEM, solving the following system of equations given by Kitiyodom et al. (2005):

$$\left(\mathbf{C} + \mathbf{K}_\mathrm{c} + \mathbf{K}_\mathrm{p}\right)\mathbf{u}_\mathrm{p} = \mathbf{f} \tag{1}$$

where $\mathbf{C}$ is the soil stiffness matrix obtained by integrating Mindlin (1936) solutions for vertical and lateral forces applied within an elastic homogeneous half-space, $\mathbf{K}_\mathrm{c}$ is the stiffness matrix of the flexible pile cap, $\mathbf{K}_\mathrm{p}$ is the stiffness matrix of the pile group consisting of Euler-Bernoulli elastic beams, and $\mathbf{u}_\mathrm{p}$ is the tunnelling-induced displacement vector of the piled foundation. $\mathbf{f} = \mathbf{C}\,\mathbf{s}$ represents the external force vector acting on the piles due to the vector $\mathbf{s}$ of the vertical and lateral tunnelling-induced greenfield movements.

In the case of a rigid cap connected to the pile head, the equilibrium equation was written as

$$\mathbf{A}^\mathrm{T}\left(\mathbf{C} + \mathbf{K}_\mathrm{c} + \mathbf{K}_\mathrm{p}\right)\mathbf{A}\tilde{\mathbf{u}}_\mathrm{p} = \mathbf{A}^\mathrm{T}\mathbf{f} \tag{2}$$

$$\mathbf{u}_\mathrm{p} = \mathbf{A}\tilde{\mathbf{u}}_\mathrm{p} \tag{3}$$

where $\mathbf{A}$ is the geometric matrix of the rigid constraint and $\tilde{\mathbf{u}}_\mathrm{p}$ is the displacement vector that includes the rigid cap displacements and the displacements of the pile nodes not connected to the cap (i.e. embedded into the ground).

3 RESULTS FOR TUNNELLING NEAR TO CAPPED PILE GROUPS

3.1 Pile displacements and internal forces

In this section, the response of pile groups to tunnelling is analysed considering tunnelling-induced displacements and forces (i.e. results from step (2)). Two deep foundations are considered consisting of 2x2 and 3x3 vertical pile groups with a length L_p of 25m and connected to a rigid and elevated cap; these cases were previously chosen by Loganathan et al. (2001) and Basile (2014). Two tunnel depths z_t of 20 and 30m are used to compare the effects of tunnelling adjacent to and beneath the pile group, respectively. The considered TPGI scenarios are summarised in Figure 1, which illustrates the geometrical and elastic parameters of the problem as well as the labels used for the piles. In this paper, positive axial forces are tensile.

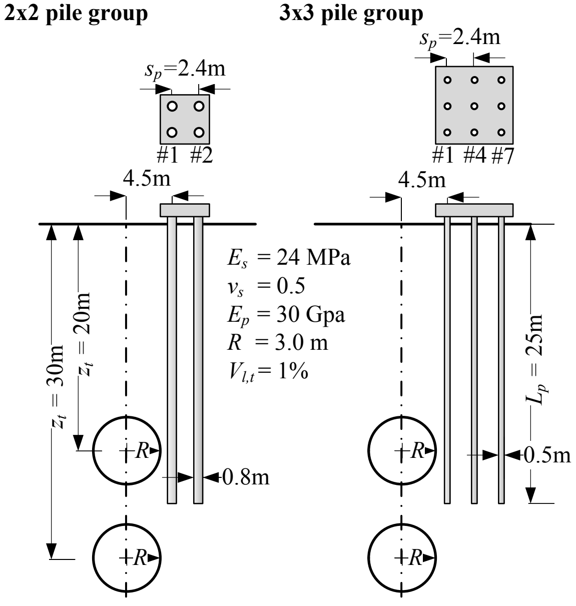

Figure 1. Scenario considered for tunnelling near to capped pile groups.

Tunnelling-induced displacements and forces are displayed in Figure 2 and Figure 3 for the

2x2 and 3x3 pile groups, respectively. For the case of tunnelling adjacent to the piles, the developed FEM model is validated against the results obtained using the Boundary Element Method (BEM) by Loganathan et al. (2001) and Basile (2014), who used the computer programs GEPAN and PRGROUP, respectively. Lines are used for the proposed FEM model results while BEM data are plotted with markers. Note that only internal force data were provided by Basile (2014) for the 3x3 pile group.

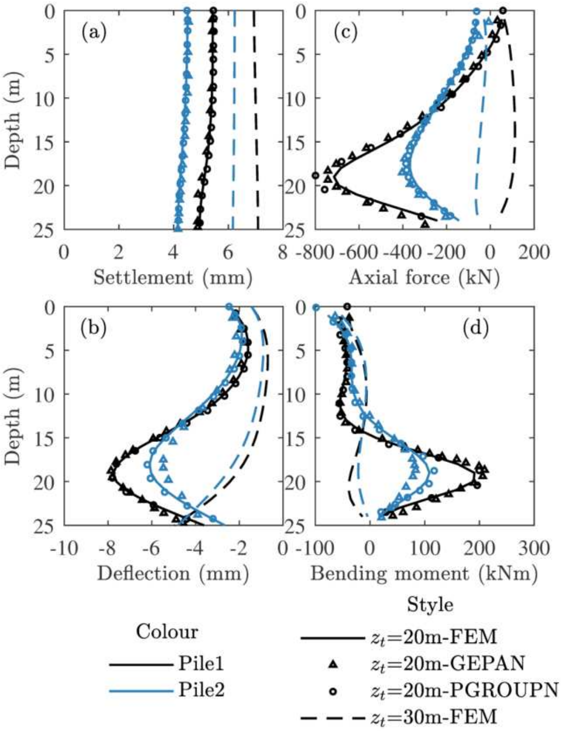

Figure 2. Tunnelling near to the 2x2 pile group.

Figure 2 illustrates a good match between the FEM and BEM results, particularly with respect to the Basile (2014) outcomes near to the pile cap. This good agreement is confirmed also for the 3x3 group in Figure 3.

The effect of increasing tunnel depth is also considered in Figures 2 and 3 (compare solid and dashed lines). The tunnelling-induced pile deflections and their associated bending moments are significantly decreased when tunnel depth z_t increases from 20 to 30m. This confirms previous work that indicated the potential for pile bending is minor when tunnelling beneath piles (e.g. Soomro et al. 2017). On the other hand, pile settlements at the cap and along the pile shaft increased with increasing tunnel depth, while the magnitude of the pile axial force is lower for the deeper tunnel. However, tunnelling-induced tensile forces were induced along the entire pile close to the tunnel for tunnelling beneath the pile group, while tensile axial forces were induced only at the rigid cap for a tunnel adjacent to the pile group.

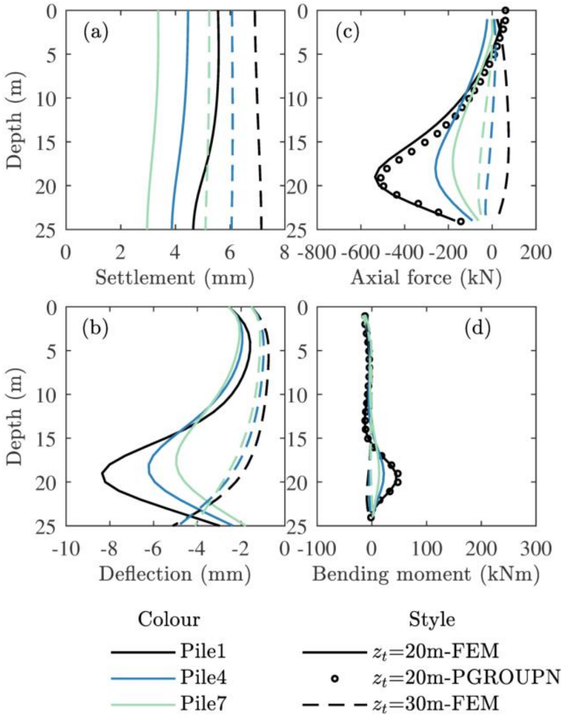

Figure 3. Tunnelling near to the 3x3 pile group.

3.2 Displacements of the rigid cap

When estimating the effects of tunnelling on pile foundations, the pile head and cap displacements are of interest to assess the impact on the superstructure. As a first approximation, by neglecting the superstructure-pile-soil interaction, the cap displacement due to tunnelling can be imposed at the superstructure base to evaluate the deformations and additional forces due to tunnelling. Alternatively, the substructure approach could be used by replacing the foundation with interactive springs and the tunnelling effects as an equivalent system of forces.

Loganathan et al. (2001) suggested that, for design purposes, the tunnelling-induced bending movements and axial forces within a pile group could be estimated by analysing the tunnel-single pile interactions. This approach, however, is not fully viable for the displacements of the cap. Therefore, in this section, the cap displacements due to tunnelling are considered for both tunnelling beneath and adjacent to the capped pile group.

The 2x2 pile group shown in Figure 1 was analysed by varying the horizontal offset *x* of the cap centre from the tunnel centreline. Results are displayed in Figure 4 for tunnel depths z_t =20 and 30m.

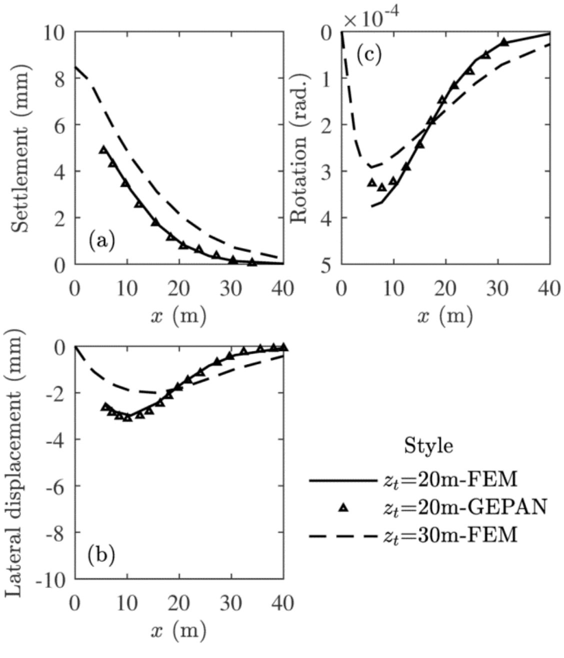

Figure 4. Displacement of the cap for the 2x2 pile group.

Firstly, the data shows that the FEM predictions agree with the simulations obtained by Loganathan et al. (2001) using GEPAN for z_t = 20m. Secondly, the comparison between the trends for z_t = 20 and 30m indicate that the increase in tunnel depth: (i) had a marginal influence on the cap lateral displacement, (ii) decreased the maximum rotations obtained for the lower values of tunnel-pile group offset (i.e. *x* lower than 15m), and (iii) resulted in a slight rise of the foundation settlement. Finally, note that, in the considered scenarios, the tunnel-pile group interaction is affected by counteracting mechanisms associated with increasing the tunnel depth z_t: although tunnelling beneath piles is associated with greater potential for settlements than tunnelling adjacent to them, the increase in z_t results in smaller greenfield movements impacting the given foundation. Therefore, TPGI analyses are needed in the preliminary design stage for an effective design.

4 RESULTS FOR TUNNEL-CAPPED PILE GROUP CLASH

In this section, the capability of the continuum-based model to provide preliminary predictions of pile settlements and internal forces resulting from a tunnel-pile clash are evaluated by comparing its results with those from 2D hydro-mechanical analyses performed by Dubasaru et al. (2015), who used the Imperial College Finite Element Program. In particular, the efficiency of reinforcing the pile group by increasing the stiffness/thickness of the cap as a mitigation measure was investigated.

Dubasaru et al. (2015) carried out plane-strain FEM parametric analyses for a typical scenario in London. The stratigraphy, capped pile group and tunnel excavation scenario are displayed in Figure 5. The scenario consisted of a 5m diameter tunnel constructed centrally below a piled raft. The piles were placed in transverse rows of 3 piles with a spacing of 6m in both the longitudinal and transverse directions.

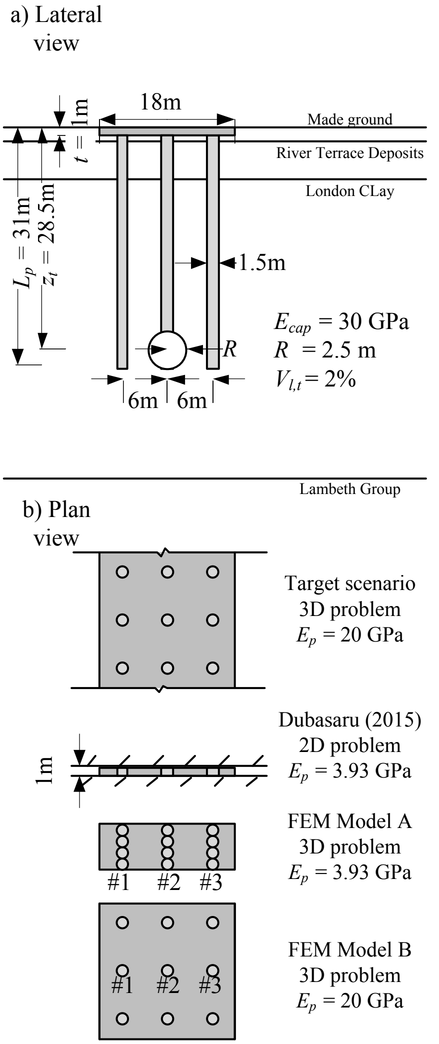

Figure 5. Scenario considered for tunnel-capped pile group clash.

In this work, the short-term foundation response to tunnelling at the end of the tunnel construction was considered. In the continuum solution, the soil was assumed as a uniform half-space with an average undrained soil modulus of E_s=200MPa and ν_s=0.5, while a design tunnel volume loss of $V_{l,t}$ = 2% was considered. At the pile head, both the conditions of a fully flexible cap (i.e. free pile heads), a semi-flexible cap with a thickness t = 1m, and a rigid cap were simulated. Despite some uncertainties regarding the boundary conditions of the refined 2D model, external vertical forces P = 8.6MN were imposed at each pile head. Finally, in the continuum-based FEM model, it was assumed that the cap was elevated (i.e. not in contact with the soil), which is a reasonable assumption considering the presence of made ground at the surface.

It is important to consider that, to model the considered piled raft in plane-strain conditions, Dubasaru et al. (2015) had to model the piles as infinitely long walls with a thickness equal to the pile diameter and a modified Young's modulus that allowed them to match the pile axial stiffness $EA=E\pi D_p^2/4$. This results in a degree of approximation. On the other hand, in the continuum-based solution, a 3D model of the foundation was adopted consisting of a 3x3 pile group (see Model B in Figure 5). In future works, the modelling of plane-strain conditions will be addressed by spacing the transverse rows at a longitudinal spacing equal to the pile diameter (see Model A in Figure 5).

For one of the outer piles (pile 1) and the trimmed pile (pile 2), results of the tunnel-pile clash are shown in Figure 6. Tunnelling-induced settlements are reported in subplot (a), while the pre- and post-tunnelling axial forces are shown in subplots (b) and (c), in which positive axial forces are tensile.

Figure 6a shows that the stiffness of the pile cap contributed to decreasing the differential settlements between the heads of piles 1 and 2. Similarly, although the magnitude of pile forces predicted with the continuum-based 3D model (lines) and the 2D refined FEM model (markers) are different, as shown in Figures 6b and c, there is a general agreement in the obtained trend of variation of axial forces. The tunnel-pile clash resulted in large post-tunnelling tensile forces near the base of the trimmed pile. The magnitude of the tensile forces could be used to predict the onset of crack formation in the piles (particularly for unreinforced piles), hence these preliminary predictions are important. On the other hand, the lateral pile 1 increased its compressive axial force along the entire shaft.

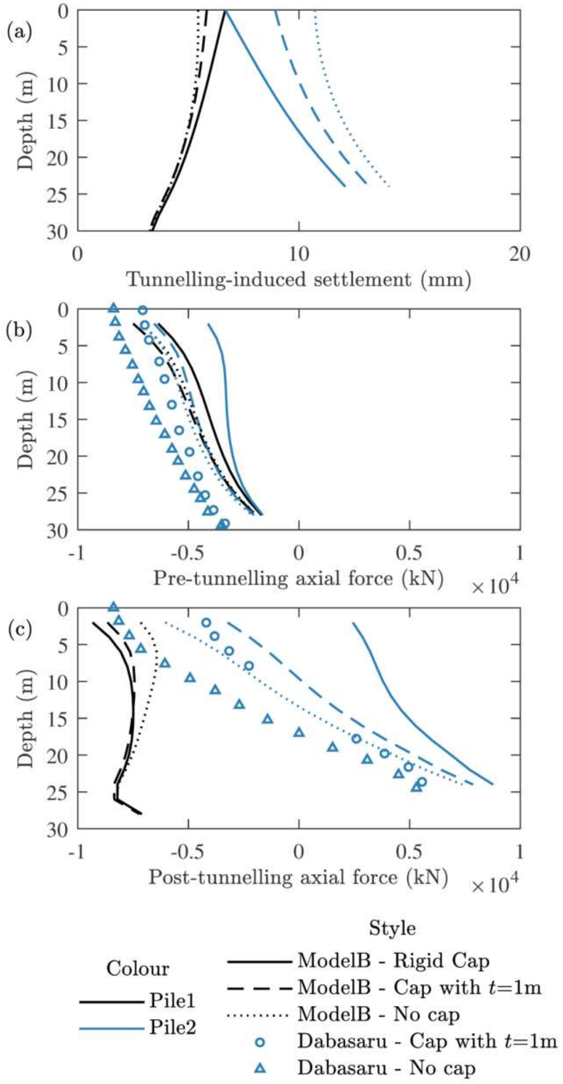

Figure 6. Tunnel-pile group clash: (a) tunnelling-induced settlements; (b) pre-tunnelling and (c) post-tunnelling axial force along the piles.

Results of the continuum-based 3D model agree with the work of Dubasaru et al. (2015) in terms of interaction mechanisms. Reinforcing a pile group with a stiff cap could contribute to decreasing the differential settlements between piles, which is a source of damage for the superstructure. On the other hand, both simplified 3D and refined 2D numerical analyses suggest that the cap stiffness has a limited effect on the tensile axial forces induced by the tunnel-pile clash near the base of the trimmed pile, however they also show that the cap contributes to increasing the tensile forces near the cap compared to the free-head condition.

5 CONCLUSIONS

This paper presented a continuum-based two-stage elastic analysis method to assess tunnelling-induced displacements and forces of capped pile groups. The following conclusions can be drawn.

This work confirmed that the bending deformations of piles are minor for tunnelling beneath piles. On the other hand, the pile settlement level is increased and the magnitude of the pile compressive axial force is reduced when the tunnel is below the base of the pile. Tensile tunnelling-induced forces were induced along the entire pile close to the tunnel only in the case of tunnelling beneath the pile group, while tunnelling-induced tensile axial force could occur due to the action of the rigid cap in both the case of tunnelling beneath and adjacent to the pile groups. For the capped pile groups analysed, the tunnelling-induced movements of the cap were found to depend on the tunnel depth through counteracting interaction mechanisms.

For a tunnel-pile clash, the proposed model can quickly provide preliminary assessments of pile differential displacements and tunnelling-induced forces while considering the cap stiffness. It was confirmed that, although the reinforcing of the pile cap could decrease the level of differential settlements between piles, tensile axial forces need to be evaluated in the trimmed pile and related to the risk for pile cracking.

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