Influence of pile raft stiffness on building behaviour in a tunnel-pile clash scenario

Influence entre raideur d’un massif sur pieux et comportement d’un bâtiment dans un scenario de collision tunnel-pieu

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ABSTRACT In a modern urban environment, the underground space becomes increasingly congested due to the high value of the land that forces the new infrastructure projects to be constructed deeper into the ground. For each new project, the potential of both expected and unexpected clashes between new tunnel alignments and the foundations of the existing structures becomes more probable. However, to date, the research on tunnel-pile clashes has been scarce. In the current study, the effects of such a situation are studied by carrying out finite element analyses for a scenario that is typical in the London ground profile. A parametric study was conducted to investigate the influence of the pile raft bending stiffness on the building settlement and the change in piles’ axial forces. It is shown that an increased raft bending stiffness helps to transfer the load from the trimmed pile to the adjacent piles, thus reducing the settlement of the trimmed pile. In the process of tunnel excavation, the pile settles due to the soil-induced downdrag and the loss of both its base and part of its shaft capacity. It is concluded that the tunnel-pile clash has a large impact on the surface structure, piles and tunnel itself.

RÉSUMÉ Dans un environnement urbain moderne, l’espace souterrain est devenu très prisé face à la montée des prix des terrains. De ce fait, les nouveaux projets d’infrastructure sont dorénavant forcés de s’installer plus en profondeur. Pour chaque nouveau projet, la probabilité de collision, attendue ou non, entre de nouveaux tunnels et les fondations de structures existantes a augmenté. Cependant, à ce jour, les études sur les collisions tunnel-pieux sont peu nombreuses. Dans cette étude, les conséquences de cette situation sont examinées au travers d’analyses par éléments finis pour un scénario qui est typique d’un profil de sol Londonien. Une étude paramétrique a été conduite pour étudier l’influence de la rigidité flexionnelle d’un massif sur pieux sur le taillage d’un bâtiment ainsi que sur le changement de forces axiales des pieux. Cette étude montre que l’augmentation de la rigidité flexionnelle du radier contribue à transférer les charges du pieu coupé vers les pieux adjacents, réduisant ainsi le taillage du pieu coupé. Lors de l’excavation du tunnel, les pieux se tissent du fait des forces d’enfoncement induites et de la perte en résistance provenant de la base du pieu coupé et d’une partie de sa surface de frottement. Nous en concluons que la collision tunnel-pieu a d’importantes conséquences sur les structures à la surface, sur les pieux et sur le tunnel lui-même.

1 INTRODUCTION

In large urban environments with congested subterranean spaces, many large infrastructure projects are currently being proposed. Due to the high value of land, the new projects are constructed deeper into the ground. This increases the potential of both expected and unexpected clashes between new and existing structures. Such clashes can have a major impact both on the new tunnel lining and on the existing structure. Several types of mitigation measures are known to have been adopted on various projects to reduce and control the effect of clashes. These can be grouped in in-tunnel and out-of-tunnel mitigation measures. The major disadvantage of the former is that their implementation causes delay in the tunnel construction, while the latter can be prepared before the tunnelling commences and can be applied independently of the underground works.

The in-tunnel mitigation measures are highly dependent on the tunnelling method. The Sprayed Concrete Lining method (SCL), being a more flexible technique than TBM or EPBM, gives the opportunity for a larger variety of mitigation measures to be im-
implemented. For instance, the pile could be isolated and fixed to the lining before cutting, or, alternatively, umbrella grouting can be adopted.

The out-of-tunnel mitigation measures were the preferred option on most projects where clashes were predicted to occur. Some of the examples include:

- Tunnelling works of the MTR Island Line tunnel in Hong Kong, where several piles of the Hua Tai Building were trimmed. This was mitigated with grouting and underpinning (GCO 1985);
- The pile foundation of the BT Building at London Bridge, London, which was causing obstructions to the Jubilee Line Extension project. The mitigation measures included underpinning and compensation grouting (Geilen & Taylor 2001);
- Construction of Boston’s Silverline, where tunnelling works were obstructed by the wooden piles of the Russia Wharf Buildings (Figure 1). It was decided to adopt underpinning, structural jacking and ground freezing to reduce and control the building movements (Williams 2003).

![Figure 1. Mitigation of tunnel-pile clash at Russia Wharf Building, Boston, USA (Williams, 2003)](image)

Despite the potentially major consequences of these clashes, research on this topic is scarce. The work presented in this paper focuses on the clash between a new tunnel alignment and an existing pile raft foundation. In particular, the efficiency of underpinning as a mitigation measure is examined through parametric numerical analyses, by increasing the thickness (and hence the bending stiffness) of the raft. The properties of the raft are important as it transfers the load from the trimmed piles to the adjacent piles.

2 FINITE ELEMENT ANALYSES

2.1 General

The problem is studied through a number of coupled hydro-mechanical 2D finite element analyses, using the Imperial College Finite Element Program (ICFEP; Potts & Zdravković, 1999), which utilises the modified Newton-Raphson nonlinear solver with an error-controlled sub-stepping stress-point algorithm.

2.2 Geometry

The assumed stratigraphy, building layout and tunnel location are presented in Figure 2. Two distinct cases were analysed, one with a free-headed pile group and the second one with a pile raft. In the latter, the pile raft is 18 m wide and has a thickness of 1 m. Moreover, the piles are spaced at 6 m, have a diameter of 1.5 m and a length of 31 m with their bases at -20 mOD. The considered tunnel has an outer diameter of 5 m and is designed to be constructed with the Sprayed Concrete Lining technique in two stages. The primary lining with a thickness of 300 mm is applied immediately after excavation while the secondary lining with a thickness of 150 mm is constructed after 6 months. The tunnel lining was assumed to be permeable and was modelled by employing a dual no flow/atmospheric pressure boundary condition on the boundary between the tunnel lining and the soil (Potts & Zdravković, 1999). The connection between the pile and the tunnel was considered to be rigid.

2.3 2D plane strain approximation and parametric study details

In plane strain, the piles are modelled as infinitely long walls; therefore the axial stiffness, EA, and the bending stiffness, EI, of the piles have to be modified to match those of the pile rows.
The primary lining with a thickness of 300 mm is applied to the top of the chalk. The considered tunnel has an outer diameter of 5 m and is designed to be constructed with the spraying technique. The lining is 1.5 m thick and is constructed in two stages. The second stage consists of a pile raft. In the latter, the pile spacing is 6 m, the diameter is 1.3 m, and the raft thickness is 1 m. The properties of the raft are important as it transfers the load from the trimmed piles to the adjacent ground. The adopted stratigraphy is typical of the London ground profile. A bulk unit weight of 20 kN/m³ was assumed for all soils and, together with the undrained pore water pressure profile presented in Figure 4, was used to establish the initial vertical effective stress in the ground. The K₀ profile in Figure 5 was adopted for the initiation of the horizontal effective stress. After establishing the initial conditions, the following construction sequence was modelled:

- Apply 929 kN/m on each pile (free-headed pile group) or construct the pile raft and apply 155 kN/m² (pile raft);
- Rest period (40 years) to present;
- Excavate tunnel;
- Install primary lining;
- 6 months rest period then install secondary lining;
- Reach long-term equilibrium conditions.

In order to maintain the initial proposed distance between the piles and the tunnel, the wall thickness was set equal to the pile diameter. Because the current study is mainly interested in the behaviour of the trimmed pile and because the process of tunnel excavation induces predominantly an axial loading in the cut pile, the axial stiffness of the pile was adopted for this approximation. A reduced Young’s modulus of 20 GPa was adopted for the piles, accounting for stiffness decrease with time. The equivalent stiffness of the pile was calculated to be 3.93 GPa using:

\[ E_{\text{pile}} \cdot \left( \frac{\pi \cdot D_{\text{pile}}^2}{4} \right) \cdot \frac{1}{S} = E_{\text{wall}} \cdot t_{\text{wall}} \]  \hspace{1cm} (1)

where \( E_{\text{pile}} \) and \( E_{\text{wall}} \) are Young’s moduli of the pile and the wall, respectively, \( D_{\text{pile}} \) is the pile diameter, \( t_{\text{wall}} \) is the wall thickness, \( S \) is the out-of-plane pile spacing. Assuming that the building is underpinned immediately before tunnelling, an unreduced Young’s modulus of 30 GPa was assumed for the 1 m thick raft. In order to keep the geometry constant, the different thicknesses of the raft, \( t_{\text{rafts}} \), were simulated by adopting a Young’s moduli, \( E_{\text{raft}}^* \) (Equation 2), that would result in the desired bending stiffness (see Table 1 for adopted values).

\[ E_{\text{raft}} \cdot \left( \frac{1}{12} \cdot t_{\text{raft}}^3 \right) = E_{\text{raft}}^* \cdot \left( \frac{1}{12} \cdot (t_{\text{raft}}^*)^3 \right) \]  \hspace{1cm} (2)

The layout of the finite element mesh used in all analyses is illustrated in Figure 3; it consists of eight-noded quadrilateral isoparametric elements. The mesh is 200 m wide and 73 m deep, extending down to the top of the chalk.

### 2.4 Soil conditions and construction sequence

The adopted stratigraphy is typical of the London ground profile. A bulk unit weight of 20 kN/m³ was assumed for all soils and, together with the undrained pore water pressure profile presented in Figure 4, was used to establish the initial vertical effective stress in the ground. The K₀ profile in Figure 5 was adopted for the initiation of the horizontal effective stress. After establishing the initial conditions, the following construction sequence was modelled:

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- 6 months rest period then install secondary lining;
- Reach long-term equilibrium conditions.
Constitutive models

The behaviour of all soil layers, with exception of Made Ground which was modelled as linear elastic, was simulated with a non-linear elasto-plastic Mohr-Coulomb model. The non-linear response of soil before yielding was modelled with a small strain stiffness model of the Jardine et al. (1986) type. The adopted soil parameters were obtained from the study performed by Zdravković et al. (2005) on deep excavations in London. The concrete of the raft, piles and tunnel was assumed to be linear elastic. In order to model more realistically the behaviour of sprayed concrete, an increasing stiffness with time was modelled, as presented in Figure 6, assuming a small stiffness of 8.2 GPa at an early age, which increases to a maximum of 30 GPa at 28 days.

3 RESULTS

3.1 Influence on pile raft settlement

During tunnel excavation and pile cutting, the pile settles due to the downdrag caused by the soil movement and the loss of both base and part of shaft capacity (Dubasaru 2013). The deformation of the pile raft at the end of tunnel excavation for different raft thicknesses is depicted in Figure 7. A comparison is made with the surface settlement trough of a free-headed pile group. It can be seen that the maximum settlement decreases in magnitude and the shape of the settlement trough becomes shallower as the raft bending stiffness increases. This means that as the EI of the raft increases, the load that is transferred from the cut pile to the adjacent piles increases as well.
ure for buildings on already thick rafts. Moreover, Figure 8 demonstrates that settlement of the raft at the end of consolidation follows the same pattern as at the end of tunnel excavation.

3.2 Influence on pile axial forces

The variations of axial force along the cut pile in a free-headed pile group and with a 1-metre thick pile raft are presented in Figures 9 and 10, respectively. In the case of the pile raft, the working load on the pile is smaller due to the central position of the pile and the presence of the raft which distributes the load to the adjacent piles. Prior to tunnel excavation, the axial force gradually reduces with depth. As the tunnelling commences, a large tensile axial force develops in the lower part of the pile, with a risk of a tension crack occurring in the concrete. Similar behaviour was reported in other studies of tunnelling below existing piles (e.g. Lee 2012).

The change in the axial force is caused by the fact that the soil close to the tunnel excavation moves towards the newly created tunnel opening, which induces a downward movement on the pile, while the upper soil resists this movement.

In the case of the pile raft, the tensile axial force is induced over a greater length of the pile than in the case of the free-headed pile group. This is due to the rigid connection between the pile and the raft, which does not allow the pile to settle as much as in the case of the free-headed pile when it is dragged downwards by the movement of the soil towards the tunnel excavation.
With the development of consolidation settlements, the tension force in the pile reduces. The tunnel acts as a shallow foundation and restricts the movement of the pile, hence reducing the tension in the lower section of the pile. It can be seen that after tunnelling, in the case of free-headed pile, the working load remains the same, whereas in the case of the pile raft the working load is being redistributed to the adjacent piles.

Figure 11 indicates that the presence of the raft induces a larger tensile axial force in the pile than in the case of the free-headed pile, both in short- and long-term conditions. Furthermore, the tensile force in the pile increases as the bending stiffness of the raft increases, since it deforms less and hence restricts the movement of the pile. As consolidation occurs, the tensile axial force in the pile reduces.

As the bending stiffness of the pile raft increases, the axial compressive force in the trimmed pile after tunnel excavation reduces (Figure 12). The difference between the force before and after tunnelling gives an indication of the extent of the load transfer from the trimmed pile to the adjacent piles. Furthermore, for stiffer rafts, the working load that is being transferred to the adjacent piles is larger.

4 CONCLUSIONS

In this paper, the influence of the pile raft thickness on the behaviour of the existing surface structure, when one of its piles is cut as a consequence of a tunnel-pile clash, was studied. It was shown that the presence of the raft helps to transfer the load from the trimmed pile to the adjacent piles, reducing the settlement of the cut pile. The maximum settlement decreases in magnitude as the raft thickness, and hence its bending stiffness, increases.

During the tunnel excavation, the pile settles due to the loss of both its base and part of its shaft capacity. The downward movement of the soil towards the newly created tunnel opening induces large axial tensile forces on the lower section of the pile. In the case of the pile raft, due to the rigid connection between the pile and the raft, this tensile axial force is induced over a greater length of the pile than in the case of the free-headed pile group. After tunnelling, the compressive axial force in the upper section of the pile decreases as the bending stiffness of the raft increases. Increasing the bending stiffness of the raft was proven to be an efficient mitigation measure to reduce the differential settlement and hence the damage of the surface structure.

This study would benefit from validation against a monitored case study, in which the building and piles would be instrumented. The latter could be monitored by means of fibre optics installed in the cored, and subsequently grouted, pile. This would allow the strain of the pile to be measured, which can then be used to determine the change in pile axial force during tunnelling. Subsequently, the case study could be back-analysed with 3D analyses, which would model more accurately the tunnel-pile interaction.

REFERENCES

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