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Assessing tunnel-structure interaction effects in London Clay

Évaluant les effets de l'interaction structure-tunnel dans l'argile de Londres

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ABSTRACT: In the context of tunnelling in urban areas, the serviceability of existing infrastructure must be guaranteed when these structures are subjected to tunnelling activities in their vicinity. Tunnel construction inevitably causes movements in the tunnel surroundings. It can also lead to potentially differential settlements of existing buildings with associated serviceability problems. To prevent such problems, the accurate prediction of tunnelling-induced building settlements becomes essential. In this paper, the case study of the construction of the Elizabeth line beneath a site in Whitechapel, London, is simulated using 2D finite element (FE) analysis. The investigation considers first the analysis of greenfield conditions, for which field measurements are available. The numerical results are shown to be in very good agreement with field measurements which validates the adopted soil models. The second part of the study involves the analysis of tunnelling beneath a building, where the influence of the building and the characteristics of its foundations on the shape of the settlement trough is evaluated.

RÉSUMÉ: Dans le contexte du creusement de tunnels en zones urbaines, la fonctionnalité des infrastructures existantes doit être garantie lorsque ces structures sont soumises à des activités de tunnelisation. La construction de tunnels provoque inévitablement des mouvements dans les environs du tunnel, comme des tassements différentiels des bâtiments existants avec des problèmes de fonctionnalité associés. Pour prévenir ces problèmes, la prédiction précise des tassements des bâtiments dus à la tunnelisation devient essentielle. Dans cet article, la construction de la ligne Elizabeth sous le site de Whitechapel, Londres, est simulée à l'aide d'une analyse par éléments finis en 2D. Cet article commence par l'analyse des conditions de terrain vierge. Les résultats numériques sont en très bon accord avec les mesures sur le terrain, ce qui valide les modèles de sol adoptés ainsi que leur calibration. La deuxième partie de l'étude concerne l'analyse de la tunnelisation sous le bâtiment, où l'influence du bâtiment et des fondations sur pieux sur la forme de la cuvette de tassement est évaluée.

Keywords: Tunnelling; finite element analysis; tunnel-structure interaction; piled raft foundations; London Clay.

1 INTRODUCTION

Space overuse has been a worrying issue in big cities. Therefore, due to space limitations, new developments have made greater use of underground space. One concern impeding underground construction is that this may cause potential effects on the surrounding superstructures. In London, tunnel excavation and its influence on neighbouring structures has been a widely researched topic.

Tunnelling can cause ground loss which leads to surface settlement, which affects the structures above. Many studies have been carried out to predict the influence of tunnel excavation on existing superstructures (Potts and Addenbrooke, 1997; Franzius et al., 2004). However, existing studies regarding tunnel-structure interaction mostly assume buildings or foundations sitting on ground surface, overlooking more complicated deep foundations, which could change the building response.

This paper is based on a case study, using greenfield data to validate the numerical model, then explores influence of tunnelling on the building with piled raft foundation using 2D Finite Element (FE) analysis.

2 FINITE ELEMENT ANALYSIS

2.1 Geometry

The chosen case study is the construction of the Elizabeth Line, west of Whitechapel underground station in East London. This site consists of Vallance Road Gardens and a building nearby supported by a piled raft foundation along Castlemain Street, which offers adequate field data for both greenfield and superstructure existing conditions to validate the analysis results and study tunnel-structure interaction.

The ground profile found at this site is recognized to be typical London geology, with Made Ground being the top layer of 4.2 m thickness, followed by River Terrace Gravel (3.3 m thick), London Clay (36.4 m thick), Lambeth Group Clay (5.9 m thick) and

Lambeth Group Sand (4 m thick). They are underlaid with the Thanet Sands Formation, which is 11.5 m thick, with the Chalk bedrock set as the bottom boundary of the FE model (Chong, 2015).

The building modelled in this analysis is a 3-storey structure found nearby Vallance Road Gardens which is 86 m long, 10 m wide and 10.5 m high. It is sitting on a piled raft foundation, which is assumed to consist of a 1.5 m thick foundation slab and 20m long piles, spaced 4 m apart and with a diameter of 0.5 m.

The two vertical boundries of the model are set to be normally fixed and impermeable. The bottom horizontal boundry is set to be fully fixed and the top horizontal boundry is free to deform in any directions. Both are set to be permeable.

2.2 Soil properties and initial stresses

Made Ground is modelled as a linear elastic-perfectly plastic material with a Mohr-Coulomb failure criterion, a Young's modulus of $E = 10$ MPa, a Poisson's ratio of 0.25 and a friction angle of 25°. The other strata are modelled using a perfectly plastic Mohr-Coulomb yield surface combined with an isotropic small-strain stiffness model to describe their elastic response (Taborda et al., 2023a, 2023b). The soil model parameters were adopted from Gawecka et al. (2017) and are listed below in Table 1 and Table 2.

The initial vertical total stress is prescribed by the saturated unit weight of the soil ($\gamma = 19$ kN/m^3 for Made Ground and $\gamma = 20$ kN/m^3 for the remaining materials). The coefficient of earth pressure K_0 is taken as 0.5 for the Made Ground and River Terrace Gravel. For London Clay, K_0 is equal to 1.5 for the top 10 m, 1.25 for the next 10 m and 1 for the remainder and all the other layers below London Clay, a variation which is based on the profile described in Schroeder (2003).

The initial effective stress is also affected by the pore water pressure distribution. This site has a perched aquifer above the London Clay, with the water table found to be 4.2 m below ground level, and a bottom aquifer in the Thanet Sands with the pressure head at 40 m below ground level, as indicated in Environmental Agency (2010). All clay layers are considered as undrained materials and the following nonlinear anisotropic variation of permeability with depth is adopted (Taborda et al., 2023c):

$$log_{10}k_y = a(y - y_{LC}) + b \quad (1)$$

$$k_y > k_{y,min} \quad (2)$$

$$k_x = 2 \cdot k_y \quad (3)$$

where y_{LC} is the value of the coordinate y at the top of London Clay; k_x and k_y are permeabilities along directions x and y, respectively; $k_{y,min}$ is the minimum permeability along direction y; a and b are model parameters, here assumed to take the values of 0.0215 and -4.5259, respectively. This variation of permeability matches that adopted in Avgerinos (2014) who calibrated it based on data reported for Heathrow Terminal 5 by Hight et al. (2007).

2.3 Modelling of tunnel

There are three major tunnels passing through this site, which are the Running Tunnel East (RTE), Crossover tunnel and the Tunnel Boring Machine tunnel. The first two are Sprayed Concrete Lining (SCL) tunnels. The axes of these three tunnels are all set to be 25.9 m below the ground surface around this area. For simplicity, only the RTE tunnel is considered, as it was excavated first. The construction sequence consists of a pilot tunnel (6.2 m diameter, 250 mm lining thickness), which is then enlarged to obtain the final diameter (9.12 m, 350 mm lining thickness). The RTE tunnel lining was simulated with the plate element, adopting a Young's modulus of 30 GPa and a Poisson's ratio of 0.15. The unit weight of shotcrete was taken as 24 kN/m^3.

3 GREENFIELD CASE

A 2D plane-strain FE model is set up in PLAXIS 2D based on the Vallance Road Gardens area to simulate the tunnelling effect without the influence of buildings above. The tunnelling process is simulated using the volume loss method, where the unloading level associated with tunnel excavation is varied until the desired volume loss is obtained. The ground surface settlements obtained in the analysis are presented in Figure 1 along with the field data (Chong, 2015).

The maximum settlement obtained for the pilot tunnel is 14.9 mm, which is slightly bigger than the field data (12.4 mm). An excellent match is obtained for the remainder of the settlement trough. For the enlargement tunnel, the numerical model yielded a maximum settlement of 29.7 mm, which is very close to the field measurements (30.4 mm). The very good agreement between field data and numerical results validates the adopted modelling approach.

Table 1. Mohr-Coulomb strength properties adopted (Gawecka et al., 2017).

Material	Angle of shearing resistance ϕ (^{0})	Cohesion c (kPa)	Dilatancy angle ψ (^{0})
River Terrace Gravel	35	0	17.5
London Clay	25	5	12.5
Lambeth Group Clay	27	25	13.5
Lambeth Group Sand	34	0	17
Thanet Sands	40	0	20

Table 2. Small-strain stiffness properties adopted assuming $p'_{ref} = 100\ kPa$ *(Gawecka et al., 2017).*

Material	G_{ref} (kPa)	m_G	a	b	$R_{G,min}$	G_{min} (kPa)
River Terrace Gravel	41939.61	1.0	0.000145	1.00	0.03511	3000
London Clay	51743.55	1.0	0.000056	0.90	0.06450	2667
Lambeth Group Clay	51924.52	1.0	0.000110	0.95	0.04662	2667
Lambeth Group Sand	81346.31	1.0	0.000015	1.00	0.14557	1000
Thanet Sands	65275.23	1.0	0.000046	0.85	0.02631	2000
Material	K_{ref} **(kPa)**	m_K	r	s	$R_{K,min}$	K_{min} **(kPa)**
River Terrace Gravel	49843.08	1.0	0.000247	1.25	0.15440	3000
London Clay	26692.73	1.0	0.000127	1.80	0.13275	5000
Lambeth Group Clay	61331.71	1.0	0.000065	1.40	0.07589	5000
Lambeth Group Sand	49843.08	1.0	0.000026	0.90	0.08377	5000
Thanet Sands	29813.53	1.0	0.000155	1.10	0.27947	5000

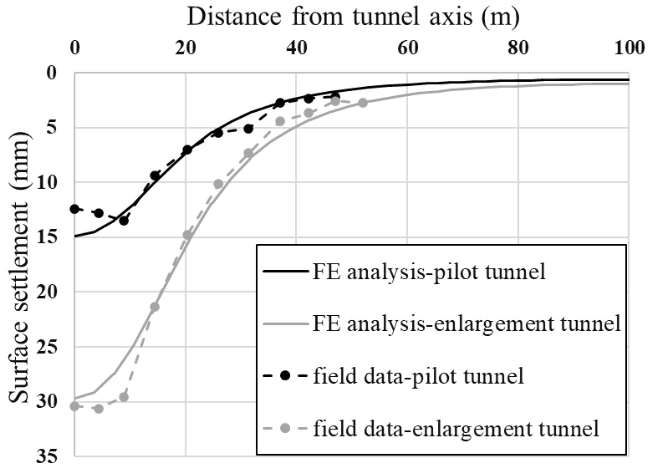

Figure 1. Comparison of 2D FE analysis results with field data (Chong, 2015).

4 TUNNEL-STRUCTURE INTERACTION

The tunnels at this site were excavated after the construction of the building along the Castlemain Street. In the numerical model, once building construction is complete, the ground is set to consolidate under the building load for 14 years before tunnel construction. The construction sequence of the RTE tunnel includes excavation of pilot tunnel, pilot tunnel lining construction, excavation of enlargement tunnel and enlargement tunnel lining construction.

Three different scenarios are considered herein to study the influence of piles and the building stiffness on the surface settlement. The first case analysed consists of a simplified model containing only the foundation slab and building load (i.e. the influence of piles is disregarded). Subsequently, two more analyses are carried out, introducing first the pile foundations and then the building stiffness.

In these analyses, the concrete foundation slab is modelled with solid elements, adopting a Young's modulus of 30 GPa for concrete. The building stiffness is added using additional plate elements in PLAXIS2D, with the stiffness corresponding to the 3-storey building: the Young's modulus E is taken as 30 GPa, while the second moment of area I is calculated using the parallel axis theorem assuming the neutral axis is located at mid-height of the building (Franzius et al., 2004). The equivalent cross section area A of the plate is the sum of the cross-sectional area of the three slabs. The piles are modelled with plate elements, correcting for pile spacing in the out of plane direction, adopting a Young's modulus of 30 GPa.

The results obtained for the three analyses are shown in Figure 2 in terms of surface settlement troughs, using the same unloading values as in the greenfield model, since the same tunnelling technology was employed. Piles are shown to have a rather significant influence on the ground surface settlement trough due to tunnelling. The maximum settlement of the piled raft foundation at tunnel axis after enlargement is approximately 1.3 times larger than that obtained when having only the raft foundation. However, it is also clear that a much narrower trough is obtained when the presence of piles is considered, leading to larger differential settlements and distortions. These differences are perhaps caused by the transmission of loads to greater depths when including pile foundations, as well as effects associated with the bending sriffness of the piles.

After adding building stiffness, the shape of settlement trough is significantly shallower and wider than either of the two previous cases, suggesting that neglecting this important factor would be overly conservative when assessing the impact of tunnelling on the building.

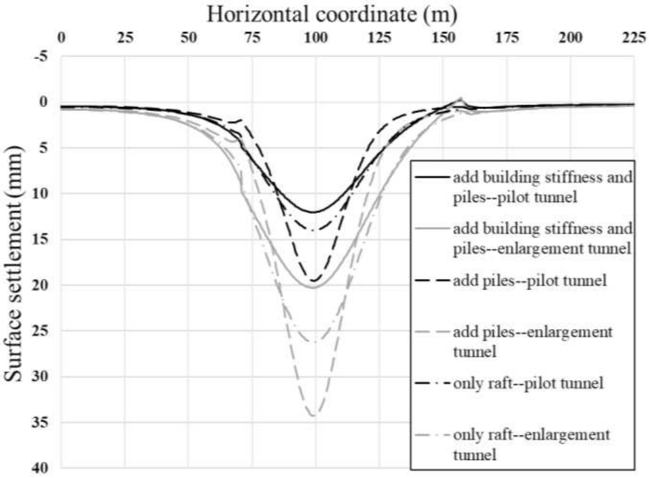

Figure 2. Influence of building stiffness on settlement trough.

5 CONCLUSIONS

The present paper investigates the effect of tunnelling works on surrounding buildings. To this end, plane-strain Finite Element analyses are carried out based on a typical London site. A greenfield analysis is performed first to validate the adopted soil models and a good agreement with field measurements is reached. Subsequently, a tunnel-building interaction study is conducted, characterising the influence of the presence of piles and that of the building stiffness on the settlement trough. The obtained results show that the piled raft foundation has a different response to tunnelling, leading to a deeper and narrower settlement trough when compared to the case where only a raft is considered. Furthermore, the inclusion of the building stiffness has a significant impact on the deformations associated with tunnelling, leading to shallower and wider settlement troughs.

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