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Tunnelling Beneath Piled Structures (Based on Mohr–Coulomb criterion)

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Abstract

This paper investigates the interaction between tunnelling in soft soil and adjacent piled structure. Several three-dimensional finite element analyses are performed to study the deformation of pile caps and piles during the construction of a nearby tunnel. The comparison between free field analyses with those of coupled analyses is also presented. To simulate the tunnelling process and its effects on piled structures, one symmetric half of the soil medium, the tunnelling boring machine, face pressure, the final tunnel lining, the pile caps, and the piles are modelled in several construction phases.

The paper is organized into three parts: the first part describes the adopted numerical model; the second part investigates the response of pile caps during tunnelling; and the last part is concerned with the deformation of piles in the presence of the superstructure.

Keywords

Finite element, tunnelling, soil structure interaction, pile foundation, three-dimensional analysis.

1. Introduction

Construction of tunnels requires assessing their impact on existing structures particularly for tunnelling in soft grounds near pile foundation [1-3]. This may result in increasing pile deformations and altering the distribution of internal forces in piles, pile caps, and the supported superstructure [e.g. see 4-10]. Various empirical relationships between tunnelling induced ground movement and associated structure damage were introduced based on the analysis of previous case histories [11-18]. In the second stage, the building response to tunnelling is determined by subjecting the building structure to the soil movements calculated in step 1. Thus, this approach does not account for the structure-tunnel interaction. Mroueh and Shahrour [6] explored the impact of constructing urban tunnels on adjacent pile foundations using an elastoplastic three-dimensional finite element model. Their analyses were carried out for both single piles and groups of piles. Numerical results showed that tunnelling induces significant internal forces in adjacent piles. The distribution of these induced internal forces depends mainly on the position of the pile tip relative to the tunnel horizontal axis as well as the distance between the pile axis and the tunnel. Other numerical studies have provided. This paper presents a three-dimensional finite element model in which an elastoplastic constitutive relation for the soil is adopted to capture the response of piled structure during tunnelling.

2. Numerical Modelling

The soil volume is modelled by means of 15-node wedge elements. The 15-node wedge elements are created in the 3D mesh extension procedure. This type of elements provides a second order interpolation of displacements. The soil behaviour is assumed to be governed by an elastic perfectly-plastic constitutive relation based on the Mohr–Coulomb criterion with a non-associative flow rule. The discretion of the numerical model can be reviewed in details in reference (18). The mesh presented in Fig. 1 is used for finite element analysis

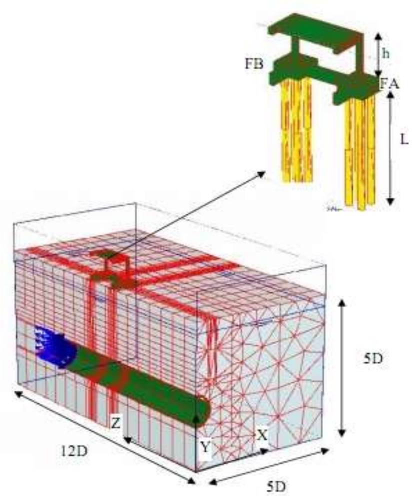

Fig. 1 Example of 3-D coupled analysis in case of one-bay superstructure (after Zidan and Ramadan 2015)

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3. Tunnelling structure interaction

3.1 Soil movement

Figure2 presents the displacement of ground surface (y direction) induced by the tunnel construction and its comparison to free-field surface displacement profile. Note that the presence of structure affects the soil surface deformations especially beneath the ground beam and pile cap. Fig. 7c shows that the settlement in y direction is almost flat in the vicinity of the structure, has a sharp decrease thereafter, and becomes slightly smaller than that of the free field case at moderate distances away of the structure (*x≥2.5D*).

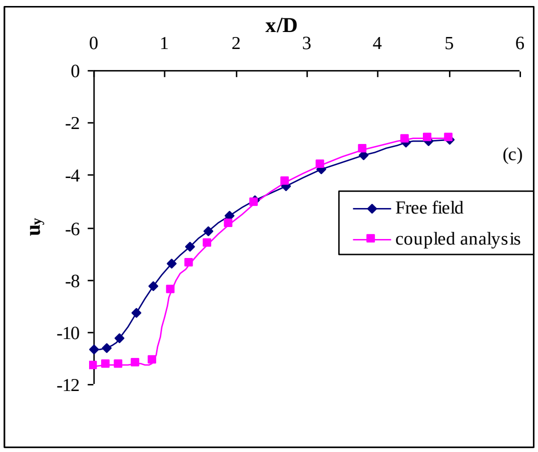


Fig. 2 Ground surface displacements for free field and coupled analyses (a) x direction; b) z direction; and c) y direction.

3.2 Pile deformation

The group of curves presented in Fig.3a shows the deflected shapes of piles the YX (u_x). These figures show that, when the tunnel face is approaching the pile, the deflection in x direction increases with the progress of tunnelling and the maximum displacement occurred at a depth of 0.7L from pile top. After the tunnel face moves across the pile, the displacement at y=0.7L decreases with the progress of tunnel construction and maximum lateral movement of pile shifts position to the pile tip. Figure 3b shows the distribution of the lateral (longitudinal) movement of piles in z-direction along the pile length. It indicates that as the tunnel face progresses towards the structure, the pile lateral movement in z-direction increases. A maximum pile displacement of 6mm is observed at a depth of 0.75L from pile top. Note that lateral displacement in z-direction is observed at pile head; .This represents the movement of superstructure and has its maximum value of 2.5mm when the tunnel face is closest to piles. After the passage of tunnel face under the pile cap, the value of u_z decreases with the progress in and the maximum translation shifts position to the tip of pile.

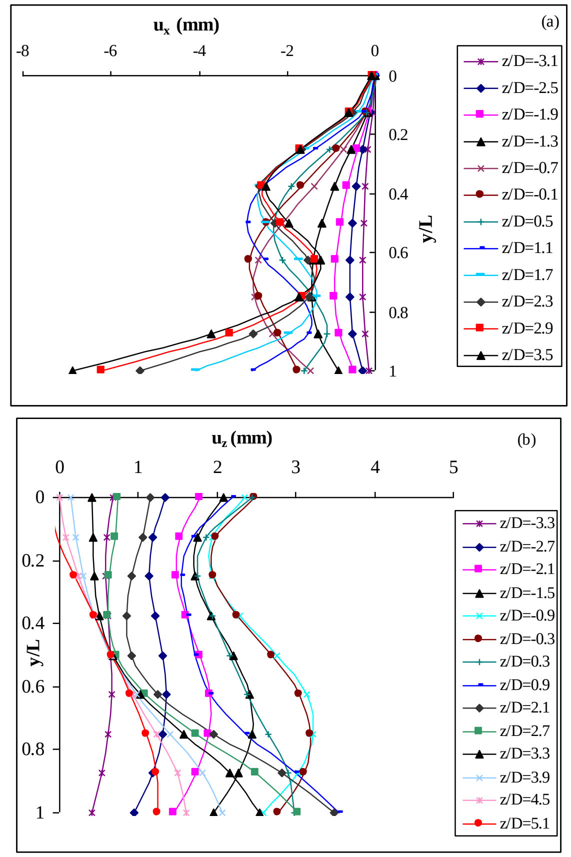


Fig. 3 Pile deformation in x direction during tunnelling (a) ux; (b) uz

3.3 Influence of tunnelling-structure interaction on Pile deformation

Figure 4 illustrates the effect of the modelling assumption (including/excluding the superstructure elements and stiffness) on the piles' transverse deformation (ux) while Fig. 5 presents the same data for the piles; longitudinal deformation (uz). It is observed from Fig. 4 that neglecting the influence of superstructure interaction results in large errors in estimating the transverse deformation of pile heads. While the superstructure stiffness in the analysed example almost fully constrains the pile heads, significant displacements of pile heads are observed when the superstructure is not included in the analysis model. Besides, neglecting the influence of the superstructure reduces ux by about 20% in pile middle third. When combined together, the errors resulting from neglecting the superstructure interaction significantly reduce the curvature of piles and, consequently, underestimate pile internal forces. Finally, Fig. 5 shows that the effect of superstructure interaction on the longitudinal deformation of piles (uz) is less-pronounced that its effect on pile transverse deformation.

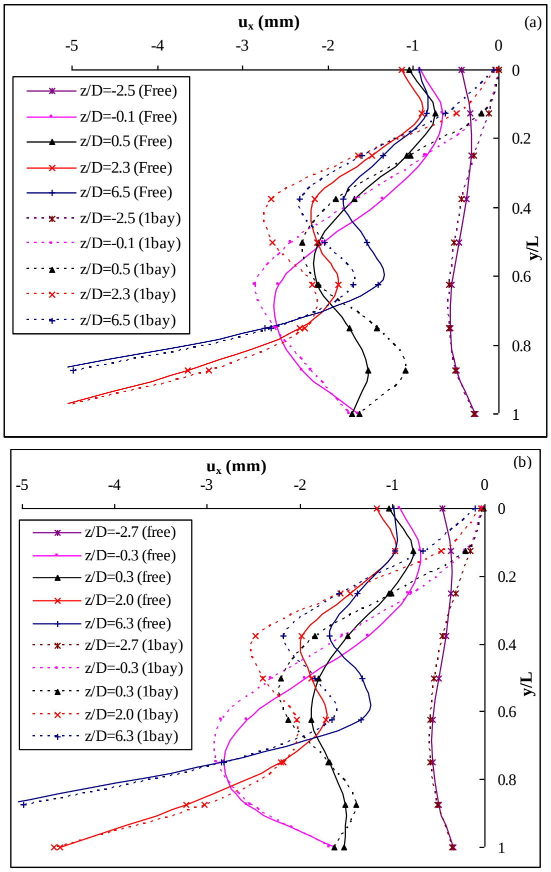
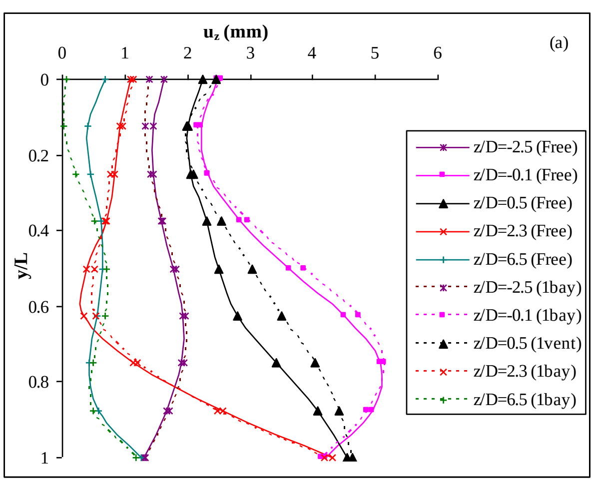


Fig. 4 Influence of super-structure interaction on piles' transverse deformation (ux) during tunnelling for one bay structure: a) P1; b) P2



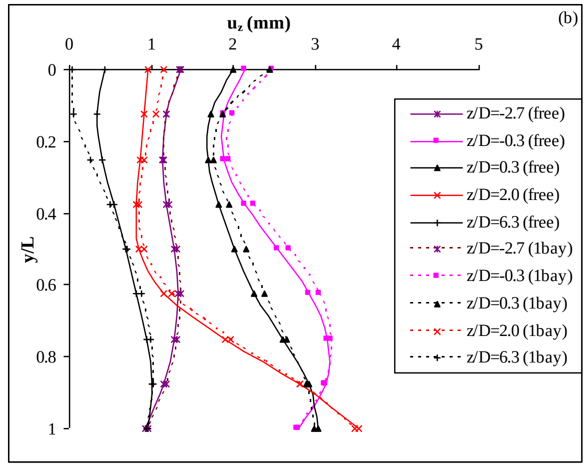


Fig. 5 Influence of super-structure interaction on piles' longitudinal deformation (uz) during tunnelling for one bay structure: a) P1; b) P2

Conclusions

Based on the obtained numerical results, the following conclusions are drawn.

1. Compared to the free field displacements at ground surface, the structure presence appreciably reduces the horizontal displacements (in two directions) and makes the settlement profile uniform. Away of its vicinity, the structure effect on ground surface displacements in all directions is marginal.
2. The horizontal displacement of the structure foundation parallel to the tunnelling direction increases as the tunnel face approaches the pile cap and attains its maximum when the tunnel face crosses beneath the structure.
3. Tunnelling beneath piled structures produces considerable differential settlements between pile caps. The maximum differential settlement between pile caps for the coupled analysis, which includes the superstructure, is about 50% more than the corresponding value for the free field analysis (which assumes no superstructure).
4. Analysis of superstructure systems with one bay and two continuous bays along the tunnel longitudinal axis showed that, compared to the one-bay structure, the pile cap movements of the two-bay structure were reduced by up to 34%, 5%, and 12% in the transverse, longitudinal, and vertical directions, respectively.
5. As tunnel construction progresses towards the piles, they continuously deflect in double-curvature (like a fixed-pinned beam)

profile. After the construction operation passes the piles' location and continues to progress away of the piles, the pile deflected geometry changes into triple-curvature. As the pile curvature is larger in the latter case, higher pile internal forces would be developed.

6. Compared to the exact analysis which includes the stiffness of the superstructure, the often made assumption of free piles (ignoring the interaction with the superstructure) is found to be unjustified. Numerical results showed that the free-pile analysis underestimates the flexural deformation of piles by more than 20% and, consequently, underestimate pile internal forces.

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