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Three-dimensional finite element analysis of the interaction between tunneling and adjacent structures

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ABSTRACT: This paper concerns a study of the interaction between tunnelling in soft soils and adjacent structures (piles foundations and surface structure). Analyses are performed using a full three-dimensional non-linear finite element model that takes into consideration the presence of adjacent structures during the construction of the tunnel.

The paper is composed of three parts. The first part describes the numerical model used in this study, the second part deals with the analysis of piles response to tunneling. The third part concerns a full three dimensional analysis of the construction of a shallow tunnel in proximity of to a two level building.

1 INTRODUCTION

Construction of tunnels in urban area requires assessment of the impact of tunneling on the stability and integrity of existing structures (pile foundations, buildings). Several studies have been reported on this topic, using in situ observations and numerical modeling. Compilation of case histories leaded to the elaboration of empirical relationships between tunneling-induced ground movement and existing-structure damage (Boscardin et al., 1989, Lee et al., 1994, Mair et al., 1996). These methods are widely used in practice. Numerical analyses were also performed using simplified approaches, which generally include two steps. The first step concerns the determination of tunneling-induced ground movement using either empirical, analytical or numerical methods like those proposed by Peck (1969), O'Reilly and New (1982), and Sagaseta (1987). The structure response to tunneling is determined in the second step mainly by using explicit methods with results of the first step as input. In this approach, structure damage is probably overestimated because of the neglect of the structure stiffness in the prediction of the tunneling-induced ground movement.

This paper includes analysis of two majors problems encountered in tunneling in urban area. The first one concerns tunneling in proximity of existing piles, while the second deals with the interaction between tunneling and existing building. Analysis is performed by means of a fully three-dimensional finite element modeling using an elastoplastic constitutive relation for the soil material. The originality of this work lies in the numerical modeling of the tunnel construction in presence of structures. The first part of the paper presents the numerical model used in this study. The second part concerns analysis of the impact of tunneling on groups of piles. The third part deals with the interaction of tunneling with a two-level building structure.

2 NUMERICAL MODELLING

Analysis of the tunneling-structure interaction is performed in two stages. The first one is concerned with the determination of initial stresses in the soil mass that is prior to the tunnel construction. It is performed using a finite element calculation considering the self-weight of both the soil and the existing structures. Displacements are reset to zero at the end of this stage, which means that results presented hereafter are due to tunneling. The second phase concerns the numerical simulation of the construction of the tunnel in presence of the structure. The tunnel construction is modeled by deactivation of soil elements located in the excavated zone and activation of lining elements. Analysis is performed in different steps according to figure 1 (Mroueh 1998, Mroueh & Shahrour 1999a).

Each step corresponds to the progression of the tunnel face by a distance L_{lin}. It includes:

- A partial deactivation of soil elements situated in the section to be excavated; the deactivation procedure is supposed to be governed by parameters α_{dec} and L_{dec} which stand for the ratio of stress release (unloading level) and the length of the unlined zone, respectively. The variation of these parameters have significant effects on tunneling induced soil-movements and allows the procedure to reproduce efficiently the tunneling process in various configurations of tunnel depth location, tunnel diameter and soil mechanical properties, as shown in Mroueh (1998). This procedure takes into consideration the presence of the boring machine and the TBM sequences;

- Activation of lining elements located in the new section and a full release of stresses in this section;

The stability of the tunnel face during tunneling is ensured by the application of a uniform front pressure 'p' on the tunnel face.

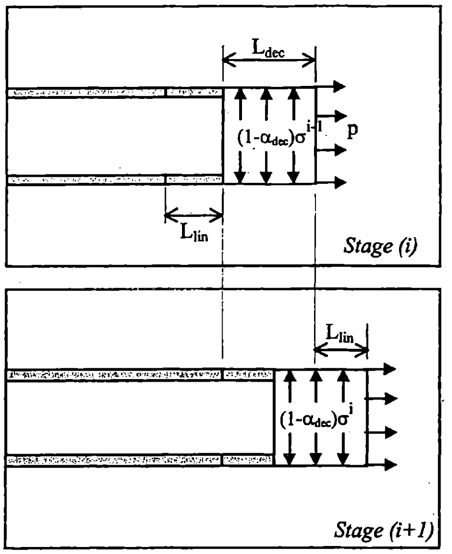


Figure 1. Procedure used for tunnelling modelling (Mroueh, 1998).

Numerical simulations were performed by means of the finite element program PECPLAS (Shahrour 1992, Mroueh 1998, Mroueh & Shahrour 1999b) which presents facilities for the solution of three-dimensional and non-linear soil-structure interaction problems. A sparse storage scheme is used in this program. The solution of the linear system is carried out using the bi-CGSTAB iterative method (Van der Vorst, 1992) coupled to the SSOR preconditioning operator (Successive Symmetrical Over- Relaxation).

3 INTERACTION BETWEEN TUNNELLING AND A GROUP OF PILES

3.1 Presentation

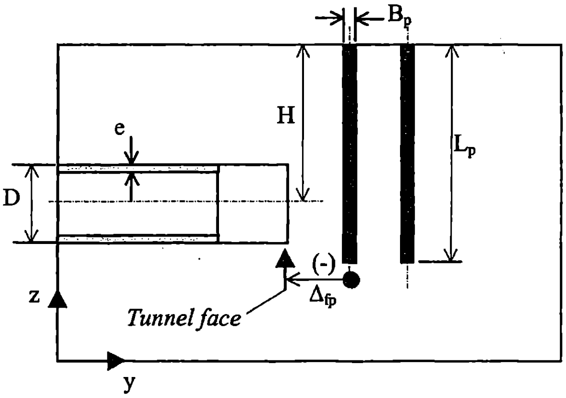
The problem under consideration concerns the interaction between the construction of a shallow tunnel and an adjacent group of piles. The tunnel diameter and cover depth are equal to D = 7.5 m and H = 2.5D, respectively. The behavior of the lining is assumed to be governed by a linear-elastic relation with a Young's modulus E = 35,000 MPa and a Poisson's ratio ν = 0.25. The axial and bending stiffness of the lining are equal to K_{sn} = 4978 MPa and K_{sf} = 7.4 MN.m², respectively. The pile length and width are equal to L_p = 22.5 m and B_p = 1 m. The group is composed of 2x2 piles with a spacing S = $4B_p$ (figure 10a). The front and rear piles are located at a distance Δ_{tp} = 1D and Δ_{tp} = 1.5D from the tunnel center, respectively (distance between the piles axis and the tunnel center-line), and the piles tip are bellow the tunnel horizontal axis from a distance of i_{tp} = +0.5D.

The soil behavior is assumed to be governed by an elastic perfectly-plastic constitutive relation based on the Mohr-Coulomb criterion with a Young's modulus E = 30 MPa, a Poisson's ratio ν = 0.3, a cohesion C = 5 kPa, a friction angle φ = 27° and a dilatancy angle ψ = 5°. The behavior of the pile is assumed to be linear-elastic with a Young's modulus E = 23,500 MPa and a Poisson's ratio ν = 0.25. The axial and bending stiffness of the pile are equal to EA = 23,500 MPa and EI = 1960 MN.m², respectively. Table 1 summarizes the characteristics of the soil, the liner and the pile material.

Table 1. Mechanical properties used in the reference example

Material	E (MPa)	ν	c (kPa)	φ (°)	ψ (°)
Soil(sandy)	30	0.3	5	27	5
Liner(Concrete)	35,000	0.25	-	-	-
Pile(Concrete)	23,500	0.25	-	-	-

The finite element mesh used in numerical modeling is presented in figure 3. It includes 3111 twenty-node isoparametric hexahedral elements and 14300 nodes. The extension of the soil mass is fixed to 12D in the lateral axis (x), 7D in the longitudinal axis (y) and 5.5D in the vertical axis (z).



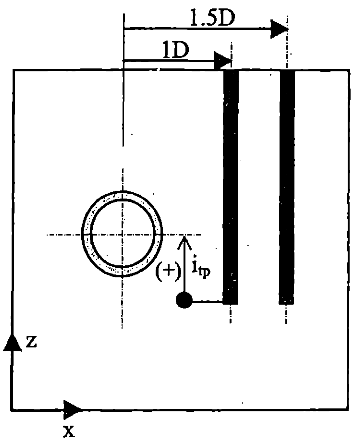


Figure 2. Interaction between tunneling and a group of piles.
a) Longitudinal view
b) Lateral view

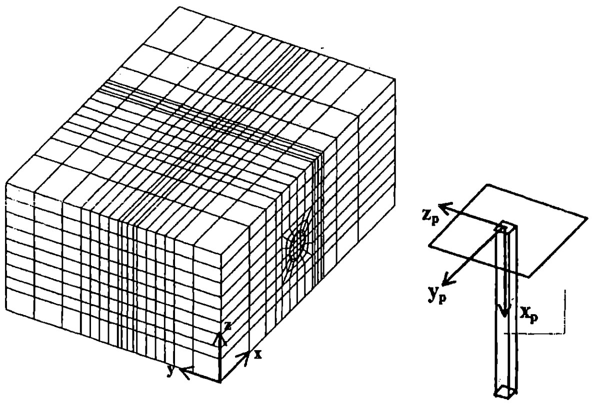


Figure 3. Three-dimensional finite element mesh used in the analysis of piles/tunneling interaction.
(3111 20-node isoparametric hexahedral elements ; 14,300 nodes ; 38,222 dof.)

The construction of the tunnel was performed in 12 steps using the following parameters for the excavation procedure: α_{dec} = 0.5 and L_{dec} = 1D, and length of the excavated section at each step L_{lin} = 0.5D. These parameters have been chosen in order to induce some realistic soil movements at the surface soil, with comparison with some empirical methods and in-situ observations.

3.2 *Numerical results*

The reference example concerns the construction of the tunnel presented in proximity of a free-head group of piles. In this section, we will use present some results of the impact of tunneling on a single pile that has been studied and published elsewhere (Mroueh & Sharhour, 2001).

Figures 4a&b show results obtained for the interaction between tunneling and a free-head group of piles. It shows also results obtained for the interaction between tunneling and corresponding single piles. We observe that internal forces induced by tunneling in the group elements are lower than those induced in single piles. This result shows a positive group effect in particular for rear piles, for which we observe a reduction of about 60% of the maximum axial force and about 45% of the maximum bending moment. The group effect is less important for the front piles, for which we observe a reduction of about 20% of the maximum axial force and an a negligible reduction of the bending moment. Results concerning the front piles are in good agreement with centrifuge tests performed on a group of piles in a clayey soil (Loganthan et al. 2000).

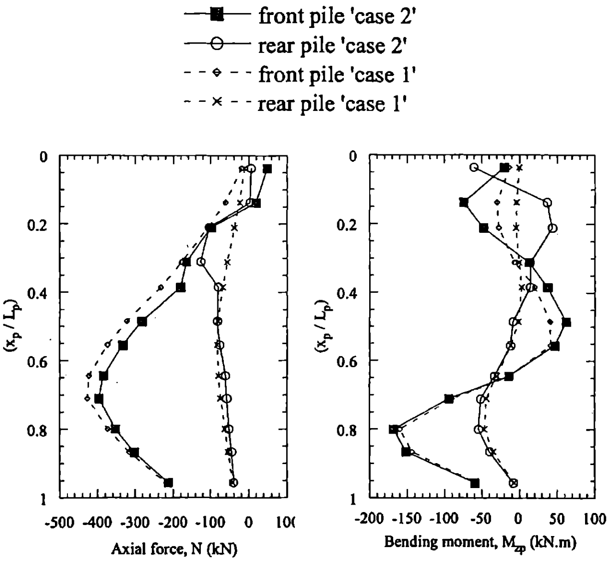


Figure 4. Tunnel construction adjacent to a 'free-head' group of piles - case (1)

3.3 *Influence of the condition at the group head*

Figure 5 shows the influence of the presence of a cap on the interaction between tunneling and the group of piles presented in figure 3. The cap is assumed to be out of contact with the ground (figure 5a). It can be observed that the presence of the cap affects the piles response in the upper part (x_p/L_p < 0.3). It induces a small tensional axial force in the head of the front piles (about 50 kN) and a significant bending moment at the head of the rear piles (about 60 kN.m,). The upward soil movement induces tensile force in the front pile. Since the upper section of piles is less affected by tunneling than the lower section, the presence of the cap can be neglected in the analysis of the interaction between tunneling and groups of piles fixed in a cap, which is not connected to the ground surface.

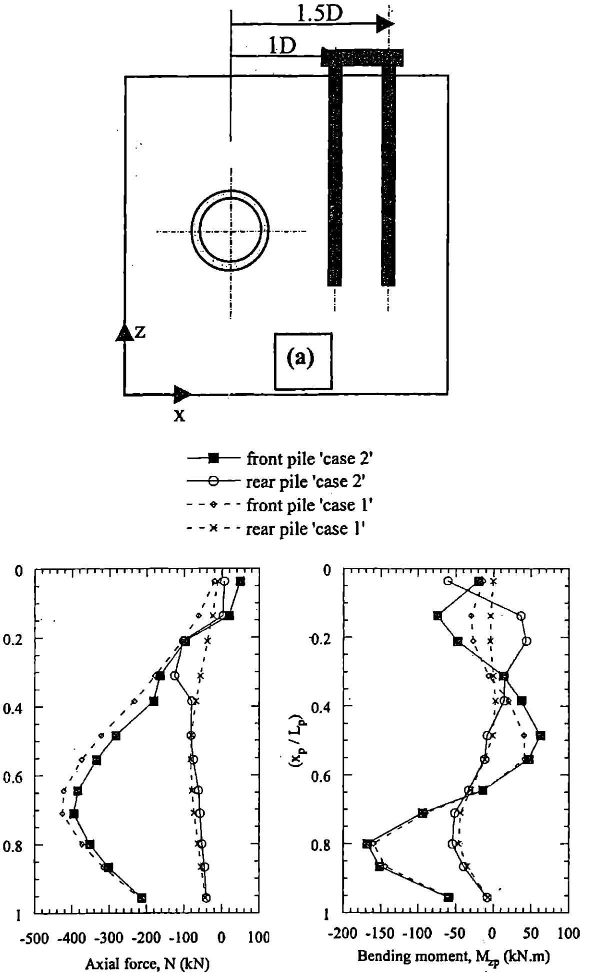


Figure 5. Tunnel construction adjacent to the braced group of piles

4 ANALYSIS OF INTERACTION BETWEEN TUNNELLING AND ADJACENT FRAME-STRUCTURE

4.1 Presentation

The second problem concerns the influence of tunneling on a two-level frame structure presented in figure 6. The longitudinal section of the tunnel is assumed to coincide with that of the building. The tunnel parameters are the same than the precedent study, and structure characteristics are given by columns spacing as = bs = 5m and height of each level hs = 4m. The respective axial and bending stiffness are equal to EA = 3200 MN and EI = 43 MN.m^2 for columns and to EA = 4000 MN and EI = 83 MN.m^2 for beams. The soil behavior is described with the same constitutive law than the first study, with the same parameters.

The study is carried out using the finite element mesh presented in figure 6b. It includes 3912 20-nodes hexahedral elements, which give rise to 19,017 nodes and 52,533 degrees of freedom.. The structure is considered using 20-nodes hexahedral elements.

The lateral boundaries of the mesh were located such that they do not affect the tunneling-structure interaction. The distance between the lateral boundaries and the central frame is equal to 4D. Concerning the bottom boundary, it is supposed that rigid substratum is located at a depth of 2.5D from the tunnel center.

Computation is performed in 15 steps using the following parameters for the excavation modeling: ratio of stress release α_{dec} = 0.7, length of the unlined zone L_{dec} = 1D, and length of the excavated section at each step L_{lin} = 0.5D.

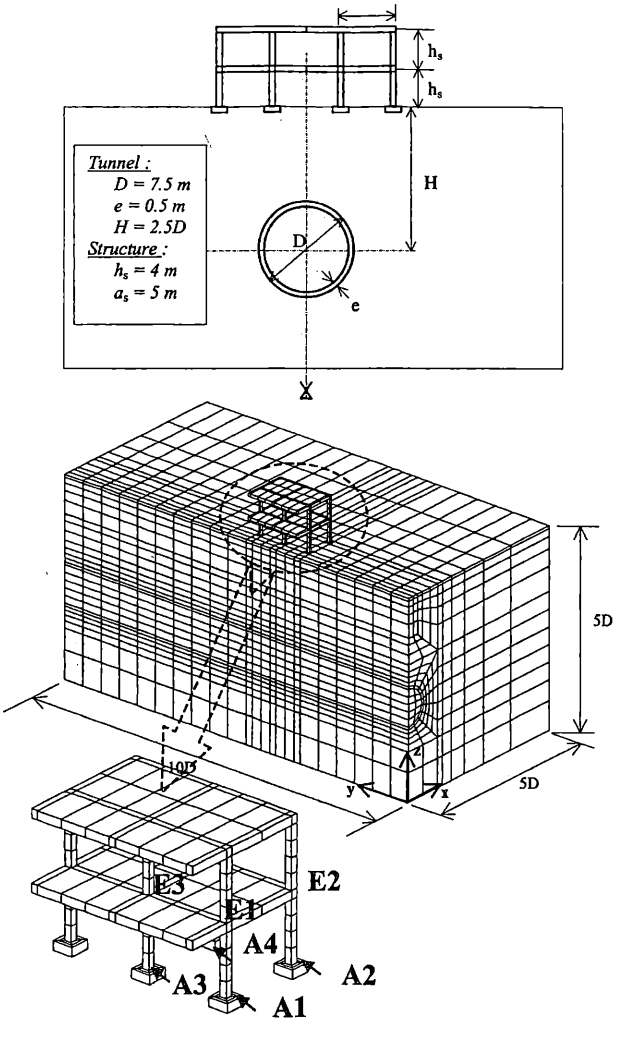


Figure 6. Tunneling-adjacent structure interaction
a) Geometry under consideration
b) Finite element mesh (3912 hexahedral elements HEX20 ; 19,017 nodes ; 52,533 dof)

4.2 Numerical results

Figure 6a presents the settlement profile induced by the construction of the tunnel that is compared to the free-field ground settlement. It can be observed that the presence of the structure induces a reduction of the soil settlement with regard to that obtained in free-field condition. However, in the proximity of the structure foundation, we observe an increase in the settlement, which is due to the plasticity induced by the building self-weight and tunneling as illustrated in figure 6b.

Table 2 presents internal forces induced by tunneling in the columns of the frame. It shows a tension axial force in the front columns 1 and 3, with a maximum value of about 62 kN in column 3, and a maximum axial force of about 25 kN in column 1, which is about 60% inferior to that induced in column 3. This result indicates a transfer of the axial loading from the front lateral column to the front centre one. In the rear column 4, tunnelling induces an axial compression force, with a maximum value of about 34 kN. Concerning the bending moment, it can be observed that tunnelling induces high bending moment in rear columns in comparison with that induced in front columns. The maximum bending moment in the rear column 4 is about 30% superior to that induced in the front column 3.

Table 2. Coupled analysis: internal forces due to tunnelling

Units : kN, kN.m	A1	E1	A3	E3	A4	E4
Axial force	25	25	62	62	-34	-34
Bending moment	-30	52	-28	52	-32	74

4.3 *Influence of the building self-weight*

Generally, analysis of the tunneling-structure interaction does not take into consideration the influence of the self-weight of the structure in the determination of initial stresses. In order to analyze the impact of this hypothesis, the precedent analysis is compared in figure 7 to another analysis which neglects the contribution of the self-weight of the structure to initial stresses. It can be observed that the consideration of the self-weight of the structure induces an increase in the soil settlement in proximity of the foundations. Moreover, the differential settlement between the front and rear foundations, which constitutes a key parameter in the soil-structure interaction, is reduced by about 62% when the structure weight is neglected. The influence of the self-weight of the structure is due to plasticity induced in the proximity of the building foundations as illustrated in figure 7b.

Table 3 shows the influence of the self-weight of the building on the tunneling-induced internal forces. It shows that the neglect of the self-weight of the structure causes a decrease of about 35% in the axial force induced in the front column and an increase of about 20% in the axial force of the rear column.

Concerning the bending moment, it can be noted that the neglect of the self-weight of the building yields an increase of about 27% in the bending moment in the front column and an increase of about 13% in the bending moment in the rear column.

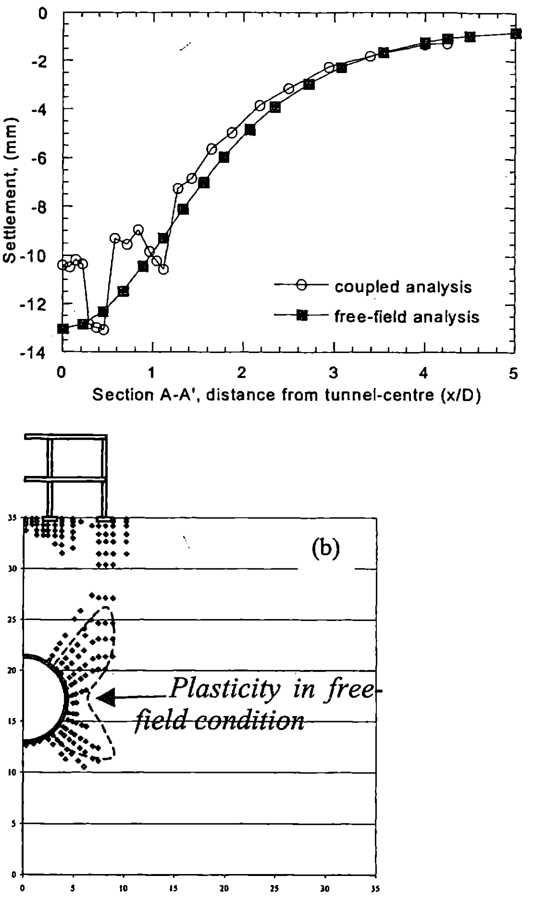


Figure 6. Full 3D coupled analysis: Comparison with simplified approach

a) Ground Settlement profile along (A-A') axis

b) Extension of plasticity in transverse section

4.4 *Simplified approach*

This section concerns comparison between the full-coupled approach and the simplified approach, which neglects the presence of the structure in the determination of the tunneling-induced ground movement. In this approach, the tunneling-induced forces were determined from the structure response to the displacements calculated in free-field conditions (table 4).

Table 5 shows a comparison of the full-coupled and simplified approaches. It can be observed that the simplified approach overestimates by about 100% the axial force in the rear column 4, but agrees well with the full-coupled approach for the axial force in the front column 3. Concerning the bending moment, the simplified approach largely overestimates the bending moment in the structure, in particular in the front column. Indeed, the simplified approach gives a maximum bending moment, which is equal to 195 kN.m in the front column, while the full-coupled analysis predicts for this column a maximum bending moment of 32 kN.m.

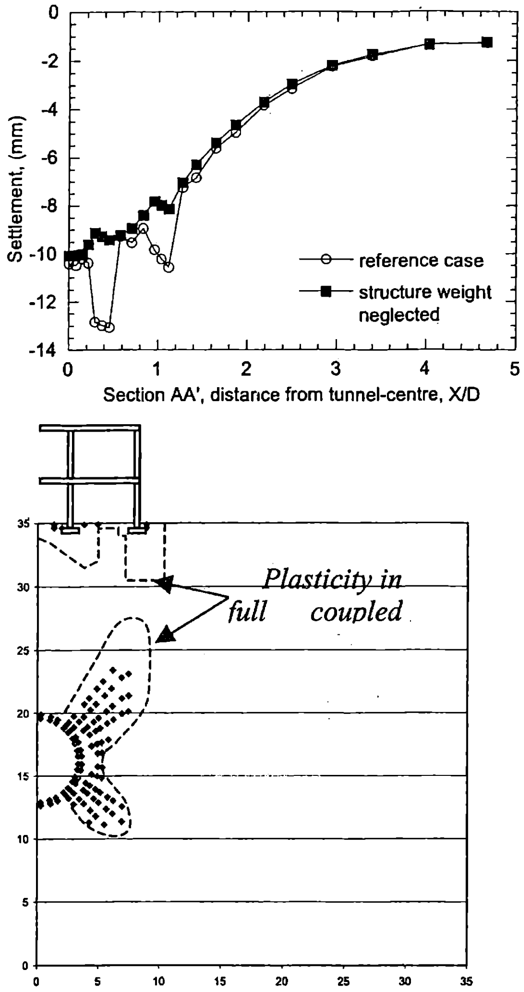


Figure 7. Influence of consideration of the structure self-weight on the tunneling-structure interaction
a) Ground settlement profile along (A-A') axis
b) Extension of plasticity in a transverse section

5 CONCLUSION

This paper included analysis of the interaction between tunneling and adjacent structure in soft soils. Analysis is performed using a full three-dimensional finite element modeling, which takes into account the presence of the structures during tunneling.

Analysis of the interaction between tunneling and groups of piles shows a positive group effect with a significant reduction of the internal forces in rear piles. As the presence of a cap affects only tunnelling-induced forces in the upper part of piles, analysis of tunneling-piles interaction can be performed assuming a "free-head" condition for groups of piles.

Analysis of the interaction between tunneling and adjacent building shows that tunneling-induced forces largely depend on the structure presence. The neglect of the structure stiffness in the tunneling-structure analysis yields significant overestimation of internal forces in the structure. The simplified approach, which considers the free-field soil movement in the calculation of the tunneling-induced forces, is then conservative. Analysis also showed that it is of major interest to consider the building self-weight in the determination of initial stresses in the soil mass that exist prior to the tunnel construction. Indeed, the neglect of the building self-weight leads to an important underestimation of the tunneling-induced forces.

Table 3. Comparison of the full coupled and the simplified approaches: internal forces in the central frame

	Simplified analysis		Full Coupled analysis	
	N (kN)	Mf (kN.m)	N (kN)	Mf (kN.m)
A3	67	-110	62	-28
E3	67	94	62	52
A4	-67	-195	-34	-32
E4	-67	141	-34	74

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