Impact of tunnelling on neighbouring piles: Experimental study on 1g reduced scale model of TBM

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ABSTRACT: Within the framework of the European project NeTTUN, the Laboratory of Civil Engineering and Building Sciences of ENTPE in Lyon (France) is in charge of a large experimental campaign to investigate the impact of tunnelling on neighbouring piled structures. For this study, an original reduced-scale physical model of EPBS is used. This "1g" laboratory model is able to reproduce the main features of the excavation method. For this new experimental program, the miniature EPBS advances inside a large tank filled with a model soil (dry sand) in which instrumented piles were pre-installed. In this paper, the authors describe briefly the original 3D device and present significant results concerning the impact of tunnelling on single piles and pile groups installed above the tunnel in construction. In connection with the practice, the tunnel – soil – piles interaction is analysed in regard to the frontal pressure applied by the TBM on the tunnel face and the ground volume loss occurring around the machine.

1 INTRODUCTION

When tunnels are constructed in urban areas, they often come close to pre-existing structures, such as pile foundations. Perturbations of tunnel construction on these neighbouring structures must be considered during design and construction of the tunnel. Ground movements due to tunnelling may induce bending moments, lateral and vertical loads, settlements and lateral deflections in the piles, which may lead to structural damage or failure of the piles or the supported structure.

The interaction between piles and a tunnel in construction is a complex three dimensional problem. To this date, several experimental approaches have been carried out to analyse the effects of tunnelling on piled foundations (Bezuijen, 1994, Loganathan et al., 2000, Jacobsz et al. 2004, Lee and Basset, 2006, Marshall and Mair, 2011, …). These different studies carried out in the laboratory on 1g or centrifuged models aim at a better understanding of tunnel - piles interaction and a quantification of the influence of each dominating parameter on the structural responses. Parameters like foundation type (single pile, group of piles) and geometry (relative tunnel – pile position), volume loss induced by tunnelling, ground characteristics, pile loading history were considered. However, most of these experiments were carried out under plane strain conditions by modelling the volume loss due to tunnel excavation by decreasing the tunnel diameter or the radial support pressure. As a result, these models do not adequately account for the variations of settlements both in the longitudinal and the transverse direction, which can induce significant flexural and torsional effects on the structures. These effects are particularly critical and detrimental in the case of historical monuments.

In the framework of the NeTTUN European project, laboratory tests are performed on a normal gravity reduced-scale model of Earth Pressure Balanced Shield (EPBS). The study is carried out by considering the conditions of similarity deduced from dimensional analysis which govern the transposition of the research results to real life situations. The highly sophisticated design of the machine allows us to simulate the 3D excavation process closely, taking realistically into account several factors affecting the ground volume loss around the machine. In particular, with this original piece of equipment, the volume loss can be controlled directly via the frontal pressure. Hence a parametric study can be conducted to assess its impacts on the main structural responses.

This paper presents firstly the details of the ENTPE's reduced scale model in its current configuration to perform a 3D analysis of the impact of tunnelling on neighbouring piled structures. This is followed by results concerning TBM – soil – pile interaction during the excavation process.

2 THE PHYSICAL MODEL OF EARTH PRESSURE BALANCED SHIELD

2.1 *The reduced-scale model of TBM*

The ENTPE earth pressure balance shield model is presented in Figures 1 and 2. This model, with a geometric scale between 1/4 and 1/20 in reference to the diameter of the machine, consists of a 0.55m cutter head (A), a conical working chamber (B), a screw conveyor inclined at an angle of 10° (C), a horizontal screw conveyor (D), a cylindrical steel shield tail (E), four hydraulic jacks (F), a frame carrying the whole assembly, a stiff steel container placed in front of the TBM frame and containing the model soil (G). The tested ground dimensions are 2m long, 2.7m wide and 2.2m high.

To start excavation, the TBM enters the ground through a circular opening located on one of the side walls. Afterwards, the principal stages of the EPBS tunnelling process are simulated: excavation of the ground with the cutter head, confinement of the tunnel face with the excavated material contained inside the excavation chamber, extraction of this material with the inclined screw conveyor, immediate radial support of the excavated ground by means of the sliding cylindrical shield tail. For these tests, the maximum excavation length is 1m. To this date, the presence of water table and groundwater flow are not taken into account in this device.

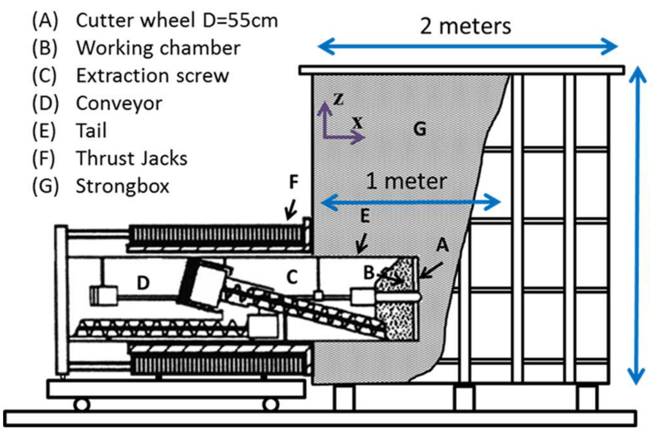

Figure 1. Longitudinal cross sectional of the TBM model of ENTPE.

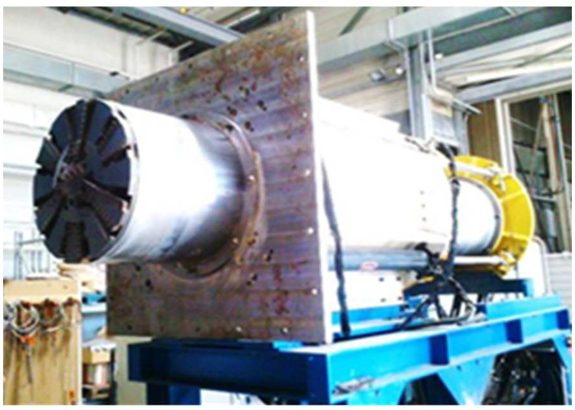

Figure 2. Reduced – scale TBM model of ENTPE.

In the ENTPE model, machine parameters as well as soil behaviour are directly monitored under real time conditions. The TBM model features an extensive instrumentation system very similar to those of real TBMs. This on-board instrumentation consists of three total pressure cells fixed on the walls of the working chamber to measure ground stresses at the sides and on the roof of the chamber, four dynamometers fixed at the tip of the hydraulic jacks to measure the total thrust exerted on the TBM, four hydraulic pressure cells to provide the measurement of the torques of the screw conveyor and the cutter head, a linear displacement sensor to indicate the shield penetration rate, an electronic scale to deliver real time measurements of the mass of materials discharged at the rear of the shield.

2.2 *The model piles*

Several model piles with length L_p=1070mm (Fig. 3) were manufactured from aluminum alloy (Young's modulus: E) tubing with an outer diameter D_p=50mm and a thickness e_p=5mm to study the effects of tunnelling on the structural responses of neighbouring piles, in particular in terms of settlement, axial load, longitudinal and transverse bending moment distributions. The dimensions and mechanical characteristics of the model piles were defined by considering the conditions of similarity deduced from a dimensional analysis that control the transposition of the results to real piles. In addition to gravity conditions (g*=1), a geometric scale factor (L*) equal to 1/11 was considered in accordance with the range of geometric scale ratio considered for the model of TBM. In addition, special attention was given to the validation of similitude conditions concerning the pile stiffness factors (E*, E*I*, E*A*). The characteristics of the model piles and the corresponding real piles are given in Table 1.

To study axial load and longitudinal/transverse bending moment distributions inside the piles, each instrumented pile was equipped with eighteen measurement cells placed along its length. Six cells were used to measure axial load and twelve cells to measure the transverse and longitudinal bending moments.

		Scale factor	*Model scale*	*Full scale 1/11*
D_e	mm	L	50	550
e_p	mm	L	5	55
L_p	m	L	1.4	15.4
A	cm^2	L^{2*}	7.07	3
I	cm^4	L^{4*}	18,1	265196
E	GPa	L*	70	770
EI	$GN.m^2$	L^{5*}	$1.3\ 10^{-5}$	2,04
EA	GN	L^{3*}	0.049	65,9

Table 1 Characteristics of the model piles and the corresponding real piles

All these cells were instrumented with strain gauges, connected in full Wheatstone bridges to produce a temperature compensated system. The cells were covered with a protection film to prevent sand ingress during testing.

2.3 *Soil model*

The model soil used in the present study is prepared from Hostun HN31 dry sand. This fine silica sand is characterized by a grain density of 2.65, an average diameter d_{50} of 0.35mm and a uniformity coefficient of d_{60}/d_{10}=1.4 (Berthoz, 2012). Note that the choice of this purely frictional model soil has been made by considering the conditions of partial similitude concerning the soil stiffness factor (E*=L*) and the Mohr Coulomb failure criterion (φ*=1). Moreover, due to the low level of overburden prevailing in the reduced-scale model, the soil mass is prepared in a loose state (ρ_d=1350kg/m^3, e=0.96, I_D=6%) in order to approach the ideal similitude on the volumetric behaviour (Scott, 1989). A flexible rubber pipe fed with a screw conveyor was used to deposit the sand into the soil container. A constant drop height (300mm) and a constant flow rate (90kg/min) were imposed to guarantee a uniform sand density.

During the TBM advance, the stress – strain evolutions of the ground are monitored by means of several sensors laid in the ground when the container is filled. The ground monitoring system is composed of:

- 7 internal total stress cells to measure the stress variations in the horizontal (σ_{xx}, σ_{yy}) and vertical (σ_{zz}) directions (x, y, z are relative to the Cartesian coordinate system given Figure 1),
- 24 LVDT displacement sensors to measure in real time the vertical displacements (uz) of the ground surface,
- 6 modified LVDT laid in the ground to measure the internal vertical displacements (uz) in the vicinity of the piles.

In addition, a digital image correlation (DIC) system is used to measure the reference ground surface displacement field during the tunnelling tests.

2.4 *Piles Jacking*

Single pile or a piles group were positioned in the ground while filling the container. Prior to tunnel excavation, the piles were installed into the ground at 50mm (1 pile diameter) from its final position. Then, to fully mobilize the tip force and the shaft friction, pneumatic jack mounted on support frame was used to push the pile down to its final position with a quasi-constant rate of penetration (≈2mm/mn). After the piles have reached its target position (Fig. 3), the pneumatic pressure is decreased to leave only the working loads acting on the piles during the TBM excavation process. In the present study, the ultimate bearing capacity of the piles was measured during a preliminary test and was defined as the value causing a settlement equal to 5% of the pile diameter (O'Neil & Reese, 1999). Furthermore, the working load was taken equal to be 50% of this ultimate bearing capacity.

3 EXPERIMENTAL PROGRAM

The experimental campaign carried out with the TBM model of ENTPE in the framework of the NeTTUN European project aims to acquire a better understanding of the TBM - soil - pile interaction, to analyse the influence of each dominating parameter on the structural responses, and to develop an exhaustive database for the development and the calibration of numerical models. Various parameters that affect the TBM - pile interaction are studied such as the type of foundation (single pile or group of piles), the relative position between pile and tunnel, the pile loading history and its working load, the TBM excavation rate and the frontal pressure applied on the tunnel face.

In the present paper, typical results of five tunnelling tests carried out with the ENTPE reduced-scale model of EPBS are presented. Among these tests, a first one (named TV) has been performed under greenfield conditions (without piles) to provide reference data. Three tests (named TP_1, TP_2 and TP_3) were performed with a single pile (pile P1) installed above the tunnel axis according to the configuration given in Figure 3. For these tests, the tip of the axial pile is located at 1D above the tunnel centreline when the TBM penetrates into the ground. The fifth test considered in this paper (named TGP) was carried out in the presence of a group of piles installed above the tunnel axis (Fig. 3). The pile group is constituted by

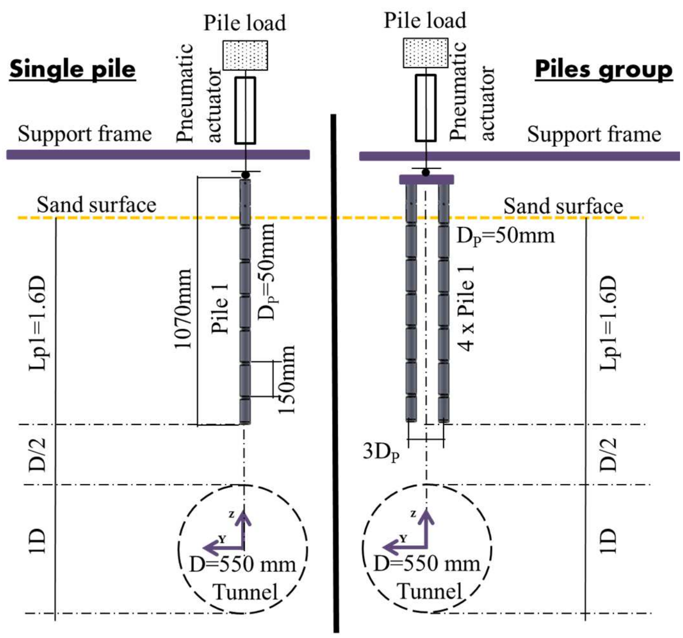

Figure 3. Geometric configurations of the tests carried out with single pile or piles group.

four single piles P1 connected together thanks to a rigid steel cap. In this configuration, the distance between the axis of two neighbouring piles is equal to 150mm.

During these different tests, three different levels of frontal pressure named “Low”, “Intermediate”, and “High” (respectively index L, I and H) were applied by the TBM on the tunnel face to study the effect of this pressure on the tunnel – pile interaction. Based on previous tests, the “intermediate” pressure may be considered as the pressure ensuring face stability and minimizing ground displacements around the TBM.

Moreover, all the excavation tests presented in this paper have been carried out by verifying a steady excavation rate. The latter is obtained by maintaining a constant amount of material in the working chamber during the TBM advance. Consequently, a close attention was paid during excavation on the tunnelling ratio and pressures inside the working chamber (Figure 4). The tunnelling ratio is defined as the ratio between the soil mass extracted from the working chamber per unit time (this mass is measured in real time on the model of TBM) and the soil mass entering in the working chamber per unit time (estimated by means of the ground density and the TBM advancement rate). The steady state is reached when the pressures inside the working chamber are constant and the tunnelling ratio close to 1. Table 2 gives the main characteristics of the five tests considered in this paper.

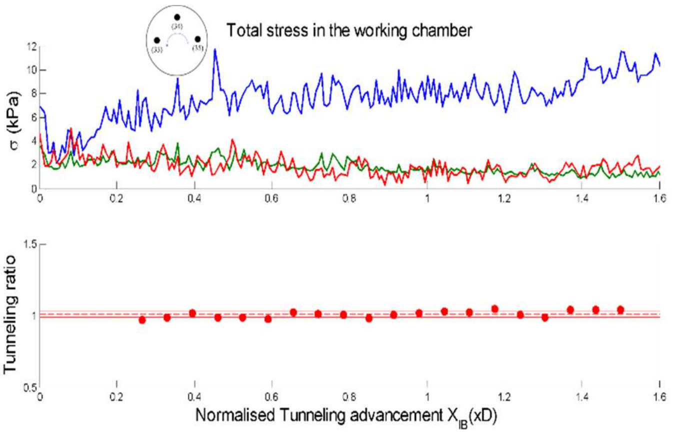

Figure 4. Example of soil pressures measured on the wall of the working chamber and corresponding values of tunnelling ratio according to the TBM advancement (test TV_{2I})

	Soil density ($kN.m^{-3}$)	*Frontal pressure (kPa)*	*Working load (daN)*	*K_0*
TV_{2I} Greenfield test Intermediate pressure	13.3	36		0.3-0.57
TP_{1I} Intermediate pressure	13.5	38	33	0.2-0.6
TP_{2L} Low pressure	13.4	13	31	0.23-0.43
TP_{3H} High pressure	13.3	57	32	0.2-0.6
TGP_{1I} Intermediate pressure	13.5	34	116	0.2-0.7

Table 2. Main characteristics of the different tunnelling tests

4 TESTS RESULTS

4.1 *Transversal settlement through*

Figure 5 shows the transversal settlement profiles in the TBM face section corresponding also to the pile section (X_{PT}=0) for the five different tests. First, as shown by Peck (1969) modified Gaussian curves fit quite well all the tests. Additionally, at the pile section, the settlement magnitude and the volume loss (V_L) are widely influenced by the frontal pressure applied by the TBM. Measured volume losses lie in the same range of magnitudes as those observed on worksites. Volume losses range between 0.9% for X_{PT}=0 and 2.5% for X_{PT}=0.7D (end of the test not presented in Figure 5) in the case of an intermediate frontal pressure. Lastly, note that for this same level of frontal pressure, the pile tends to increase the soil settlement. In contrast, grouped piles decreases the magnitude of the soil settlement whereas volume loss stays the same: piles modify the settlement trough width and grouped piles reinforce the soil.

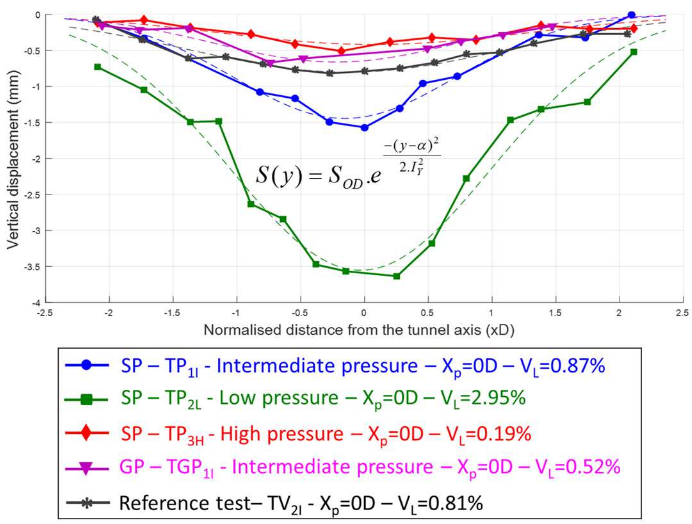

Figure 5 Transverse profiles of surface settlements measured during the different tests above the tunnel face (X_{PT}=0)

	S_{0D}	α	Iy
TV_{2I}	-0.81	-0.11	1.22
TP_{1I}	-1.47	-0.09	0.72
TP_{2L}	-3.55	-0.03	1.01
TP_{3H}	-0.23	0.08	0.98
TGP_{1I}	-0.77	-0.2	1.03

Table 3. Gaussian coefficients

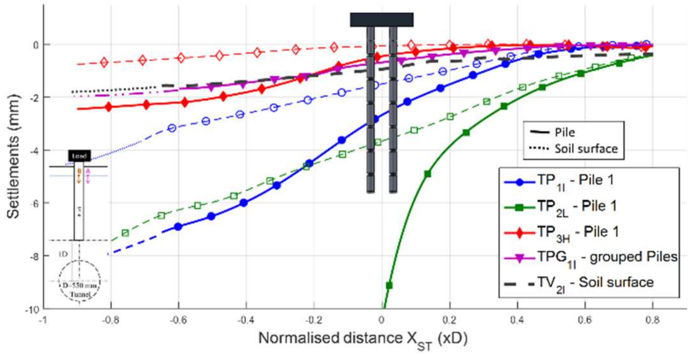

Figure 6. Vertical displacements of the piles and of the surrounding soil surface measured during the tunnelling tests.

4.2 *Pile settlements*

Figure 6 shows, for three tests performed at three different frontal pressures, the pile and soil surface settlements localized at the vicinity of the pile. Settlement curves are plotted according to the TBM relative position from the considered pile or surface displacement sensor. The longitudinal soil profile considered above the tunnel axis in the case of Greenfield condition and the piled group settlements are also plotted in the Figure 6.

In the case of single piles, note that settlement range of the pile and the neighbouring soil are closely related to the imposed frontal pressure. Moreover, the distance of settlements beginning at the front of the TBM decreases when the frontal pressure increases. The vertical settlement of the pile located above the tunnel always settles more than the neighbouring soil surface. Note that this trend is growing once the TBM face passed. At comparable level of face pressure (intermediate pressure), the presence of the pile seems to accentuate the soil surface settlement due to the load transfer between the pile and the soil. In opposite, the presence of the piled group seems to reinforce the soil and limit its settlement due to the piled group effect. This result is in good agreement with 2D experimental results (Jacobsz, et al., 2004) or 2D numerical results (Jongpradist, et al., 2013).

4.3 *Tip force*

Figure 7 shows the ratio between the axial force at pile tip and the load applied at the pile head according to the normalized distance between the pile and the tunnel face (X_{PT}). In those tests with a single pile, this ratio reached its minimum value when the tunnel face is below the pile (X_{PT}=0). Whereas for other tests with a pile group, the above minimum was reached when the tunnel face has bypassed the pile (X_{PT}=-0.2).

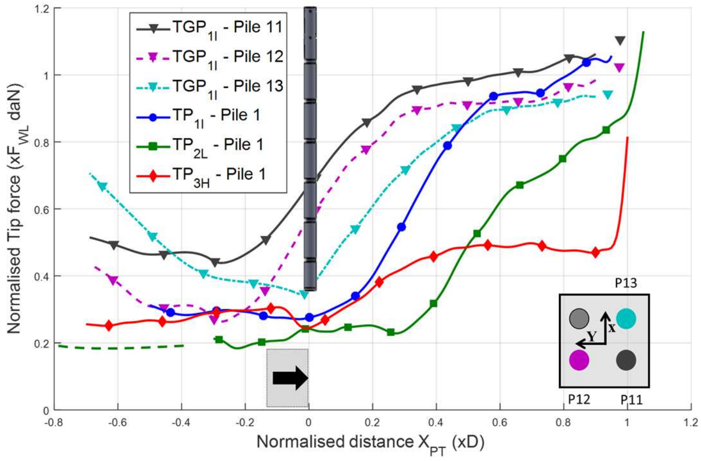

Figure 7. Evolution of the ratio between the tip force and the load applied to the head of the pile

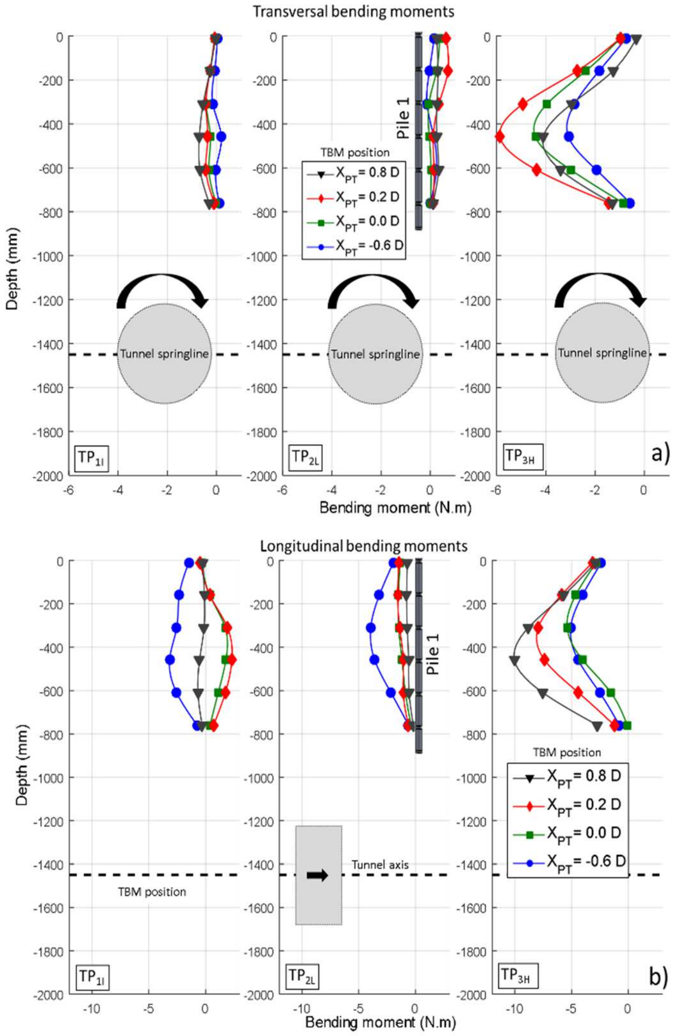

Figure 8. Transversal (a) and longitudinal (b) bending moments measured along the axial pile at different distance (X_{PT}) of the tunnel face during the different tests

The decrease of tip force during tunnelling is due to the mobilization of positive shaft friction along the pile in the presence of relative soil – pile displacements. This decrease is all the greater as the relative soil – pile displacements is high. Thus, note that the ratio is stabilizing for single piles (0.25) then the tip force ratio for the grouped pile is higher (0.4). As seen previously, the pile group settles less than the single pile.

4.4 *Transverse BM vs. longitudinal BM*

Figure 8 shows the transversal (a) and the longitudinal (b) bending moments along the single pile 1 at different tunnel face positions and for three different frontal pressures. Due to the symmetry of the problem, null bending moment might be anticipated. However, this was not observed experimentally on the TBM model. Transversal bending moments developed due apparently to the effects of the cutter wheel rotation. Note that this phenomenon is amplified when the frontal pressure is high.

At the same time, longitudinal bending moments along the pile evolves strongly with the TBM advance. The applied frontal pressure influences the longitudinal bending moments when the pile is located in front of the TBM. In this position, the TBM tends to push the piles along the tunnelling direction. However, it should be emphasized that starting from 0.6D at the rear of the TBM (X_{PT}=-0.6D), the longitudinal bending moments appear to be independent of the applied frontal pressure. At such distances behind the TBM face, only the shear stresses developed along the shield seem to have an influence on the bending moment.

In the case of intermediate tunnel face pressure, Figure 9 shows that a single pile is subject to bending in both directions but predominantly in the longitudinal direction. On the other hand, in the case of a pile group, longitudinal and transversal BMs are quite similar ($M_x \approx M_y$). This difference in behaviour is due to the difference relative to the fixity condition at the pile head. Piles in a group settle less than a single pile but are mechanically more solicited.

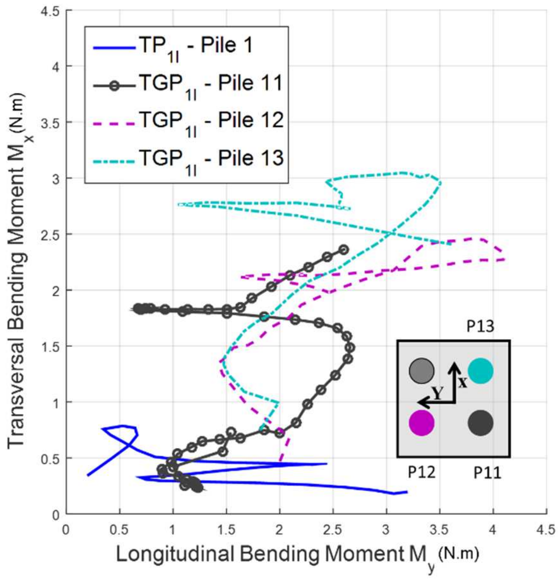

Figure 9. Maximal transversal and longitudinal bending moments measured along axial pile and axial grouped piles

5 CONCLUSIONS

In the framework of the NeTTUN project, a 1g reduced-scale model of EPB TBM was used to assess TBM-soil-pile interactions. Results obtained with this original device show that it is capable of simulating the 3D excavation process closely and confirm the relevance of this model to analyse the impacts of tunnelling on neighbouring structures, in particular piled foundations. A part of these results (soil – pile settlements, axial pile loads and bending moments) appears to be in good agreement with those reported in the literature and obtained under plane strain conditions when it is possible. Moreover, the tests carried out with the 3D TBM model showed non-negligible flexural effects on the piles due to the spatial variations of ground stresses in the longitudinal direction induced by the TBM advancement. These effects were not considered in previous works.

6 ACKNOWLEDGEMENT

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