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Prediction of surface settlements induced by TBM using Artificial Neural Networks method

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ABSTRACT: This paper presents a methodology to correlate ground surface movements and TBM operation parameters based on Artificial Neural Networks. The methodology is applied to the vertical ground surface movements obtained on Contract 2 (4.7 km long) of the subway line B tunnel of Toulouse (France) excavated with an Earth Pressure Balanced TBM. The determination of the most influential TBM operation parameters is based on an elimination procedure. The employed ANN allowed also to study the effect of different types of soil on ground movements.

1 INTRODUCTION

Tunnels built in urban zones are generally, for economic reasons shallow tunnels. The construction of this kind of tunnels can not be realized without having an impact on the existing buildings. The use of new construction methods such as shield Tunnel Boring Machine (TBM) enables to control ground deformations and to guarantee stability in variable geological contexts. In order to ensure an optimal performance of the TBM, it is necessary to identify well the role of its different operation parameters which control the displacements created during different excavation phases. Theses displacements are transmitted towards surface and the resulting ground settlements can affect the nearby constructions. The reduction of ground displacements requires a good knowledge of the TBM operation parameters which are indeed related to many other elements such as the nature and the mechanical characteristics of the excavated soils, the tunnel dimensions, its depth and the performance of excavation ensured by the TBM.

According to the observations carried out on various building sites, the description of settlements has been until recently mainly based on geological and geometrical parameters (Peck 1969). Comprehensive numerical and analytical analysis (Vanoudheusden 2006, Kasper & Meschke 2006) are still time consuming methods and alternative approaches are required to correlate ground movements to TBM operation parameters. In addition, these methods have for the moment considered only simple parameters of the ground-machine interaction. The pressures applied by the TBM during the various phases of confinement (Oota et al. 2006) and annular void grouting (Komiya et al. 2001) are thus generally regarded as the most influential factors on ground displacements. Other TBM operation parameters have also been studied such as the TBM advance rate (Melis et al. 1997), the jack thrusts (Matsushita et al. 1995) and the parameters of TBM deviations during its advance (Vanoudheusden 2006).

Recent studies showed that the artificial neural network (Shahin et al. 2004, Jaksa et al. 2008) can be employed successfully for the prediction of settlements induced by tunnelling (Neaupane & Adhikari 2006, Yoo & Kim 2007). Compared to the usual design methods, they allow analyzing a larger quantity of data by integrating more complicated nonlinear combinations (Kim et al. 2001). The excavation parameters, particularly those of TBM operation, are more easily analyzed with ANN (Javadis 2006, Santos & Celestino 2008). This approach is less severe on the consideration of the geological conditions for settlements prediction; it does not require an identification of the soils' constitutive laws and parameters to represent the variability of the ground (Yoo et al. 2009).

The aim of this paper is to propose and evaluate a methodology based on the ANN to predict vertical ground surface movements, taking into account TBM operation parameters and other geological (nature and thickness of the different soil layers concerned by the tunnel excavation) and geometrical parameters (diameter and depth of the tunnel). The methodology is applied to the particular case study of Contract 2 of Toulouse subway line B tunnel (France). This 4.7 km long tunnel has been excavated by an Earth Pressure Balanced machine (EPB) in the highly overconsolidated Toulouse "molasses". Then, a procedure of successive elimination is proposed to identify the most influential TBM operation parameters affecting settlements. Concerning the geological parameters, the effect of different types of soil on the form and the amplitude of displacements will also be analyzed.

2 CASE STUDY: TOULOUSE SUBWAY LINE B TUNNEL

The 12.6 km long subway line B of Toulouse has been realized with three different pressurized-face TBM techniques: earth pressure balanced TBMs for contracts 2 and 5; slurry shield machine for contract 4; and contract 3 was realized by a compressed air TBM. The tunnels run through the Toulouse "molasses" (hard sandy clay with pockets and lenses of very dense sand). Geotechnical investigations have shown that in these formations, K_0 is greater than 1, generally close to 1.7 (Vanoudheusden 2006). This molasses are covered by alluvia formations and made ground. The excavated diameter is 7.8 m for Contract 2 with a cover ranging from 1.2 to 2.8 diameters. The water table is mostly found 4 m below ground level.

The research project METROTOUL (2002–2005) has been initiated to collect and analyze the results of the different monitoring devices installed during the excavation of the tunnel as well as several of its 21stations (Vanoudheusden 2006).

2.1 *Geological database*

The geology has been determined by more than 300 boreholes drilled within 30 to 50 m from the tunnel axis and through all the soil layers of interest to the project (Antea et al. 2000). On the average, one investigation point was installed every 63 m along the tunnel drive.

For the analysis presented in this paper, the geological data of Contract 2 containing nature and thickness of each soil layer were collected from the boreholes carried out on this contract. The different soil layers are distributed in five categories: Cover (alluvium or fill), Clay, Sandy clay, Sand and "Hard" conglomerate.

The thickness of each type of soil was calculated between the level of the tunnel axis and the ground surface. Statistical analysis is carried out to determine the most frequent geological profiles (Table 1). For this statistical analysis, the thickness of each soil layer is normalized to the tunnel axis depth.

Table 1. Most frequent geological profiles found in the boreholes of Contract 2.

Profile	Cover %	Clay %	Sandy clay %	Sand %	Hard %	Frequency %
1	25	3	45	22	5	12.63
2a	30	40	20	0	10	8.42
2b	30	40	30	0	0	8.42
2c	40	30	30	0	0	8.42
2d	42	26	26	6	0	8.42

Only 95 boreholes were considered in this analysis (the closest boreholes to the 95 transverse settlement profiles containing at least 3 levelling points). The main five geological profiles which represent almost half of the cases found along Contract 2 will be employed in the analysis.

2.2 *In-situ measurements*

The vertical ground surface movements were monitored during the different tunnelling phases by precise levelling of transverse profiles installed every 30 m along the tunnel drive. Each profile consists of at least 5 points located on pavement or on the nearby buildings. Unfortunately, the number of monitoring points close to the tunnel axis is very small (precise levelling is a manual operation and therefore, for safety reasons, only a few points were installed in the middle of streets or boulevards when the tunnel alignment was following them). For the analysis presented in this paper, only points located on buildings are employed, considering that the corresponding movements appeared to be more accurate than those of points installed on the pavement. Based on the small observed amplitudes of displacements and their fast stabilization, only short-term movements (compiled between –20 m and +50 m after the TBM passage) are considered in this analysis. Figure 1 shows the measured ground displacements represented in a cross section according to X/H, with X the horizontal distance of the levelling point from the tunnel axis and H is the depth of the tunnel axis in the corresponding cross section.

It should be mentioned that the data presented were collected along the Contract 2 (4.7 km) where the variation of the TBM operation parameters along it, can affect the form and amplitude of the displacement trough and which explains the observed variation of displacements with X/H. At the ends of the settlement trough (±4X/H), the

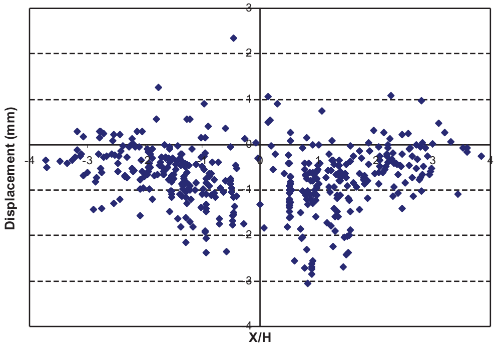

Figure 1. Ground surface displacements measured along Contract 2, represented in cross section.

small movements can be related to the uncertainty of measurements which can thus be estimated at approximately ±0.5 mm. The simulation of such small displacements is one of the difficulties of this analysis, especially with the measured accuracy of about 0.5 mm.

More than 150 TBM operation parameters were recorded on Contract 2. In a first analysis, the following 10 main parameters have been selected by Vanoudheusden (2006): TBM advance rate, hydraulic pressure used for the cutting wheel, confining pressure at the tunnel face, annular void grouting pressure and volume of grout, total jack thrust, time required for the excavation and installation of one tunnel lining ring, horizontal and vertical guidance parameters *Diffdh* and *Diffdv* (which represent change in horizontal and vertical TBM divergence from the design alignment) and total work required for one ring excavation.

3 GROUND SURFACE DISPLACEMENTS PREDICTION

An ANN methodology was used to determine correlation between ground displacements and TBM parameters. The analyzed TBM operation parameters were selected by a preliminary analysis [Boubou *et al.* (2009)] carried out on this contract which did not consider the geological variability along the tunnel drive. The elimination procedure (section 4) used to determine the most influential TBM operation parameters showed that the best description of the observed ground displacements is obtained with the following 7 parameters: TBM advance rate, confining pressure at the tunnel face, vertical guidance parameters *Diffdv*, total jack thrust, the volume of injected grout, hydraulic pressure used for the cutting wheel, and the time required for the excavation and installation of one tunnel lining ring.

In this study, these 7 parameters are employed as the ANN inputs in addition to 5 other parameters representing the geology (thickness H_i of each type of soil). A last parameter [exp $(-X^2/H^2)$] which represents the horizontal distance between the levelling point and the tunnel axis normalised by the tunnel depth was added to the ANN inputs. This parameter was used in order to privilege the data that are close to the tunnel axis (which are of small quantity) by considering an exponential form of X/H.

Out of the 432 available levelling points (Fig. 1), the points that do not belong to a transverse profile of at least 3 points and up to 5 points have been discarded. Thus only 95 levelling points have been considered and their corresponding data have been associated to local geology resulting from the analysis of the closest boreholes.

The optimized ANN geometry is then the following: 13 inputs, two hidden layers with 7 neurons in each one, one output. An optimal number of 6000 calculation cycles was used to perform the ANN training, where 60% (57 values) of data have been used for the actual training and the remaining 40% (38 values) for the validation step. The ANN performance is evaluated by the Root Mean Square Error (RMSE) of the validation step given by Equation 1:

$$RMSE\,\% = \frac{\sqrt{\dfrac{\sum (S^2 - C^2)}{N}}}{\sqrt{\dfrac{\sum S^2}{N}}} \tag{1}$$

where S is the measured value of the displacement; C is the value of the displacement computed by the ANN; and N is the number of considered points for the validation set of data. This definition implies that RMSE should be as low as possible.

The first calculation yields value for RMSE equal to 13.13% at the validation step (Fig. 2). The histogram of the differences between calculated and the corresponding measured displacements showed a Gaussian distribution with 76.3% of the differences smaller than 0.75 mm (Fig. 3).

Calculated settlement trough was drawn in a cross section for the set of mean values of TBM parameters by varying X/H between −4 and +4. Considering the five main geological profiles, Figure 4 shows that the shape of the settlement trough is strongly influenced by the geological conditions. Profile 1 having 22% of sand gave a true settlement trough without the heave behaviour that is observed in some case close to the trough centre. On the other hand, the presence of 10% of conglomerate in the profile 2a induces the smallest settlement at the tunnel axis of all five geological

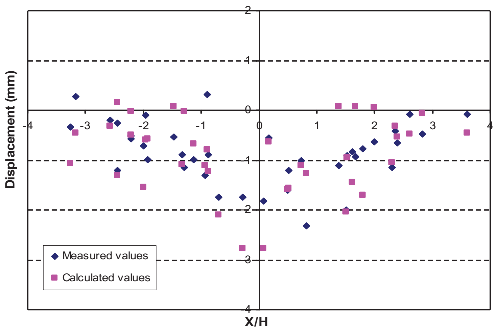

Figure 2. Calculated against measured displacements (validation step).

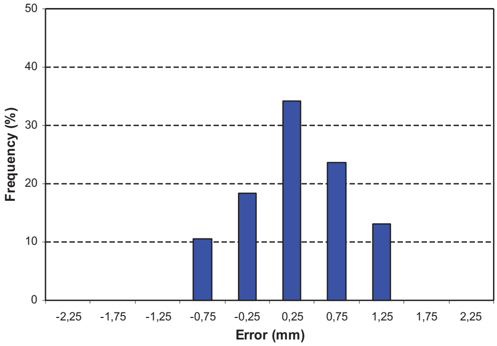

Figure 3. Histogram of the differences between measured and calculated displacements.

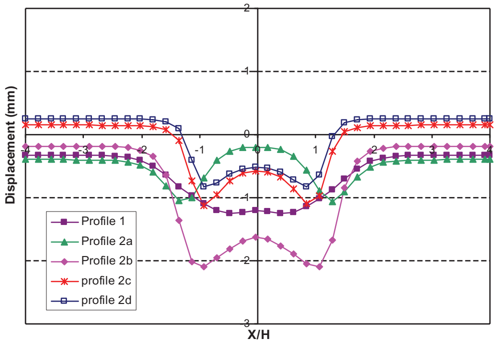

Figure 4. Displacement troughs traced for the principal geological profiles of Contract 2.

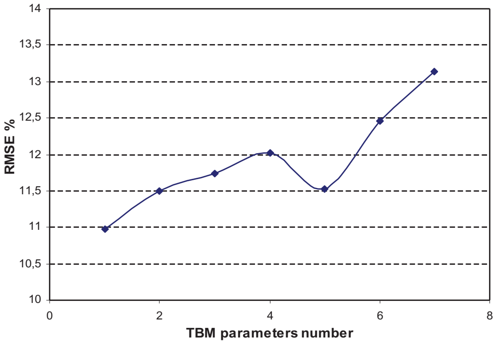

Figure 5. Evolution of RMSE value according to the number of TBM operation parameters employed in the analysis.

profiles. The predicted heave in the trough centre is relatively more important for the profiles 2a, 2b and 2c having an important existence of clayey soil. This behaviour has been observed on all the contracts of Toulouse subway line B and numerical simulation has shown that it can be explained by the highly overconsolidated character of the soil (in particular the clayey molasses) and the corresponding value of K_0.

In order to classify the TBM operation parameters according to their influences on displacements prediction, a procedure of successive elimination of parameters (Boubou et al. 2009) has been applied to the 7 parameters used in this analysis.

4 TBM PARAMETERS ELIMINATION PROCEDURE

The principle of this procedure is that at each step, the parameter that degrades the least the RMSE value when it is not considered in the ANN calculation will be eliminated. It has been noticed that the elimination of some parameters can even improve the RMSE value. The successive elimination of the parameters decreased the value of RMSE up to 5 parameters when this value starts to increase again (Fig. 5). Thereafter the value of RMSE starts to degrade, which is related to an insufficient number of parameters employed in the analysis (conclusion also confirmed by the histogram of the error distribution).

The optimal number of parameters is then 5 parameters, the classification of these parameters according to their importance is presented in Table 2.

The analysis carried out after the elimination of the two least influent parameters (P_1 and P_2) reduces the RMSE value to 11.5%. In this case (calculation with 11 parameters) 81.6% of the points present a difference between predicted and observed displacement smaller than 0.75 mm, compared to 76.3% in the initial case with 13 parameters (Fig. 6).

It can be concluded that the ANN is well adapted to the description of ground surface vertical movements and correlation with TBM parameters. The

Table 2. Classification of TBM parameters according to their relative increasing importance.

N	Parameter
1	Time required for one tunnel ring realisation
2	Hydraulic pressure used for the cutting wheel
3	*Diffdv*—vertical guidance parameter
4	TBM Advance rate
5	Confining pressure
6	Volume of injected grout
7	Total jacks thrust

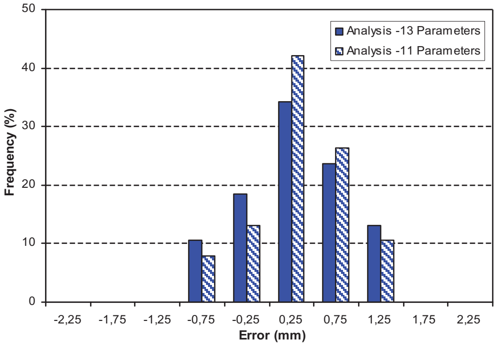

Figure 6. Error distribution histogram for two cases with 11 and 13 parameters employed in the analysis.

proposed methodology is based on both TBM operation parameters and geological data without defining any correlation between ground surface displacements and the employed data. The ANN is based on the training examples in order to calculate the required displacement. Using an optimal number of TBM operation parameters improves the prediction results. A parametric study will thus be required in order to better interpret and physically estimate the influence of each parameter on the results. Concerning the geological data, the role of each geological profile will be presented in the following section.

5 EFFECT OF THE GEOLOGY ON GROUND SURFACE DISPLACEMENTS PREDICTION

In this analysis, the percentages of each type of soil will be varied around the percentages of one of the reference profiles (profile 2c in Table 1). Table 3 presents the different cases considered in the analyses based on the ANN with the 5 optimal TBM operation parameters.

For example, to study the effect of sand on ground displacements, three profiles were proposed (3, 4 and 5). The analysis shows that the observed heave behavior close to the tunnel axis is mainly related to the existence of the clayey soil.

Table 3. Different geological profiles considered.

Profile	Cover %	Clay %	Sandy clay %	Sand %	Hard %
3	40	25	25	10	0
4	40	20	20	20	0
5	40	10	10	40	0
6	40	20	40	0	0
7	40	40	20	0	0
8	40	30	25	0	5
9	40	30	20	0	10
10	40	20	25	0	15

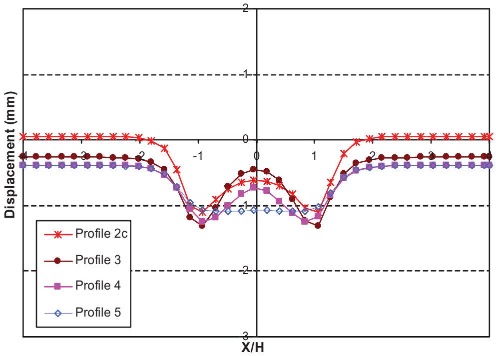

Figure 7. Effect of the sand percentage on the shape of the displacement trough.

The increase of the sand percentage (which is made by reducing the clay and the sandy clay percentages) in the suggested profiles 3, 4 and 5 gives a deeper settlement trough with a reduction in the observed heave close to the tunnel axis (Fig. 7). A settlement trough without the heave behavior is even obtained with the profile 5 (having 40% of sand and 10% of clay).

In a second step, the clay percentage was varied in the two profiles 6 and 7, the variation being made by varying the sandy clay percentage. Figure 8 shows that the increase in the clay percentage from 20 to 40% gives a deeper displacement trough with a more important heave effect close to the tunnel axis.

On the other hand, the increase of the percentage of conglomerate in the profiles 8, 9 and 10 (Fig. 9) induces a reduction in the maximum settlement at the tunnel axis and lessens the heave.

In conclusion, the higher percentages of the two types of soil “sand” and “hard” lessens heave effect close to the tunnel axis. The presence of clayey soil

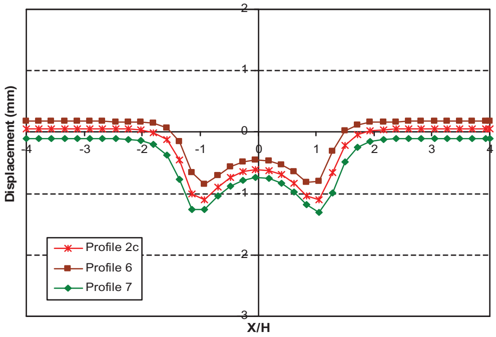

Figure 8. Effect of the clayey soil percentage on the shape of the displacement trough.

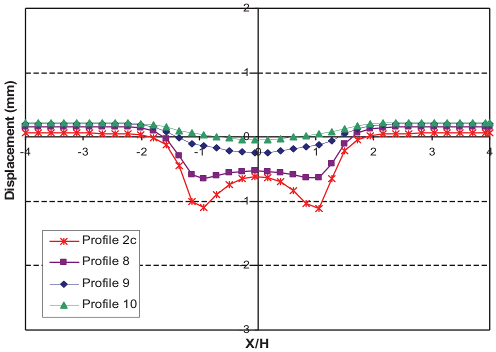

Figure 9. Effect of the hard soil percentage on the shape of the displacement trough.

gives a deeper displacement trough with heave close to the tunnel axis. It is recalled that this heave behavior has been explained by the overconsolidated character of ground particularly in the case of clayey profiles (Vanoudheusden 2006).

6 CONCLUSION

Ground movements induced by tunnelling and their correlation with TBM operation parameters and the surrounding geology were analysed using a methodology based on the artificial neural networks. Data of the Toulouse subway line B tunnel were employed to evaluate the ability of the suggested methodology to describe accurately the observed movements. The elimination procedure provided the five most influential TBM operation parameters on the ground surface settlements. Thus it is possible to analyse with the trained network the effect of the thickness of each type of soil on the shape and the amplitude of settlements. For example, the important presence of sand induces an increase in settlement whereas that of clay induces a modification of the shape of the settlement trough (with possible heave in the vicinity of the trough centre). The presented analysis showed that, based on the available excavation data, artificial neural networks can be a useful tool to predict the displacements induced by the TBM. It must be stressed that the proposed methodology does not require any a priori assumption on the shape of the settlement trough or on the relations between settlements and TBM operation parameters. The results obtained are acceptable even when in the considered case study the measured displacements are relatively small compared to the measurement accuracy. This type of analysis can be employed to determine, on a specific case, the required phenomenon or features to take into account in complex numerical models at a design phase. The developed methodology should be applied in the analysis of other cases of tunnel excavations in other geological contexts and/or with other types of TBM.

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