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Modeling the relationship between ground surface settlements induced by shield tunneling and the operational and geological parameters based on the hybrid PCA/ANFIS method

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ABSTRACT

This paper proposes a methodology that combines the Principal Component Analysis (PCA) with Adaptive Neuro Fuzzy based Inference System (ANFIS) to model the nonlinear relationship between ground surface settlements induced by an earth pressure balanced TBM and the operational and geological parameters. The study is based on data recorded during the excavation of contract 2 of the subway line B tunnel in Toulouse (France).

Prior to modeling, principal components analysis (PCA) and agglomerative hierarchical clustering (AHC) are used to describe the interrelation pattern between the TBM parameters and geology profiles.

At first, a model ANFIS based on 10 selected TBM operation parameters (geology conditions considered as homogenous) is developed and validated by drawing the settlement profiles for different reference points.

Secondly, to take into account the effect of geology on the settlements, 5 parameters representing the thicknesses of categories of soil were added as input variables. Then, a model ANFIS using the significant principal components as inputs is developed and validated. The results indicate a high correlation between predicted and measured settlements despite the low amount of data used in the analysis. In addition, the model is able to predict Gaussian troughs for the representative groups identified by the AHC. The results show that the shape of the predicted settlement troughs could be explained by the TBM parameters and soil profiles that characterize each group.

1. Introduction

The prediction of ground surface settlements induced by shallow tunnel excavation with tunnel boring machines (TBM) is a complex problem that involves a large number of TBM operation parameters that are strongly related to the encountered geology and to the pilot management of the machine. Hence, it is very difficult to model the nonlinear relationship between the settlement and parameters using conventional methods such as least squares regression (Vanoudheusden, 2006). To model this relation, Bouayad et al. (2014) used the partial least squares regression (PLSR) taking into account the interaction between TBM parameters. Despite a logarithmic transformation performed on the displacement, the developed model does not capture the high nonlinearities.

Recent studies have demonstrated that artificial neural networks (ANN) can be efficiently used to model the nonlinear relation between a large number of parameters involved in tunneling construction and the induced ground movements (Suwansawat and Einstein, 2006; Boubou et al., 2010; Mahdevari and Torabi, 2012). More recently, sophisticated models were developed using ANN with evolutionary techniques such as fuzzy logic, and support vector machines algorithms (Mahdevari et al., 2012, 2013; Ocak and Seker, 2013).

The technique known as Adaptive Neuro Fuzzy based Inference Systems (ANFIS) is proved to be a powerful tool for modeling complex problems because of its ability in treating imprecision and uncertainty that may affect data in general. It has been successfully applied to various geotechnical problems but the prediction of settlements induced by tunneling has been recently explored (Hou et al., 2009; Adoko and Wu, 2012; Bouayad and Emeriault, 2013, 2014). Hou et al. (2009) used ANFIS to predict the maximum surface settlement induced by an earth pressure balanced TBM. They showed that the error between the predicted and measured settlements does not exceed 7%, moreover, the comparison of the latter with the error given by back propagation neural network confirmed that ANFIS was more accurate.

This paper proposes a methodology that combines the Principal Component Analysis (PCA) with ANFIS method to model the nonlinear

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relationship between the ground surface settlements, induced by an earth pressure balanced TBM, and the operational and geological parameters. The study is based on data recorded during the excavation of contract 2 of the subway line B tunnel in Toulouse (France).

Prior to modeling, principal components analysis (PCA) and agglomerative hierarchical clustering (AHC) are used to describe the interrelation pattern between the TBM parameters and geology profiles.

To test the applicability of ANFIS method, a first ANFIS_IV model for the surface settlement based on 10 selected TBM operation parameters (considered as the initial variables (IV)) is developed and validated. In this case, the geology is considered as homogenous and the effect of correlations between parameters on the ANFIS performances is studied.

To take into account the effect of geology on the surface settlements, 5 parameters representing the thicknesses of categories of soil were added as input variables. Because of the great number of parameters, PCA method is used to reduce the number of input variables. Then, a second ANFIS_PC model for the surface settlements prediction, considering the significant principal components (PC) as inputs, is developed and validated.

The steps of the developed methodology are summarized as follows:

1. Determine the predominant soil profiles by analyzing the geological parameters using PCA/AHC.
2. Applying PCA to describe the correlations between TBM operational parameters and geological profiles, and AHC to classify them into homogenous groups.
3. Development of ANFIS_IV model for the surface settlement based on the TBM parameters only.
4. Development of ANFIS_PC model for the surface settlement prediction considering the significant principal components, obtained at the second stage, as input variables. The model is then validated by predicting the settlements of the main groups (profiles) identified by the AHC at the step 2.

The computation process was implemented using the Statistical and Fuzzy toolboxes of Matlab (Version 2010a).

2. Case study and geological conditions

The present study is based on the data recorded during the construction of the contract 2 of Toulouse subway line B tunnel (4.7 km in length). An earth pressure balanced TBM of 7.8 m in diameter was used to excavate this tunnel at a depth varying from 1 to 2 diameters and with a water table which is 4 m below the ground surface.

Geological investigations showed that the tunnel crosses highly overconsolidated molasses ($K_0 = 1.7$) covered by alluvium formations between 7 and 9 m thick and historical fill whose thickness may reach 5–8 m. The molasses formations, formed by 8 classes (M1–M8) as reported in Table 1 with their main characteristics (unit weight γh, friction angle φ', cohesion c' and compressive strength Rc), are very heterogeneous with mainly an alternation of the sandy clay and clayey layers. Typical geological profile identified with 4 boreholes in the vicinity of a monitoring section is presented in Fig. 1. Similar profiles have been identified at other 3 monitoring sections installed along the route of the contract 2 (Vanoudheusden, 2006).

The heterogeneity of the molasses results in the dispersion of strength characteristics (as shown in Table 1) and the deformation modulus that varies between 55 and 625 MPa (Houhou et al., 2010). Hence, to better characterize the geology, the different types of soil were grouped into five categories as shown in Table 1.

3. Data monitoring

The recorded data includes the measurements of a great number of TBM operation parameters (more than 150 parameters), and the vertical ground surface displacement monitored by precise leveling of transverse profiles installed approximately every 30 m along the tunnel drive. Each profile consisted of 5 points at least located on nearby buildings. Due to the overconsolidated character of the molasses, the observed displacements are small in amplitude (a few millimeters). They can be classified into two main zones (Vanoudheusden, 2006): pure settlements zone where the displacement profiles present a Gaussian shape as reported by Peck (1969); heave in the center zones where settlements were observed at a certain distance from the tunnel axis while reduced settlement or heave were obtained for points close to the tunnel axis. Because of the overconsolidated nature of the ground, only short-term displacements (measured when the TBM is 50 m in front of the point) are considered in the present study, with a measurement accuracy estimated to about 0.5 mm.

A preliminary analysis has led to select 10 TBM parameters that seem to be the most influential on displacements (Vanoudheusden, 2006). These parameters, considered in the present study, are as follows:

Ra: TBM advance rate, Pf: face pressure,
Pg: Annular void grouting pressure, Vg: volume of grout injected to fill the annular void,
Pw: Pressure of the cutting wheel representing the pressure required to rotate the cutter wheel, Pt: Total jack thrusts to push the TBM during the excavation of each ring,
Tr: Time required for the excavation and installation of one tunnel lining ring,
Dh and Dv: Horizontal and vertical guidance parameters respectively,
En: Total work representing the energy required for the excavation of 1 m^3 of soil.

To be used in the analysis, the values of these parameters recorded every minute have to be preprocessed and the main steps were

Table 1
Properties of the different soil formations.

Categories	Soil type	γh (kN/m^3)		Rc (MPa)		φ' (°)		c' (kPa)	
		M*	SD*	M*	SD*				
Cover (C)	Fill + Alluvium	20	–	–	–	25		0	
Clay (Cl)	M1 – Clays	21.6	0.06	0.75	0.31	31.9	33.1	80	80
	M2 – Calcareous Clays	22.2	0.08	1.05	0.60	31.2		174	
Sandy Clay (Sc)	M3 – Sandy Clays	21.7	0.08	0.54	0.23	32.6		83.6	
	M4 – Clayey Sands	20.9	0.07	0.18	0.25	30.2	36.9	52	0
Sand (S)	M5 – Fine to Medium Sands	20.4	0.09	–	–	35.7		0	
	M6 – Coarse Sands	–	–	–	–	–		–	
Conglomerate (Cg)	M7 – Argillaceous Limestone	23.7	0.09	4.04	3.37	–		–	
	M8 – Sandstone	23.8	0.08	3.57	3.03	–		–	

* M: Mean, SD: Standard deviation.