A numerical framework for soft ground tunnelling applications

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ABSTRACT
In this study, a simple constitutive model that is suitable for the analysis of natural soils in contact with geotechnical structures has been developed based on the multilaminate framework. The model takes into account the inherent and induced anisotropy, hardening, and bonding degradation effects under both loading and unloading stress conditions. The model is implemented into a finite element program, successfully calibrated and used to simulate the construction of Ottawa outfall tunnel in highly sensitive clay. A parametric study is conducted to investigate the effect of soil non-homogeneity on surface settlement and plastic zone development around the tunnel. Results indicated that the presence of a sand layer above the tunnel can lead to increasing surface settlement, depending on the depth of the layer below ground surface. It has been concluded that closed form solutions should be used with care in such subsurface conditions.

RÉSUMÉ
Dans cette étude, un modèle de comportement permettant d'analyser l'interaction des sols naturels avec des structures géotechniques a été développé en se basant sur une structure multi-plans. Ce modèle prend en compte l'anisotropie induite et inhérente, l'écrouissage ainsi que les effets dues à la perte d'adhésion sous des conditions de contraintes en chargement et en déchargement. Ce modèle a été implémenté dans un code d'éléments finis, calibré avec succès et utilisé pour simuler la construction d'un tunnel déversoir dans une argile hautement sensible à Ottawa. Une étude paramétrique est menée pour étudier l'effet de l'hétérogénéité d'un sol sur les tassements en surface ainsi que sur la zone plastique développée au voisinage du tunnel. Les résultats montrent que la présence d'une couche de sable au dessus du tunnel peut provoquer une augmentation des tassements en surface, dépendamment de l'épaisseur de la couche en dessous de la surface du terrain.

1 INTRODUCTION

Surface settlement induced by tunnelling in soft ground has been conventionally analyzed based on empirical formulae (e.g. Peck 1969); closed form solutions (e.g. Sagaseta, 1987, Virruijt and Booker, 1996, Loganathan and Poulos, 1998, Park, 2004, etc.), semi-analytical solutions (e.g. Lo et al., 1984, Rowe, 1983, etc.), or numerical analyses (e.g. Potts and Addenbrooke, 1997, Lee and Rowe, 1990, etc.). Although empirical methods have been used extensively and successfully over the years, a theoretical solution is still relevant considering the wide variation in subsurface soil conditions. However, theoretical solutions usually involve simplifying assumptions regarding the tunnel geometry, soil homogeneity, anisotropy, constitutive relation, etc. Numerical analysis provides the flexibility of simulating different tunnel geometry, excavation sequence, and allows for the application of advanced soil models.

It has been recognized by geotechnical engineers and researchers that constitutive models that account for all known characteristics of soil behaviour (e.g. strength anisotropy, rotation of principal stresses, bonding effects, viscous effects, etc.) are difficult to use and a relevant model is usually employed to solve a given practical geotechnical problem. Among these soil characteristics, the strength anisotropy and rotation of principal stresses are known to have a significant effect on the modelling of geotechnical problems.

The Critical State model developed at Cambridge (Wood, 1990) for normally consolidated and lightly overconsolidated clays is an isotropic hardening model and does not account for the rotation of principal stresses. Anisotropic hardening models (e.g. Wood and Graham 1990, Dafalias et al., 2002) do account for the rotation of principal stresses through a transitional rule described for the yield surface. However, the parameters of these models are based on tests in which no rotation of principal stresses takes place.

A multilaminate framework for modelling soft clay has been introduced by Pande and Sharma (1983) based on the work of Calladine (1971). Extensions to the model have been presented by several authors (e.g. Pietruszczak and Pande, 2001, Cudny and Vermeer 2004, Wiltafsky et al. 2002, Schuller and Schweiger 2002) to model the inherent anisotropy and destructuration of soft clays.

The objective of this study is to investigate the effect of soil bonding and non-homogeneity on the ground response to tunnelling in natural clay using a multilaminate framework that has been developed based on the work of Cudny and Vermeer (2004). Of course, tunnelling involves three-dimensional stress re-distribution in the ground, especially near the tunnel face. For the sake of simplicity, all analysis presented in this study are conducted under plane strain conditions. A brief overview of the multilaminate concept is provided in the following section.

2 THE MULTILAMINATE CONCEPT

The multilaminate framework was introduced by Zienkiewicz and Pande (1977) to model the strength anisotropy of rock due to two or many sets of families of plane of weakness. The basic idea is to consider a solid block of homogeneous isotropic, linear elastic material, intersected by an infinite number of randomly orientated planes. These planes render the solid block into an assemblage of perfectly-fitting polyhedral blocks (Figure 1). It is assumed that the deformation behaviour of such a material block is obtainable by evaluating the deformation of these contact planes under the current effective normal and shear stress components. In other words, when loads are applied to a soil mass, contact forces between adjacent particles develop which can be split into normal and tangential components. The overall deformation behaviour of the soil mass results from both deformation of individual particles and relative sliding between the particles. The latter is the major contribution to the overall strain and this contribution is accounted for in the multilaminate framework.

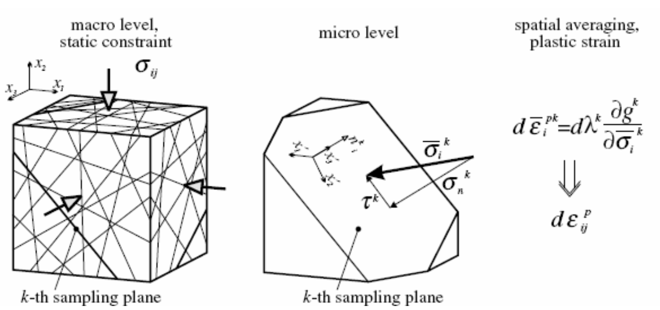

Figure 1 Schematic description of the multilaminate framework (Cudny and Vermeer, 2003)

Since the introduction of the multilaminate framework for the analysis of clayey soils in 1983, several improvements and extensions was introduced. A multilaminate plasticity formulation was presented by Pietruszczak and Pande (1987) to account for the volumetric and deviatoric hardening of soils. Karstunen and Pande (1997) incorporated the deviatoric hardening and non-associated flow rule in their multilaminate formulation. The model was used to simulate the shear band formation in NATM tunnelling (Schuller and Schweiger 2002). Wiltafsky et al. (2002) presented a formulation employing the double hardening and volumetric hardening rules. A new version of the multilaminate model was presented by Cudny and Vemeer (2004) to account for the anisotropy and destructuration of soft clay.

Different aspects of the model development including the soil behaviour under both elastic and plastic conditions, hardening rule and numerical integration procedure is discussed elsewhere (Dang, H.K., 2007). The model is implemented into Plaxis Professional V8.2 (Brinkgreve, 2001) using the User Defined module. The developed model has been verified using benchmark problems and field measurements taken during the construction of tunnels in clays. The case of the Ottawa tunnel is discussed in the following section.

3 ANALYSIS OF THE OTTAWA OUTFALL TUNNEL

The Ottawa outfall sewer tunnel runs parallel to the Ottawa River in Ottawa, Ontario, Canada. For the entire length of the tunnel, soil condition is uniform and consists of overconsolidated Leda clay. The sensitivities of the clay range from 28 for the upper layer to more than 500 for the lower layer.

The tunnel invert is located at an average depth of approximately 19.8 m below the surface. The outside diameter is 3.05 m, the inside diameter of the completed structure is 2.44 m. The tunnel was driven from its west end by a TBM machine and lined immediately with corrugated segmented steel liner rings. About 29.5 kPa air pressure was maintained in the tunnel during excavation. Grout was pumped into the space between the clay and the liner ring. On completion of the excavation, reinforced concrete segments, 0.3 m thick, were installed.

To measure the settlement induced by tunnel construction, three ground-movement gauges were installed at a depth of 3.05 m. One located at the centerline, and the others are located at 7.62 m and 15.24 m from the tunnel centerline. However, only settlements at the centerline gauge and at 7.62 m from the centerline were measured.

Finite element analysis is conducted to simulate the tunnel construction process using the developed model. The finite element mesh is shown in Figure 2. Soil parameters have been estimated using the available soil data and field testing results conducted on similar sensitive clays. A summary of soil parameters is given in Table 1, where:

ϕ = angle of internal friction;
c = soil cohesion;
ψ = dilation angle;
υ = Poisson's ratio;
λ^* = the modified compression index $\cong$ Ip/500;
κ^* = the modified swelling index $\cong 0.25\lambda^*$;
Ω = microstructure parameter;
OCR = over-consolidation ratio;
b_o = average bonding parameter;
K_o = coefficient of earth pressure at rest

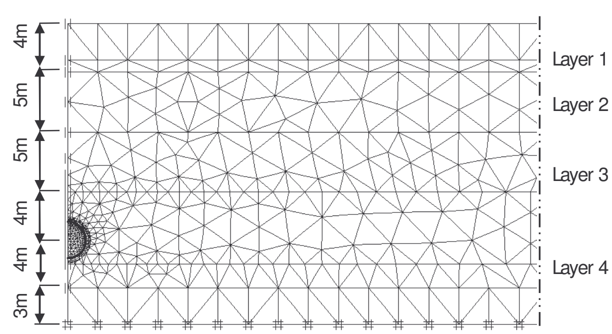

Figure 2 Finite element mesh used for the analysis of Ottawa tunnel

The calculated settlement trough is compared with the field measurements 3 m below ground surface (see Figure 3). A maximum surface settlement of 0.73 cm is calculated above the tunnel centreline which agrees with the field measurement (0.9 cm ±0.3 cm) taken during the tunnel construction. A radial stress of 92 kPa is calculated at the tunnel crown and is found to be in reasonable agreement with the stress measured in the lining (85 kPa) after the tunnel construction.

Layer	ϕ (°)	c (kPa	ψ (°)	Ko	ν	$\lambda*$	$\kappa*$	Ω_{ϖ}	OCR	b_o
1	17	0.1	0	1.48	0.3	0.092	0.023	1.20	5.50	2.05
2	17	0.1	0	1.33	0.3	0.092	0.023	1.20	5.00	1.79
3	17	0.1	0	1.14	0.3	0.056	0.014	1.20	4.00	1.44
4	17	0.1	0	0.89	0.3	0.020	0.005	1.20	3.00	1.01
5	17	0.1	0	0.70	0.3	0.024	0.006	1.20	2.50	0.68

Table 1 Soil parameters used in the analysis of the Ottawa tunnel

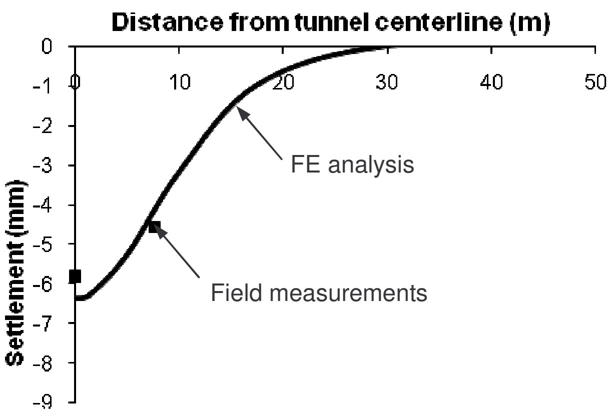

Figure 3 Soil displacement at the depth of 3m below ground surface

4 THE EFFECT OF SOIL NON-HOMOGENEITY: A PARAMETRIC STUDY

The effect of soil non-homogeneity is investigated by adopting the same problem geometry and introducing a sand layer within a homogenous clay deposit. The depth of the sand layer has been incrementally increased from 0 m to 7 m below ground surface and the corresponding surface settlement is calculated for each case. The properties of the sand and clay layers are given in Table 2.

Layer	ϕ (°)	c (kPa)	ψ (°)	ν	Ko	$\lambda*$	$\kappa*$	Ω_{ϖ}	OCR
Clay	17.0	0.1	0.0	0.3	1.0	0.1	0.0	1.2	1.5
Sand	30.0	0.1	0.0	0.3	1.0				

Table 2 Properties of the clay and sand layer

Figure 4 shows the calculated surface settlement for three different cases, namely, h = 0 m, h = 3 m, and h = 7 m. Displacements are also compared to the case of homogenous clay layer. It was found that the presence of the sand layer lead to an increase in surface settlement by up to 20% depending on the location of the layer. The closer the layer to the surface the more tunnelling induced settlement that develops. This may be explained by the confining effects that the sand layer is subjected to at greater depth which contributes to improving the shear strength of the sand layer. The extent of the plastic zone developed around the tunnel is shown in Figure 5 for the cases of h = 0 m and h = 7 m. The presence of sand layer near the tunnel crown limited the propagation of the plastic zone in the clay due to tunnel excavation.

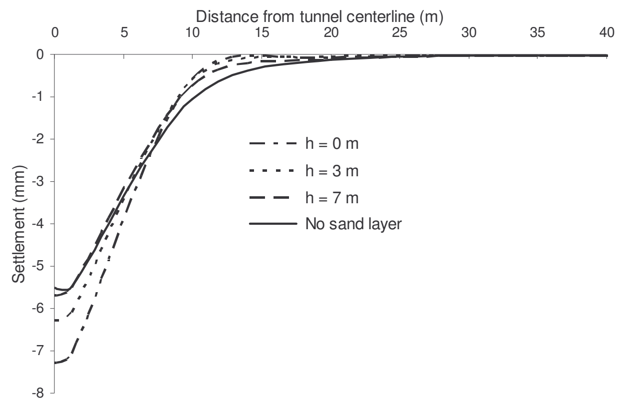

Figure 4 Effect of soil non-homogeneity on surface settlement

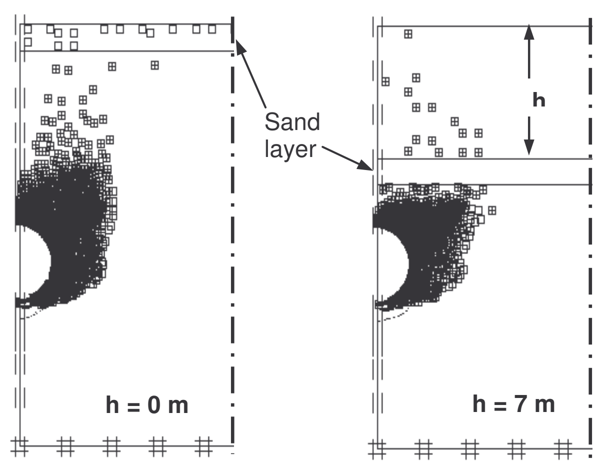

Figure 5 Effect of the non-homogeneity on plastic zone development

5 SUMMARY AND CONCLUSIONS

A numerical model based on the multilaminate framework has been developed and successfully used to investigate the effect of soil structure and non-homogeneity on the tunnelling induced surface settlement and plastic zone development around the tunnel. A parametric study was conducted to investigate the effect of a sand layer above the tunnel excavated in homogenous clay. The presence of the sand layer altered the deformation pattern and lead to an increase in the surface settlement by up to 20%. The results reported in this study should be confirmed using experimental testing and field investigation.

ACKNOWLEDGEMENT

This research is supported by Fonds Québécois de la Recherche sur la Nature et les Technologies (FQRNT) and Natural Sciences and Engineering Research Council of Canada (NSERC).

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