3D Modeling of Soil Nailed Excavations

Modélisation Tridimensionel d'excavations en Sol Cloué

Alexei Gino NÁJAR Jimenez
Polytechnic School, University of São Paulo, Brazil + alexei_najar@yahoo.es
Waldemar HACHICH
Polytechnic School, University of São Paulo, Brazil + whachich@usp.br

ABSTRACT
Quite frequently the analysis and design of soil nailed structures is based upon the Limit Equilibrium Method. This is, in a sense contradictory, since soil nails constitute a passive reinforcement which requires deformation for the resistance to be mobilized, making it desirable to be able to predict the displacements of soil nailed structures, as well as the redistribution of stresses among nails during the several phases of the excavation/installation procedure. This is especially true when nailed excavations are close to sensitive structures or utilities, as it is often the case in densely populated areas. In this study, two-dimensional (2D) and three-dimensional (3D) stress-strain analysis are compared for hypothetical and real situations, in an attempt to explore how simple a model can be adopted and still allow reasonable prediction of the behavior of nailed excavations. Solutions based on elastic-plastic Mohr-Coulomb and hyperbolic models are compared with incremental linear elastic analyses. In all cases considerable attention is focused on the choice of parameters that are compatible with the stress path prevalent in different regions of the excavated material.

RÉSUMÉ
Très souvent l'analyse et la conception de structures de sol cloué sont basées sur la Méthode d'Equilibre Limite. Cela est, en un sens, contradictoire, puisque les clous se constituent en un renforcement passif qui exige des déformations pour la mobilisation de la résistance; il serait donc souhaitable de pouvoir prévoir les déplacements des structures de sol cloué, ainsi que la rédistribution des contraintes entre les clous au cours des diverses phases de l'excavation / installation. Cela est particulièrement vrai dès que les excavations son près de structures sensibles ou d'installations de services publics, comme c'est souvent le cas dans les zones fort peuplées. Cet étude présente la comparaison d'analyses 2D et 3D pour situations hypothétiques et réelles, dans le contexte d'explorer les limites d'utilisation d'un modèle simple qui puisse encore permettre des prévisions raisonables du comportement des structures de sol cloué. Des solutions basées sur les modèles elastique-plastique Mohr-Coulomb et hyperbolique sont comparées avec analyses élastiques linéaires incrementales. Dans tous les cas, une grande attention est centrée sur le choix de paramètres qui soyent compatibles avec les trajectoires de contraintes dans les différentes régions du massif.

Keywords : Soil Nailed, 3D Numerical Analysis, Theory of Elasticity, Stress Path, Finite Element, Excavation

1 INTRODUCTION

The importance of stress-strain analyses of soil nailed structures is most evident in situations in which knowledge of the displacements around the excavation is essential for ensuring the safety of nearby buildings and utilities. 2D numerical analyses are useful for estimating displacements, but the behavior of nails cannot be properly accounted for, because they are simulated as continuous elements in the longitudinal direction. 3D numerical analyses are therefore desirable in principle, despite the added modeling effort required.

Quite complete and representative constitutive models are available, but the required evaluation of many material parameters is usually beyond the reach of day-to-day geotechnical practice. The present investigation is aimed at assessing the extent to which relatively simple constitutive models, such as those of linear elasticity, can be used to adequately represent the behavior of nailed excavations. One of the main conclusions is that even if the soil were perfectly homogeneous, different elastic parameters would have to be assigned to different regions, because of the different prevailing stress paths.

2 STRESS PATHS IN SOIL AROUND AN EXCAVATION

Results reported in the literature (Resendiz and Zonana, 1969; Lambe and Whitman, 1969; Cardoso and Carreto, 1985; apud Najar, 2008) were used to derive typical relationships between Young's modulus for different stress paths (Table 1). There are clear indications that results are also affected by the corresponding dependence of Poisson's ratio on stress paths, but this effect has not been studied here.

Table 1 - Parameters of soil

Unit weight $\gamma = 18$ kN/m^3
Coefficient of lateral earth pressure at rest Ko = 0,64
Young's modulus, compression loading $E_{CL} = 10$ MPa
Young's modulus, compression unloading $E_{CU} = 30$ MPa
Young's modulus, extension unloading $E_{EU} = 90$ MPa

Figure 1 shows some typical stress paths undergone by elements around a 7-step excavation, as well as the simple lab stress paths that represent approximately those of points B (compression unloading) and D (extension unloading).

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)
© 2009 IOS Press.
doi:10.3233/978-1-60750-031-5-1385

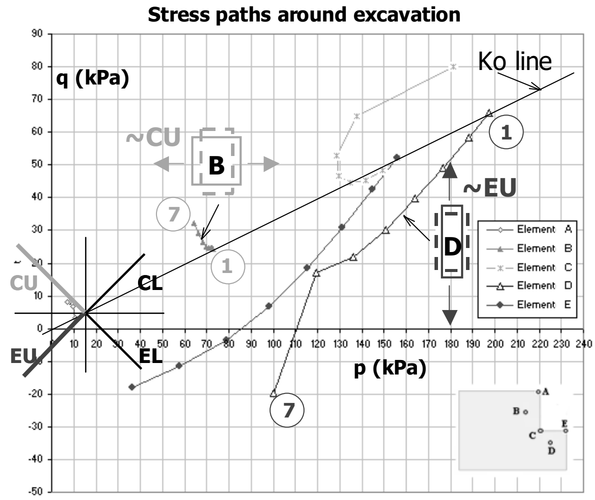

Figure 1 – Stress paths around a 7-step excavation.

Figure 2 shows the results of an iterative process, in which linear elastic analysis is started on the assumption of homogeneity, and Young's moduli are adjusted at the end of each iteration according to the resulting stress path. Except for some stress concentrations and approximation errors, essentially two regions result: one in compression unloading and one in extension unloading, such as elements B and D, respectively, in Figure 1. The typical distribution arrived at in Figure 2 is quite similar to that proposed by Eisenstein and Medeiros (1983).

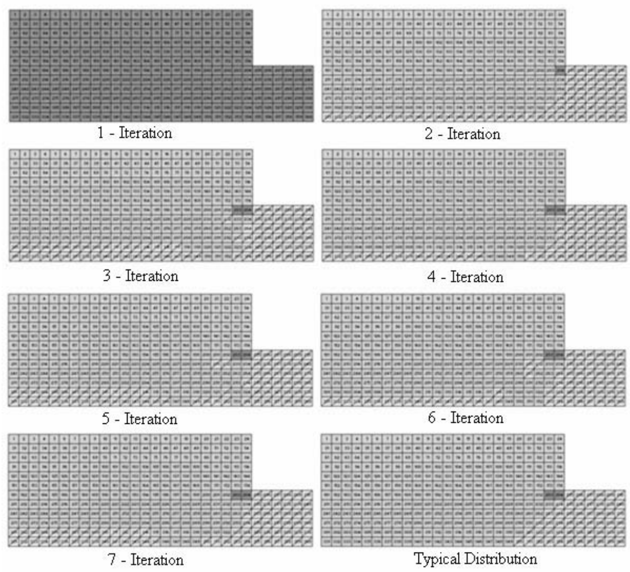

Figure 2 – Iterations carried out in linear analyses in order to arrive at a typical distribution of stress paths in the soil around an excavation (grey – CL; beige – CU; green – EU;).

Figures 3 and 4 show the calculated horizontal displacements of the face of the vertical excavation and vertical displacements of the original ground surface. One should be able to identify the unrealistic behavior of the homogeneous analysis (iteration 1) and, by contrast, the similarity of the results of all other iterations, including the final typical distribution.

This typical distribution has been adopted in all excavation steps of all subsequent 3D analyses of nailed excavations (see, for example, Figures 6 and 10). No slippage has been allowed at the nail-soil and soil-shotcrete interfaces. Each 3D analysis is performed for a slice that extends from the centerline of the nail to the midpoint between adjacent nail columns, i.e., half the horizontal nail spacing. The analyses duplicated the construction procedure: excavation for next step, nail installation, shotcrete placing.

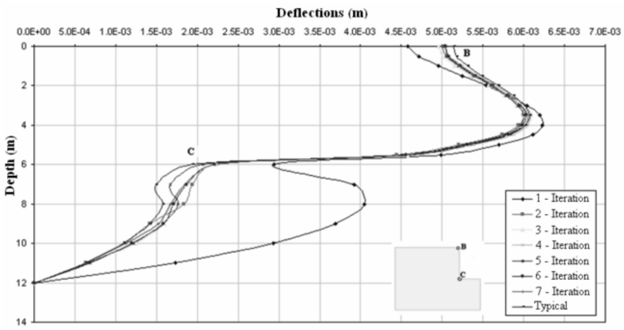

Figure 3 – Horizontal displacements of face of excavation.

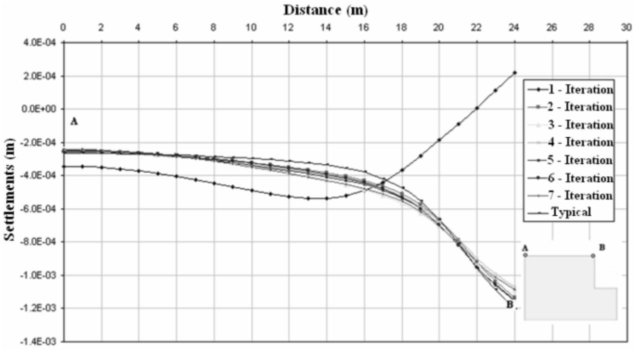

Figure 4 – Vertical displacements of ground surface.

3 COMPARISON OF 2D AND 3D ANALYSES FOR AN HYPOTHETICAL CASE

2D and 3D linear elastic analyses, with stress path dependent moduli, have been compared between themselves for a hypothetical nailed excavation, and with the results of Lima et. al (2002), who had performed a 2D analysis of the same case under the assumption of elastic-perfectly plastic Mohr-Coulomb material. The geometry of the problem is presented in figure 5, and Table 2 summarizes the parameters adopted for numerical modeling. According to Lima et. al (2002), the safety factor of the unreinforced excavation would be 1.05, as calculated by Limit Equilibrium procedures.

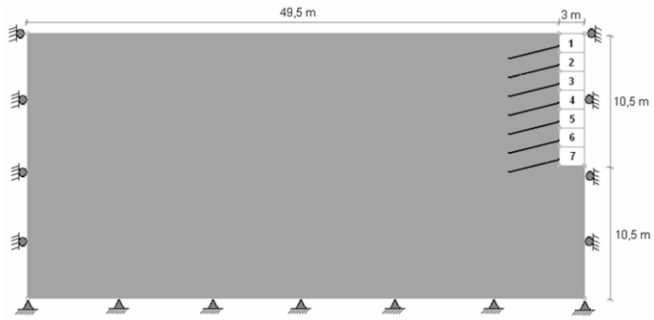

Figure 5 – Geometric model and boundary conditions.

For each stage of the excavation the soil adjacent to it was subdivided in regions (figure 6), according to the results of section 2 above. Since from one stage to the next certain regions undergo changes in stress paths, moduli had to be adjusted accordingly.

Calculated horizontal displacements of a vertical reference line located 1 m behind the face of the excavation, at midpoint between nailed sections, are displayed in figure 7. Figure 8 presents the settlements of the ground surface.

Table 2 - Parameters used in numerical modeling.

Soil:
- Unit weight $\gamma = 18.5$ kN/m^3
- Coefficient of lateral earth pressure at rest Ko = 0.5
- Young's modulus, compression unloading $E_{CU} = 45$ MPa
- Young's modulus, extension unloading $E_{EU} = 135$ MPa
- Poisson's ratio $\nu = 0.25$

Nails:
- Young's modulus E = 205 GPa
- Vertical and horizontal spacing $S_h = S_v = 1.5$m
- Length L= 6m

Shotcrete:
- Young's modulus E = 24 GPa
- Thickness t = 100mm

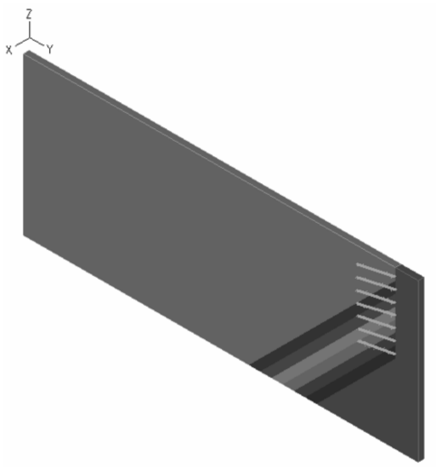

Figure 6 – Division of the soil in regions to adjust the parameters of elastic during the excavation.

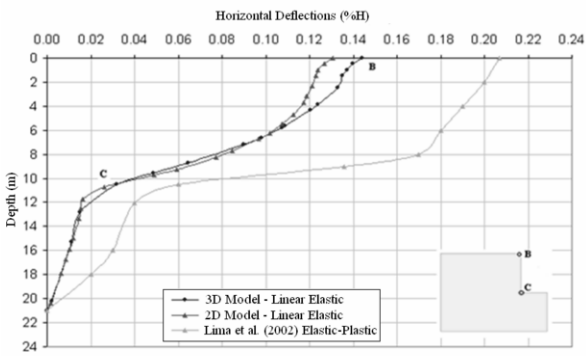

Figure 7 – Comparison of deflections profiles.

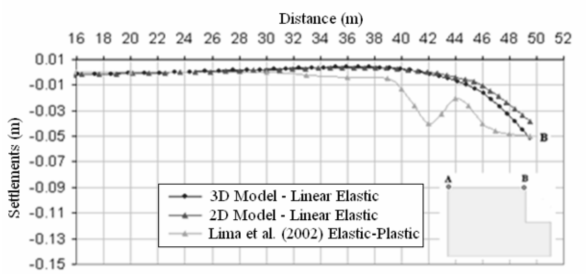

Figure 8 – Comparison of settlements profiles.

The larger displacements predicted by Lima et al. (2002) are probably attributable to the inadequacy of the 2D simulation, combined with the use of planar interface elements between the "2D nails" and the soil. The 2D model analyzed in the present study, which does not account for interface slippage, is slightly stiffer than the 3D model, as would be expected. The influence of the interface elements is more apparent in horizontal displacements. For all practical purposes the maximum vertical displacement (point B) is the same for all three analyses.

The influence of the constitutive model on the results could not be conclusively isolated from the other factors in this comparison.

4 COMPARISON OF 3D ANALYSES WITH THE INSTRUMENTED EXCAVATION OF THE DAVIS RESEARCH PROGRAM

In this section, 3D numerical analyses are compared to the behavior of a real soil-nailed excavation (Shen et. al, 1981), monitored by inclinometers and strain gauges. The geometry of the excavation and its reinforcement are shown in figure 9.

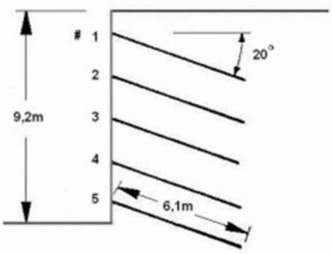

Figure 9 – Geometry of excavation and reinforcement system.

The 3D numerical analysis of the present study, as described in sections 2 and 3, is compared to the field measurements and also to the 3D numerical model analyzed by Zhang et. al (1999), which adopts a hyperbolic model to represent the behavior of the soil, with soil-nail interface elements. Table 3 displays the adopted values of Young's moduli, calculated from the coefficients of the hyperbolic model adopted by Zhang et al. (1999), while other material properties are displayed in Table 4. The values of Young's moduli correspond approximately to secant moduli at 50% of maximum deviator stress.

Table 3 – Values of Young's moduli used in 3D model.

H (m)	$E_{sec50\%\text{ - CU}}$ (kPa)	$E_{sec50\%\text{ - EU}}$ (kPa)
0.915	30752	92256
2.745	53264	159792
4.575	68763	206290
6.405	81362	244086
8.235	92256	276767
10.065	101993	305978
11.895	110878	332633
13.725	119102	357305
15.555	126794	380381
17.385	134045	402134

Table 4 – Material parameters used in numerical modeling.

Soil:	Unit weight $\gamma = 19$ kN/m^3
	Coefficient of lateral earth pressure at rest Ko = 0,64
	Poisson's ratio $\nu = 0.25$
Nails:	Young's modulus E = 205 GPa
	Vertical and horizontal spacing $S_h = S_v = 1{,}83$m
Shotcrete:	Young's modulus E = 24 GPa
	Thickness t = 100mm

As shown in Table 3, the incremental linear elastic model of this study took into account the increase in Young's modulus with confining stress, in addition to the aforementioned stress path dependency. Figure 10 exhibits the regions of soil that undergo elastic parameter changes during excavation.

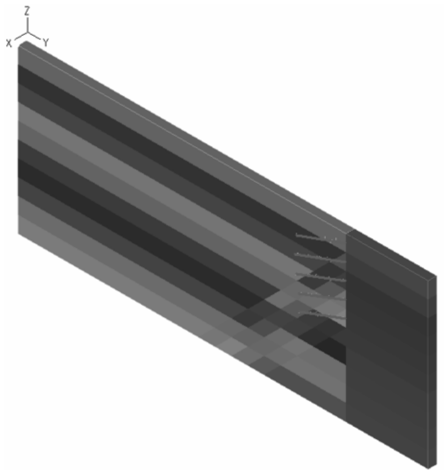

Figure 10 – Division in regions of soil near excavations to adjust the elastic parameters during excavation.

The profiles of horizontal displacements 1.5 m behind the face of the vertical excavation (the position of the inclinometers) shows that the hyperbolic model (Zhang et al., 1999) displays a better fit to the measured displacements, while the maximum horizontal displacement predicted by the incremental linear elastic model lies somewhat closer to the observed value (Figure 11).

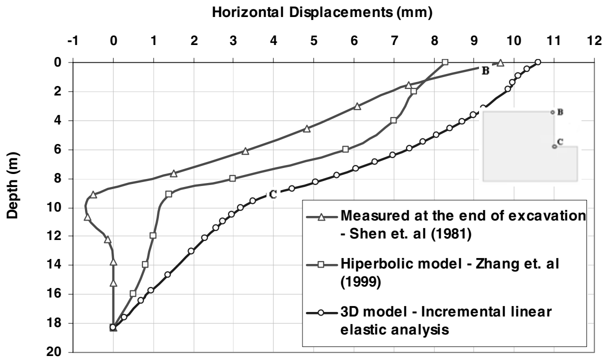

Figure 11 – Comparison of horizontal displacements.

The comparison of vertical displacements is shown in Figure 12. The large settlements measured by Shen et al. (1981) are probably due to the development of cracks during excavation, as reported in their work. The difference between the maximum displacements predicted by the 3D numerical models is close to 2 mm.

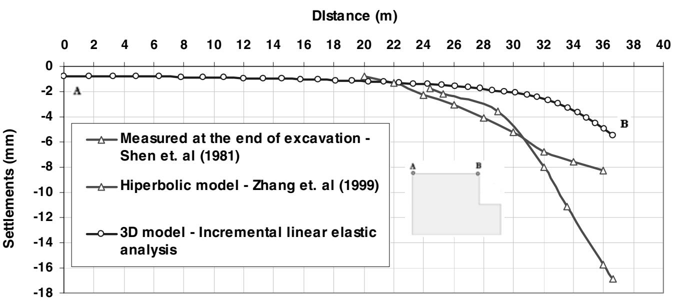

Figure 12 – Comparison of vertical displacements.

Nail tension, as measured by Shen et. al (1981), is smaller than predicted by the 3D model (Figure 13). This result is compatible with the lack of interface elements to properly represent the soil-nail interaction.

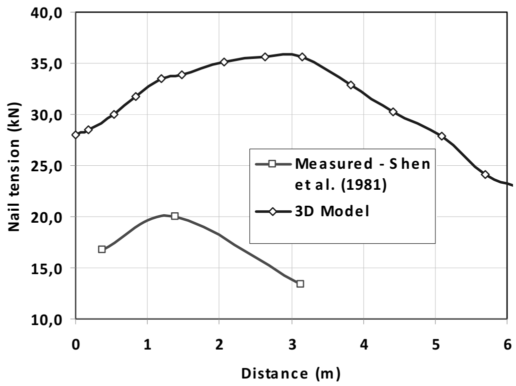

Figure 13 – Axial force comparison

5 CONCLUSIONS

The analyses suggest that 2D models are in fact too rigid due to the approximation of nails by planar inclusions and should therefore be progressively replaced by 3D models.

Simple models based on linear elasticity may indeed lead to reasonable results, as compared to field data and to analyses that adopt more refined constitutive models. However, this can only be achieved if elastic parameters are chosen so as to be compatible with the different stress paths and stress levels in different regions around the excavation.

Interface elements to represent soil-nail interaction and non-homogeneous Poisson's ratio are probably justified improvements for better predictions, and shall be investigated in the future. It is hoped that the introduction of such refinements may correct inconsistencies in the shape and value of displacement profiles (such as the horizontal displacements below the bottom of the excavation).

REFERENCES

EISENSTEIN, Z.; MEDEIROS, L. V. A deep retaining structure in till and sand: part 2: performance and analysis, 1983. **Canadian Geotechnical Journal**, Ottawa, CA, v. 20, n. 1, p. 120-130, Fev. 1983.

LIMA, A. P.; GERSCOVICH, D. M. S.; SAYÃO, A. S. F. J. Modelagem numérica de escavações grampeadas (in Portuguese). In: I CONGRESSO LUSO-BRASILEIRO DE GEOTECNIA, 1., 2002, São Paulo. **Anais...** São Paulo: 2002, p. 447-457.

NAJAR, A. G. J. **Análises tensão-deformação de estruturas de solo grampeado (in Portuguese)**. 2008. 120 p. Dissertação (Mestrado) – Escola Politécnica, Universidade de São Paulo, São Paulo, 2008.

SHEN, C. K. et. al Field measurements of earth support system. **Journal of the Geotechnical Engineering Division**, ASCE, New York, v. 107, n. 12, p. 1625-1642, 1981.

ZHANG, M.; SONG, E.; CHEN, Z. Ground movement analysis of nailing construction by three-dimensional (3-D) finite element modeling (FEM). **Journal of Computers and Geotechnics**, Barking Essex, v. 25, p 191-204, 1999.