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Numerical modelling of a tunnel in soft porous clay

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ABSTRACT: Behaviour of soft ground tunnels, and its numerical modelling, will be presented in this paper. Large deformation modes, plastic regions and soil mass failure will be discussed regarding urban tunnels excavated in soft ground. The paper presents examples of numerical modelling of tunnels excavated in soft porous clays, at Brasilia Subway System, located at the Central Region of Brazil.

1 INTRODUCTION

Numerical modelling of soft ground tunnels is a useful tool to assist the engineer, identifying deformation mechanisms associated with construction sequences, computing lining stresses and improving design. It is also possible to enhance the predictions of settlements and displacements of the soil mass (including some effects not easily quantifiable, like large displacements exhibited by soft porous clays).

Traditionally, shotcrete lined tunnels have been modelled using the Finite Element Method (FEM). More recently, however, the Finite Difference Method (FDM) has been used. Finite difference methods have the capability of modelling complex sequences of excavation and lining installation, considering elastoplastic behaviour for the soil mass, and including the affect of discontinuities by means of interface elements.

The paper will present numerical modelling of Brasilia's Subway South Wing Tunnels. These double track tunnels were excavated in soft porous clays using the NATM method. Negro and Kochen (1996) describe Brasilia underground transportation system, geology and soil conditions, tunnel design and construction, as well's as monitoring and observed performance.

2 STAGED EXCAVATION ANALYSIS BY THE FINITE DIFFERENCE METHOD

Numerical modelling of staged excavations using the finite difference method can easily include non linear effects, such as varied sequences of excavation and lining installation, post-failure behaviour, and so on.

Recent codes (e.g., FLAC - Cundall & Hart, 1992) using the finite difference method employ an algorithm known as dynamic relaxation to solve systems equations. Accuracy of results, before and after failure of soil mass, is assured by means of a technique referred to as mixed discretization. For each four sided element, four triangles are assembled and superposed, in an asymmetric way.

These codes use an explicit formulation, where the finite difference equations are dynamic equilibrium equations, written in terms of displacements and deformation velocities. Those equations are integrated over the time dimension, to get displacements, deformations and stresses at each moment. Such algorithms can use generalised constitutive equations, including strain softening models for geological materials. Dynamic equilibrium equations can result in static equilibrium, or in a steady state plastic flow.

Viscous damping is used to get a quick convergence, without losing accuracy of the solutions.

3 BRASILIA SUBWAY TUNNELS, SOUTH WING

Brasilia subway tunnels were built in soft porous clays, and some features observed during its construction were described elsewhere by Negro & Kochen (op. cit.). Figure 1 shows a layout of Brasilia Subway System. As an example of modelling using a finite difference code (FLAC), some analyses carried out for the design will be presented.

The tunnels were built using sequential excavation and shotcrete linings, reinforced with steel girders. They were built mainly in very soft porous clays. The

section analysed was located completely in soft porous clay, with blow counts ranging from 2 (above tunnel crown) to 10 around 5 m below the tunnel floor. A geological profile of this site is shown in Figure 2.

Water level at this section (at boring SP 614 - see Figure 2) was located 11 m below ground level, i.e., 3 m below tunnel crown. Geotechnical properties for the numerical analysis were based on laboratory (triaxial) tests, and on field (CPT, pressuremeter, dilatometer and horizontal plate load) tests. A nearby access shaft was intensively instrumented, as well as excavation sections located close to the shaft. Instrumentation results were back analysed, to define geotechnical parameters not measurable directly, like the coefficient of earth pressure at rest. The soft porous clay located at tunnel crown was classified as a reddish sandy clay, with SPT blow count between 1 and 6. Table I shows typical geotechnical properties

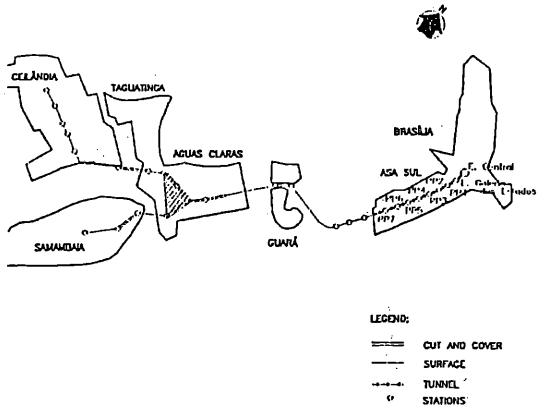

Figure 1 - Brasilia Subway System Layout

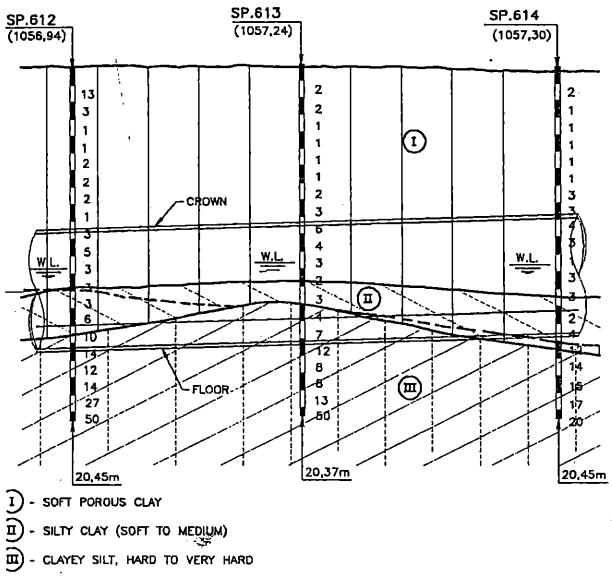

Figure 2 - Geological Profile Near Numerical Analysis Section

Table I. Range of geotechnical properties of the red porous clay

Clay Fraction	70-82%	SPT	1-6
LL	50-78%	Ko	0,6
PL	35-50%	$\varnothing^1$	23°
e_o	1,2-2,0	C^1	8-40 kPa
$\varnothing$	16 kN/m³	E_o*	8-40 MPa
WC	37-42%	* tangent Young modulus	

obtained from laboratory and field tests. Constitutive model used to represent the soil was an elastic, perfectly plastic one (with a non-associated flow rule to the Mohr-Coulomb failure criteria).

Geotechnically speaking, the red porous clay has a highly contracting structure upon shearing, a feature common to many tropical soils. This feature is known to enhance surface settlements when a tunnel is driven through it (see Eisenstein and Negro, 1985). No attempt was made to simulate this feature in the numerical analysis described.

4 TUNNEL DESIGN AND EXCAVATION SEQUENCES

The so called NATM is a widely used tunnelling method in Brazil. It has flexibility to adapt to different soil conditions, and it is possible to use readily available equipment. Typical construction sequences comprise excavation, installation of lattice girders, shotcreting the primary layer of the lining, closure of the invert, and finally shotcreting the secondary layer of the lining.

In Brasilia different excavation sequences were used to complete the tunnel cross section, depending on ground stability requirements. Negro and Kochen (op. cit.) described these sequences: fullface, heading and bench, sidedrift, etc. A construction sequence with a larger number of excavation steps was used at sections were stability conditions were not adequate.

5 NUMERICAL MODELLING OF SOFT POROUS CLAY TUNNELLING

Excavation sequence used for numerical modelling of soft porous clay tunnelling was heading excavation with a temporary invert, closed at a distance between 4,8 and 7,2 meters behind the face, followed by bench removal. Heading excavation was to be accomplished conforming a central core, to ease roof access and improve face stability. Dewatering was required for excavation.

Figure 3 shows the finite difference mesh

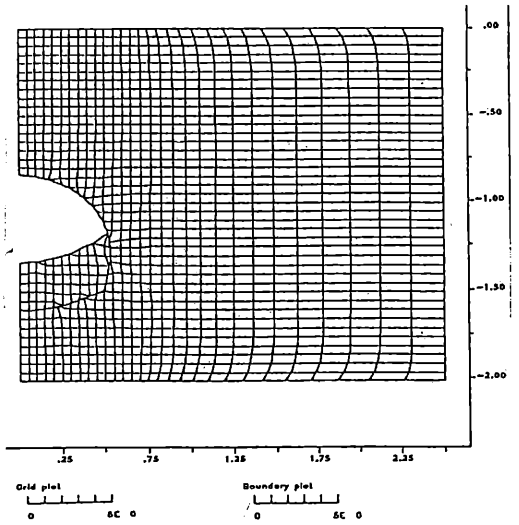

Figure 3 - Finite Difference Mesh for Heading Excavation and Lining

generated, using the program FLAC. Boundary conditions prescribed zero horizontal displacements at the lateral sides of the mesh. Mesh bottom was fixed both horizontally and vertically. Ground surface was considered free of displacement constraints. The mesh is shown for the construction phase corresponding to installation of the lining and temporary invert, after heading excavation. Figure 4 shows soil mass displacements corresponding to the final excavation phase, after completing the installation of the primary lining, including the invert arch. Due to the high deformability of soft porous clays, vertical displacements are enhanced in the soil mass displacement pattern, including soil heave at tunnel floor.

Figure 5 shows the plastic regions, for final excavation phase (primary lining installed). It shows a limited plastic region beside the tunnel springline,

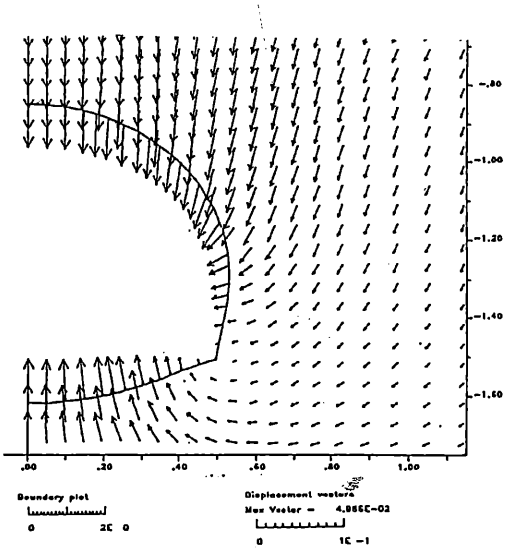

Figure 4 - Displacements for Final Excavation

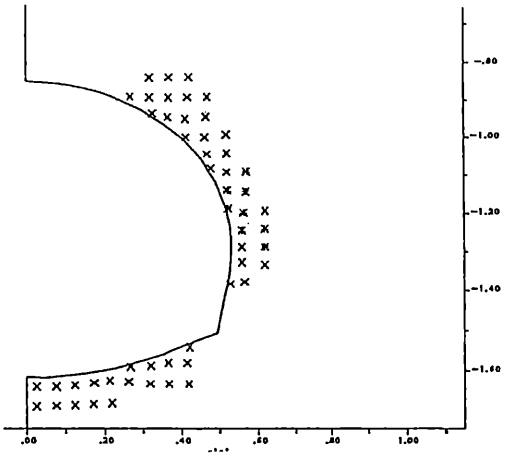

Figure 5 - Plastic Regions in the Soil Mass, Final Excavation Phase

and below tunnel floor. Figure 6 shows plastic regions after turning off the dewatering system, and the ground water level recovered. Tunnel springline region returns to the elastic deformation mode. This behaviour can be perceived by comparing figures 5 and 6. Points marked with an "x" indicate that a return to an elastic condition has taken place. Tunnel floor presents a opposite behaviour, with plastic regions spreading, and tensile stresses developing below invert arch.

During tunnel excavation, the contractor chose to use a variant excavation method (full face excavation) with a delayed closure of the tunnel invert. Numerical modelling was used to predict the behaviour of such method. Figure 7 shows soil mass displacements for a delayed invert arch installation. As a result, large settlements were anticipated, suggesting the development of failure mechanisms in the soil mass. In fact, soil mass displacement pattern resembles a roof failure mechanism. Figure 8 shows computed plastic regions for this variant excavation method. The plastic zones reach the ground surface,

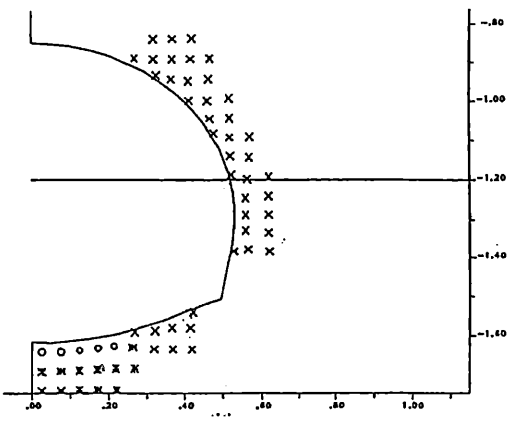

Figure 6 - Plastic Regions in Soil Mass, after Recover of the Ground Water Level

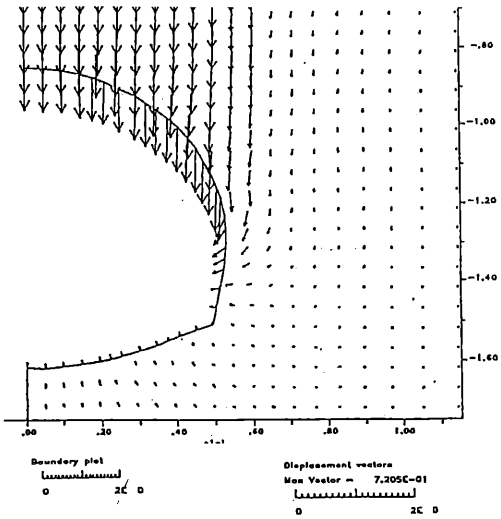

Figure 7 - Displacement Pattern for Full Face Excavation and Delayed Invert Installation

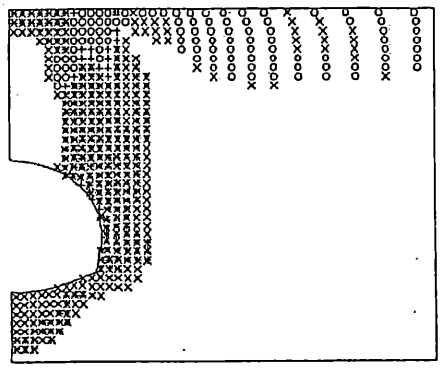

Figure 8 - Plastic Zones, Showing Roof Failure Mechanism

enabling formation of a roof failure mechanism. In fact, in a section where this variant excavation method was used, large settlements were observed. A change in the construction sequence promptly reduced the settlements to design levels.

6 FINAL REMARKS

Table II presents a comparison between predictions made (type A) and observed performance for the construction method analysed. Although the agreement is not good, the numerical modelling was quite able to predicted the overall modes of deformation, for this highly deformable ground mass.

The ability of the finite difference code to deal with large deformations allows better representation of the collapse modes. Discrepancies between predicted and measured instrumentation results can be partly caused by soft porous clay deformation behaviour, as discussed by Negro & Kochen (op. cit.).

Table II. Comparison between type A predictions and field measurements.

		Prediction	Measurement
Max Surface Settlement	mm	54	158
Final Crown Settlement	mm	49	110
Transverse Distortion	-	1:242	1:92
Horizontal Diameter Change of Support (after invert closure)	mm	36	30

REFERENCES

Cundall, P. & Hart, R. 1992. "*Microcomputer Programs for Explicit Numerical Analysis in Geotechnical Engineering*", Int. Seminar on Num. Meth. in Geomechanics, Moscow.

Eisenstein, Z. & Negro, A. 1985. "*Excavations and tunnels in tropical lateritic and saprolitic soils*". General Report Proc. 1st Intl. Conf. on Geomechanics in Tropical Lateritic and Saprolitic Soils (Tropicals'85), Vol. 4, pp 299-331.

Negro, A. & Kochen, R. 1996. "*Shotcrete Lined Tunnels Built in Soft Porous Clay*", North American Tunnelling (NAT'96), International Tunnelling Association Symposium, Washington D.C., USA.