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Numerical prediction of the behavior of an excavation in residual soils

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ABSTRACT: A finite element analysis was undertaken to evaluate the behavior of a deep, braced excavation in residual soils. The purpose of the excavation was to provide access to a tunnel constructed as part of the expansion of the subway system in São Paulo, Brazil. The stress-strain-strength behavior of the residual soils was represented by a nonassociated elasto-plastic model which was calibrated from the results of a comprehensive laboratory testing program on undisturbed soil samples. The elasto-plastic model was able to reproduce the behavior of the residual soils under different stress paths. The numerical results of the simulation include the displacements within the soil mass adjacent to the excavation and the loads in the structural components of the excavation. Although there is no development of a generalized failure mechanism, the numerical results indicate that the shear strength of the residual soils is fully mobilized in localized areas towards the bottom of the excavation.

1 INTRODUCTION

Prediction of ground movements within the soil mass surrounding excavations is a design issue of major relevance for excavation projects, particularly in densely populated urban areas. Numerical modeling (e.g. the finite element method) has been particularly suitable for evaluation of the behavior of excavations projects in big metropolises. A recent example is the numerical evaluation of the Boston Central Artery Project (Whittle and Ladd, 1997). However, the accuracy of the numerical modeling effort very much depends on the adequacy of the stress-strain-strength relationship used to represent the behavior of the soils surrounding the excavation. Specifically, the constitutive model should be able to capture the soil behavior under the several stress paths which are typical of excavation projects.

Elasto-plastic models have been particularly useful in representing the behavior of soils under different stress paths. However, most of the experience reported in the technical literature has been on the use of elasto-plastic models for reconstituted clays and sands. Little experience has been accumulated so far on the use of elasto-plastic models to represent behavior of undisturbed samples of in-situ, unsaturated soils. A comprehensive laboratory testing program was undertaken as part of this investigation, which included testing of unsaturated samples sheared under stress paths representative of excavations. The results of this experimental program provide much-needed experience is presented regarding the use of elasto-plastic models to represent the behavior of undisturbed, unsaturated samples of residual soils.

The finite element simulation of the excavation was performed using the computer code ANLOG (Zornberg and Azevedo, 1990), which is a multi-purpose program developed specifically for analysis of geotechnical projects. The program incorporates the use of a nonassociated elasto-plastic model (Lade, 1977, 1979), which was selected in this investigation to represent the behavior of residual soils. Specifically, the numerical investigation evaluated the behavior of a deep, braced excavation in residual soils which provided access to a tunnel constructed as part of the expansion of the subway system in São Paulo, Brazil. The predicted behavior of the excavation is presented, including the displacement and stress fields induced in the residual soil mass during the different stages of the excavation.

2 CHARACTERISTICS OF THE FINITE ELEMENT PROGRAM ANLOG

ANLOG is a multi-purpose, nonlinear finite element program developed for analysis of geotechnical projects (Zornberg and Azevedo, 1990). One of the models implemented in the program is the nonassociated elasto-plastic model developed by Lade (1977, 1979). In order to facilitate simulation using sequential analyses a macro-command structure was implemented in the program, which is a particularly useful feature to simulate the construction of geotechnical structures such as excavations, embankments, and foundations.

Lade's elasto-plastic model includes two yield surfaces: a conical shaped (plastic expansive) yield surface which is characterized by a nonassociated flow rule, and a cap-type (plastic collapsive) yield surface which is governed by an associated flow rule. Accordingly, the total strain increments are divided into elastic, plastic expansive, and plastic collapsive components.

Because of the nonassociativity of the plastic expansive yield surface, the stiffness matrix of the finite element problem becomes nonsymmetrical. Several numerical schemes can be implemented to enable the use of symmetric equation solvers if the tangential stiffness matrix is nonsymmetrical (Xiong, 1985; Pande and Pietruszczak, 1986). ANLOG incorporates different techniques, in addition to the use of non-symmetric solvers, in order to allow the use of symmetric equation solvers in the analyses (Zornberg and Azevedo, 1990).

The macro-command structure is associated with the use of a set of compact and independent subprograms, each designed to compute one or just a few basic steps in the finite element simulation process. This approach has been used the programs FEAP (Zienkiewicz and Taylor, 1991) and GeoFEAP (Espinoza et al., 1995) developed at the University of California at Berkeley. Eight-node isoparametric elements are used to model soil, and three-node bar elements were used to simulate struts and anchors.

The stiffness matrix is formulated considering both the stress-level and the stress-history in each element. Several incremental-iterative approaches based on the Newton-Raphson scheme have been implemented in the program. The stress integration carried out during each equilibrium iteration is performed through an explicit integration technique, in which forward integration is performed over a sufficiently large number of sub-increments in order to provide the required accuracy.

3 MODELING OF SÃO PAULO RESIDUAL SOILS' BEHAVIOR

The city of São Paulo is located in a tertiary sedimentary basin of fluvial-lacustrine origin. The sediments that were deposited in the basin underwent a weathering process which left signs such as mottling and precompression induced by desiccation. A comprehensive laboratory testing program was undertaken as part of this investigation in order to characterize the stress-strain-strength behavior of the residual soils in the São Paulo sedimentary basin (Parreira, 1991). A typical geotechnical profile includes an upper layer of "Residual Red Clay" underlain by a layer of "Residual Variegated Soil". The investigation included laboratory testing of undisturbed samples of these two residual soils. The results of this testing program were subsequently used to calibrate the elasto-plastic model used for the numerical simulation phase of this investigation.

The "Residual Red Clay" is a porous soil with a void ratio typically greater than 1.0 and SPT values ranging from 4 to 11. As this residual soil is typically located above the water table, the testing program on this material was performed under unsaturated conditions. The Red Clay material appears typically in two horizons, with the upper one generally showing more intense weathering. However, soil samples from both Red Clay horizons yielded the same shear strength envelope.

The laboratory tests were performed using unsaturated samples tested at the in-situ moisture content. Drained conventional triaxial compression (CTC) tests were performed at confining pressures of 49, 98, and 196 kPa. The volumetric strains in the unsaturated triaxial specimens were determined by internal measurement of the radial deformation of the samples during testing. The results from the CTC tests were used to define the plastic expansive parameters of Lade's model. The testing program also included hydrostatic compression (HC) tests, which were used to define the plastic collapsive parameters of the model. The elastic parameters were obtained from unloading triaxial tests. Table 1 presents the parameters obtained for the "Residual Red Clay" after calibration of the elasto-plastic model. A description of the different parameters, which are all nondimensional, is provided by Lade (1977, 1979).

The parameters for the "Residual Red Clay" listed in Table 1 were used to predict the behavior of this material

Table 1. Summary of elasto-plastic parameters for the residual soils.

<table>
<tr><th colspan="4"></th><th>Red Clay</th><th>Variegated Soil</th></tr>
<tr><td colspan="3" rowspan="3">Elastic Parameters</td><td>K_{ur}</td><td>153.97</td><td>1051.46</td></tr>
<tr><td>n</td><td>0.56</td><td>0.11</td></tr>
<tr><td>ν</td><td>0.25</td><td>0.29</td></tr>
<tr><td rowspan="10">Plastic Parameters</td><td colspan="2">Collapsive</td><td>p</td><td>0.019</td><td>—</td></tr>
<tr><td rowspan="9">Expansive</td><td rowspan="2">Failure</td><td>η_1</td><td>133.63</td><td>561.12</td></tr>
<tr><td>m</td><td>0.88</td><td>1.20</td></tr>
<tr><td rowspan="3">Plastic Potential</td><td>S</td><td>0.40</td><td>—</td></tr>
<tr><td>t</td><td>3.67</td><td>—</td></tr>
<tr><td>R</td><td>-17.46</td><td>—</td></tr>
<tr><td rowspan="4">Work Hardening</td><td>P</td><td>0.41</td><td>—</td></tr>
<tr><td>l</td><td>0.44</td><td>—</td></tr>
<tr><td>α</td><td>1.65</td><td>—</td></tr>
<tr><td>β</td><td>0.00</td><td>—</td></tr>
</table>

under a CTC stress path. The behavior predicted by Lade's model under a CTC stress path is compared in Figure 1 to the laboratory test results. The agreement is very good for both the deviatoric stress and the volumetric strain curves. Moreover, Figure 2 compares the behavior of the "Residual Red Clay" under a HC stress path as predicted by the model and as obtained experimentally. The figure also shows a very good agreement under this stress path.

Reduced triaxial compression (RTC) is a stress path typical of excavations. In a triaxial test following this path, the axial stress in the sample is held constant while the confining stress is reduced from an initial hydrostatic condition. Figure 3 compares the behavior under a RTC stress path as predicted by Lade's model and as obtained from the laboratory tests. The agreement between predicted and experimental results is very good. It is worth noting that all the parameters presented in Table 1 were obtained using laboratory results only from HC and CTC tests. Consequently, the agreement observed in Figure 3 for tests performed under a RTC stress path, which was not used in the calibration process, evidences the ability of the model to represent the soil behavior under multiple stress paths. Volumetric strains are not presented in Figure 3 because of the difficulty of conducting internal measurements of radial strains in unsaturated soil samples for the case of RTC testing.

The "Residual Variegated Soil", located below the "Residual Red Clay" layer, was also tested as part of the experimental program. This material varies from sandy soils to fat clays and has SPT values ranging from 16 to 22. The preconsolidation pressure of this soil, determined from the samples retrieved as part of this study was approximately 800 kPa. Consequently, the Variegated Soil is highly overconsolidated and, for modeling purposes, was considered to behave as an elastic, perfectly plastic material. As plastic strains were not accounted for in the Variegated Soil because of the overconsolidation, the corresponding plastic parameters were not determined. However, failure and elastic strain parameters for the Variegated Soil were defined using Lade's formulation. Table 1 also shows the parameters obtained in this study to model the behavior of the "Residual Variegated Soil".

4 DESCRIPTION OF THE CASE HISTORY

The case history under investigation is a deep, braced excavation constructed during the expansion of the subway system in São Paulo, Brazil. The excavation, named Poço Salas Técnicas, provided access to a tunnel which is now the Paulista Line of the São Paulo subway system. The behavior of this excavation is evaluated using the finite element code ANLOG described in Section 2 and the parameters for of the residual soils defined in Section 3.

The 4.5 km long Paulista Line was constructed in 1991. As the line goes through densely populated commercial areas, it was constructed by underground excavation using the NATM and shield tunneling techniques. Figures 4 and 5 show a plan view and a cross-section of the deep excavation under investigation. The excavation was over 31 m deep and it was located next to an existing 17-story building which had two underground levels. The potential settlements that might have been induced in the building during the excavation were of particular concern.

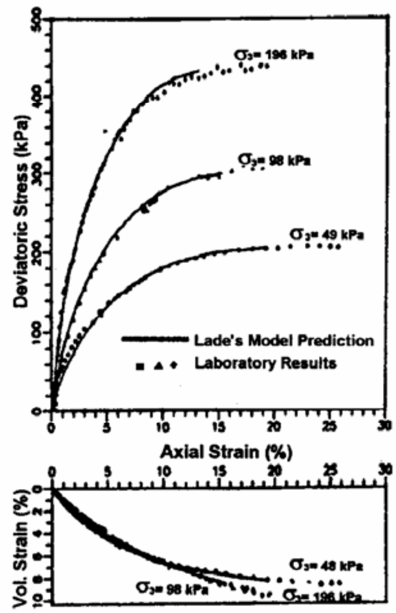

Figure 1. Comparison between measured and predicted behavior of the "Red Clay" under CTC stress path.

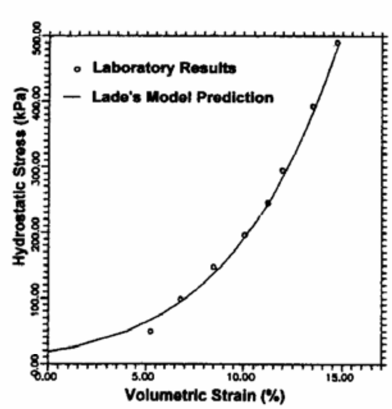

Figure 2. Comparison between measured and predicted behavior of the "Red Clay" under HC stress path.

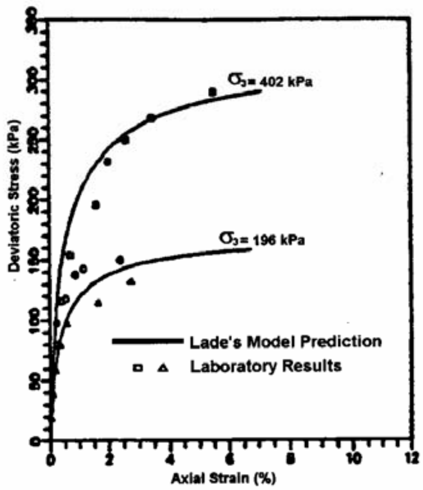

Figure 3. Comparison between measured and predicted behavior of the "Red Clay" under RTC stress path.

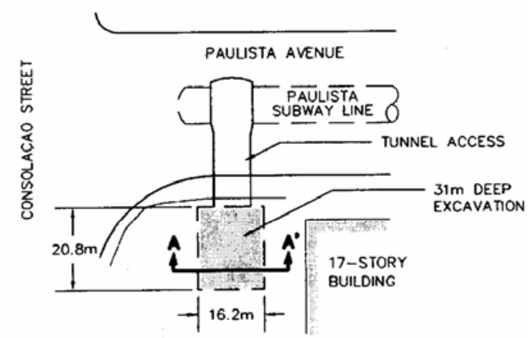

Figure 4. Plan view of the Poço Salas Técnicas Excavation.

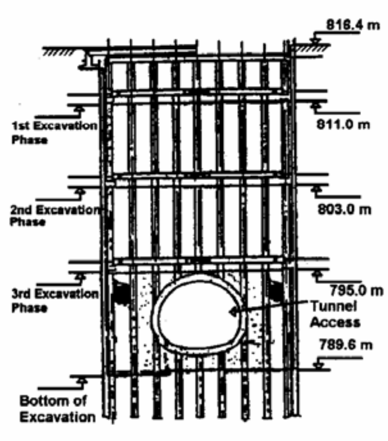

Figure 5. Cross-section A-A' of the excavation.

The retaining structure for the excavation included a soldier pile and lagging system. Moreover, three strut levels were used to support the excavation. The geotechnical profile at this specific location included approximately 18 m of "Residual Red Clay" underlain by the "Residual Variegated Soil" layer. The water table, initially located at the base of the Red Clay layer, was lowered before the excavation to a depth of approximately 35 m (i.e. 4 m below the bottom of the future excavation).

5 FINITE ELEMENT PREDICTION

The finite element mesh used in the numerical simulation of the excavation consisted of 481 nodal points and 147 elements. Eight-node isoparametric elements were used to simulate the soil and three-node bar elements were used to simulate the struts. The numerical simulation of the excavation included two sets of analyses:

a) analyses performed to define the state of stresses existing in the soil mass previous to the excavation; and
b) analyses performed to simulate the different phases of the excavation under investigation.

Figure 6 shows schematically the analyses described in (a) above. An adequate definition of the initial state of stress within the soil mass plays an important role in the numerical simulation of geotechnical projects involving nonlinear analyses. The first step undertaken to define the initial state of stresses was to characterize an original geostatic state, which was defined by the soil unit weight and the at rest earth pressure coefficient K_0 for each of the materials (Figure 6.1). The next analysis was to simulate an excavation of two underground levels in the building adjacent to the future deep excavation (Figure 6.2). Then, as the adjacent building was founded in concrete piers resting on top of the Variegated Soil Layer, a distributed loading was applied to simulate the effect of the building foundations (Figure 6.3). Finally, lowering of the water table performed prior to the deep excavation was numerically simulated. This was analyzed by applying body forces equal to the unit weight of water in order to account for the increase in effective stresses in the dewatered soil elements (Figure 6.4). The state of stresses obtained at the end of this fourth analysis corresponds to the initial stress existing within the soil mass prior to the deep excavation under investigation.

Figure 7 shows schematically the analyses performed as part of the set (b) of analyses described above. Four successive finite element analyses, corresponding to each of the four construction phases in the excavation were simulated. The initial excavation phase did not include placement of struts (Figure 7.1). However, the next three phases of the excavation (Figures 7.2 to 7.4) included

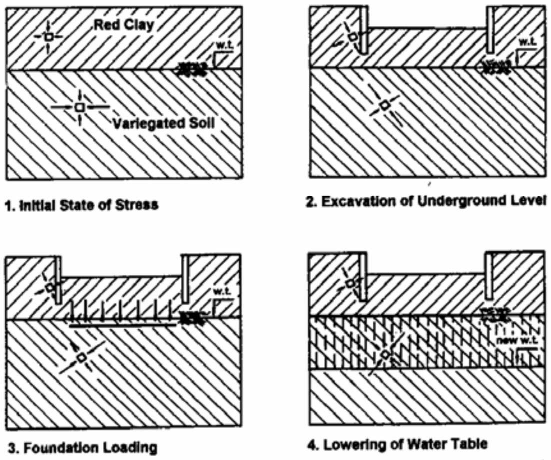

Figure 6. Schematic representation of the analyses performed to define the stress state before the excavation.

installation of struts, which were simulated by activating the bar elements representing these structural elements. The finite element analyses were performed using the Standard Newton-Raphson Method to solve the nonsymmetric stiffness matrix of the problem.

Stress and displacement fields were obtained in the soil elements for each stage of the analysis. Moreover, the loads in the structural elements of the excavation were also estimated. Settlements predicted for the adjacent 17-story building were negligible. This is consistent with the magnitude of the settlements observed in the building after excavation took place. Prediction of the development of the compressive stresses in the three strut levels are shown

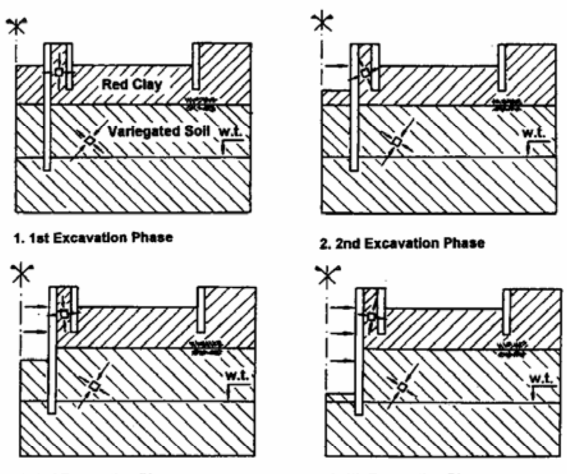

Figure 7. Schematic representation of the analyses performed to simulate the different excavation phases.

in Figure 8. Lateral displacements of the wall excavation, predicted during the four phases of the excavation, are shown in Figure 9. The bottom strut level exerts a comparatively high force, which is evident in the displacement pattern observed in Figure 9.

Figure 10 shows contours of mobilized shear strength within the soil mass adjacent to the excavation. The mobilized shear strength in the figure is defined as the ratio between the plastic expansive stress level at failure and the plastic expansive stress level that corresponds to the actual state of stress in each location. The mobilized shear strength defined in this way equals one when the soil reaches its ultimate shear strength and is higher than one before the soil reaches failure.

The figure shows that the analysis predicts no development of a generalized failure mechanism. However, the analysis predicts that the shear strength of the soil is fully mobilized at the bottom of the excavation, where the soil is subjected to a vertical extension stress path, and along the excavation wall towards the bottom of the excavation, where the soil is subjected to a RTC stress path. The maximum lateral displacement (37 mm) predicted on the excavation wall (Figure 9) matches the location at which the shear strength is fully mobilized. Figure 10 also shows the stabilizing effect induced by the comparatively high force exerted by the lower strut level, which can be observed by the presence of a "bulb" where the shear strength of the soil is far from being fully mobilized.

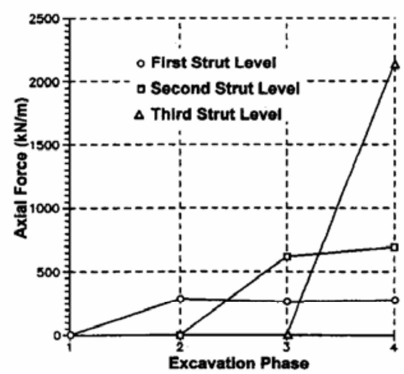

Figure 8. Predicted force per unit length developed at strut levels during the excavation.

6 SUMMARY AND CONCLUSIONS

A finite element analysis was undertaken to evaluate the behavior of a deep, braced excavation in residual soils. The purpose of the excavation was to provide access to a tunnel constructed as part of the expansion of the subway system in São Paulo, Brazil. The stress-strain-strength behavior of the residual soils was represented by a

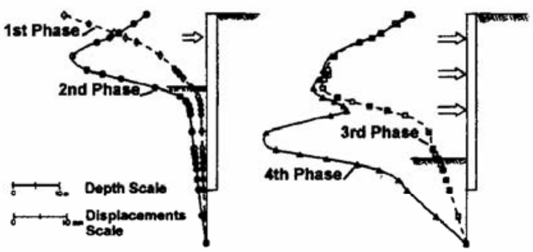

Figure 9. Predicted lateral displacements on the wall excavation during the four construction stages.

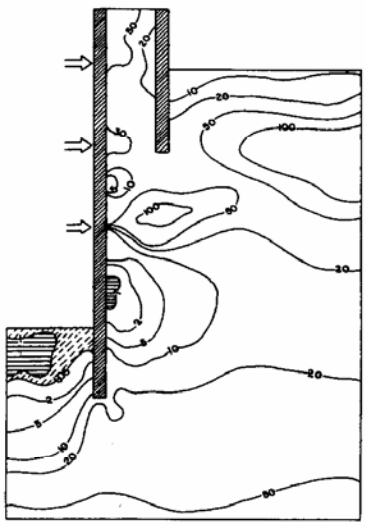

Figure 10. Mobilized shear strength predicted for the soil mass adjacent to the excavation.

nonassociated elasto-plastic model, which was calibrated from the results of a comprehensive laboratory testing program. The laboratory tests were performed on unsaturated soil samples under stress paths which are representative of excavation projects.

Comparisons between the experimental test results and the results predicted by the elasto-plastic model demonstrated the ability of the model to characterize the behavior of the residual soils under different stress paths. This is particularly relevant since there is little experience in the technical literature regarding the use of elasto-plastic models for unsaturated, undisturbed in-situ soils.

The finite element analyses were performed using the program ANLOG, which includes the use of the elasto-plastic model developed by Lade (1977, 1979). A macro-command structure was implemented in the code in order to facilitate simulation of sequential analyses. This feature is particularly useful for simulation of the different stages in the construction of geotechnical structures such as excavations, embankments, and foundations.

The numerical evaluation of the deep excavation yielded the stress and displacement fields for the soil mass adjacent to the excavation and the loads in the structural components of the excavation. Of particular relevance was the performance of a 17-story building, which was adjacent to the excavation. The analysis predicts no development of any generalized failure mechanism. However, the numerical results indicate that the shear strength of the residual soils is fully mobilized towards the bottom of the excavation.

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