Underground cavity design: the case of Bressanone (Bozen, Italy)

N. Sciarra, M. Calista & M. Mangifesta
Department of Earth Science, Chieti University, Italy

A. Pasculli
Faculty of Mathematical, Physical and Natural Sciences, Chieti University, Italy

ABSTRACT: In this paper a numerical modeling has been developed to study the feasibility of the underground ring road of Bressanone city (Bozen, Italy). The modeling has been finalized for the determination of the soil deformations around the digging and at the surface, during the execution of the gallery, in order to verify probable problems of subsidence. Also a dynamic analysis has been carried out to verify the behavior of the system in seismic conditions.

1 INTRODUCTION

The city of Bressanone (northern Italy) is a strategic point for the traffic connecting Italy with the other European nations. The current state road crossing the entire city creates great problems for intensity of traffic and consequently pollution. In order to avoid these problems, because of the topographical and logistic characteristics, because of the presence of railway and highway lines, the only feasible chose has been the realization of a tunnel under the city.

The digging would involve, along North-South direction, the foot of the right slope of the valley of the Isarco River in a zone characterized by important surface constraints like buildings, presence of the freeway and the railway line of the Brennero.

Therefore, a numerical modeling study has been carried out, utilizing *FLAC* (Itasca 2000), in order to examine the effects induced by the realization of this tunnel. In particular we report the results obtained for a typical section that presents important problems connected with the different soil state of stress taking into account piezometric level effects too.

The study has been executed also to verify the dynamic behavior of the entire system in terms of admissible strains.

2 GEOLOGICAL SETTING

The surveyed area (see Figure 1) is located at the extreme western zone of Bressanone city. By a lithological point of view the following stratigraphic succession has been identified (AA.VV. 1969):

- *Phyllites of Bressanone* - This formation belongs to a heterogeneous metamorphic complex representing the most northern member of an ancient crystalline base. The rock has gray color and along the fractures looks almost shining. The stratigraphic vergence is generally towards South with inclinations and attitude varying in agreement with the intrusive contacts of the granitic mass.
- *Moraines and fluvial-glacial deposits* - These materials are referred to both the Würm age and extensively outcrops along the surveyed area. They are constituted of lime and clay strongly consolidated and phyllitic and granitic pebbles.
- *Ancient alluvial deposits* - These deposits concern coarse gravel with sands of granitic origin. The maximum size is more than 30 cm. Locally it is possible to distinguish metric levels of lime and clays. Quartz abounds especially in the sandy fraction.
- *Alluvial cons* - These are present at the base of the cross-sectional valley cuts, caused by the erosive action of the water. Generally they are not so thic and they can be interested by a water table.
- *Alluviums* - Alluvial deposits of the Isarco valley constitute this kind of material. From a geotechnical point of view they are similar to the alluvial cons, from which differ very little in terms of the size of particles.

3 INPUT PARAMETERS

The geological and geomechanical soils characterization involved in the digging operation is of fundamental importance for the processing of an adapted projecting phase. The study includes a preliminary phase aimed to define the stratigraphic and tectonic relationships existing between the several present geologic formations, accompanied by a careful geomorphologic relief (with particular attention in the mouths of the tunnel and in the zones with low covers) and a detailed hydrogeologic relief. The study is based moreover on a finalized geognostic investigation to choose the more convenient (economically and technically) tracing.

The geognostic surveys articulated in various in situ and laboratory tests were primarily aimed at the definition of the geo-mechanical property of the soils related with the digging. Among many different surveys, 17 boreholes executed from 15 to 75 meters in depth and located in zones close to the future tracing of the digging are worthwhile to be mentioned.

The holes have been equipped with various kinds of piezometers. Also seismic prospecting was carried out to reconstruct the geological setting.

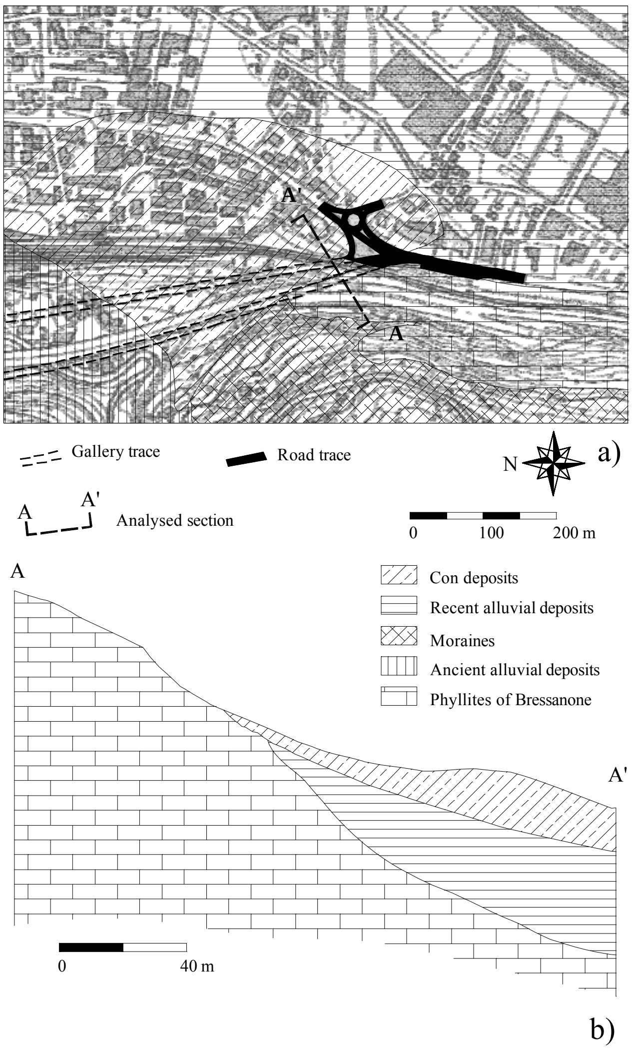

Figure 1. a) Simplified geological map; b) analyzed section.

In laboratory we have tested 36 samples obtaining indications on the particle size, the plasticity limits, the permeability and the geomechanical parameters. So we defined the values to introduce in the modeling (see Table 1).

Table 1. Physical and mechanical parameters utilized.

Lithotype	Phyllites	Recent Alluviums	Ancient Alluvium
γ sat. (Kg/m3)	2400	1900	1900
γ dry (Kg/m3)	2200	1600	1600
φ' (°)	35	38	45
E (GPa)	5.62	0.13	0.30
Cohesion (Pa)	15e4	0.00	0.00
Porosity	0.20	0.30	0.30
Permeability (m/s)	1e-07	1e-03	1e-04

About the substratum constituted by the tectonized phyllites, it has been indispensable to determine the quality of rock in order to define the Young's modulus (Em), estimated with following formula in agreement with Sarafim & Pereira (1983):

$$E_m = 10^{\frac{RMR - 10}{40}} \tag{1}$$

Thus we obtained the index RMR (Rock Mass Rating) by Beniawski’s criterion. This classification introduces the influence of the geological discontinuities on the physical and mechanical properties. It is essentially based on the analyses of the following of parameters:

- uniaxial compressive strength
- Rock Quality Designation (RQD)
- spacing of joints
- hydraulic condition
- conditions of joints

We valued each parameter by appropriate correlation tables (Scesi & Papini 1997). The results are reported in Table 2. The sum of these values is the quality of the rock.

Table 2. RMR index for the Phyllites of Bressanone.

		Index
Uniaxial compressive Strength (MPa)	50-100	7
RQD	25-50	8
Spacing of joints (mm)	< 60	5
Conditions of joints	smooth/laminar	10
Hydraulic condition	moist	10
RMR index		40*

*poor characteristics

4 MODELING

Once we gained all geotechnical, morphologic, hydrogeologic and surface infrastructure characteristics knowledge, we performed an analysis regarding a metropolitan tunnel construction frame related, in particular, with both the digging and the buildings on the surface.

Design requirements imply the realization of a double cane tunnel. The construction of one of the cane does not present big problems since it crosses a phyllitic rock substratum that provides a suitable safety during its realization. The other one is located within highly deformable granular formations characterized by variable resistance due to the presence of alluvial cone, recent or ancient alluviums and moraines. For the latter case, moreover, the presence of a water table forced us to perform a more detailed study in order to guarantee the stability conditions and to verify the possibility of filtration motions too. The digging in these conditions would require the maximum attention for the stability, in particular for the water presence and the surface yielding produced by the successive tensional slackening due to the going on of the cavity opening. In order to perform a more realistic simulation of the actual procedures of execution, the modeling has been carried out in more steps:

- numerical discretization;
- study of the initial conditions of equilibrium;
- simulation of the digging of the first cane;
- simulation of the digging of the second cane;
- dynamic analysis.

The utilized geologic section (Figure 1b) has been discretized by uniform sized and shaped grids (Figure 2). The numerical model was built up by a net of 140 × 100 square meshes whose size dimension was of 1.5 meters.

From a hydraulic point of view an almost constant piezometric surface was used in order to take into account the neutral pressures. The water seepage was not considered because of the following reasons:

- vanishing lithotypes permeability;
- the actual water path is not homogenous due to a double kind of flow through phyllites fractures and/or alluvium pores;

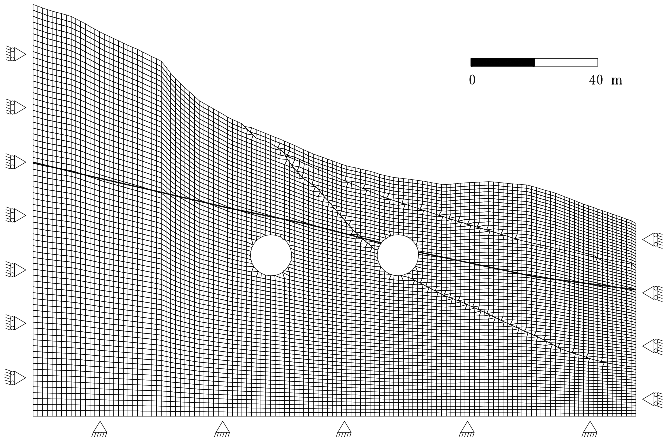

Figure 2. *FLAC* model and boundary conditions.

- further the hydraulic study pointed out that the main filtration direction is orthogonal to chosen section plane thus its analysis would not be definable.

In the reference model the existing soil tensional states before the execution of the two diggings should be known. Because of both stratigraphical and topographical surface complexity, the initial stresses states were calculated directly by *FLAC*.

From the geologic section (Figure 1b) and from Figure 2 it is possible to recognize that there are many differences characterizing the soil regions in which the two canes are located. The uphill cane concerns exclusively the phyllitic rock substratum and it is located 32 m in depth; instead the downhill cane intercepts the lithologic limit between the substratum and the alluviums and it is located 20 m in depth.

So the uphill cane digging effects were firstly analyzed and then the downhill cane was introduced to verify the final setting. In both cases the first step was concerned with the calculation of the necessary tensions to maintain the stability of the excavated walls. Then these tensions were progressively reduced coherently to the actual transient behavior, checking each time the compatibility of the strain field of the whole soil model. The progressive decrease of the maximum tensions (necessary for the equilibrium) was studied reducing, step by step, the tension of 10%. In this way it was possible to simulate in a more suitable way the tensional relaxation due to the non-instantaneous digging realization. Remarkable computer time consumption was necessary to perform this numerical process.

5 DYNAMICS ANALYSIS

In order to complete the analysis seismic simulations had been carried out. In particular we focused the local site amplification at the topographical surface and along the tunnel. Since grid elements dimension (Δl) influences the elastic waves propagation, we defined the maximum permissible frequency (f_{max}) of the input signals by the following equation:

$$f_{max} = \frac{Vs}{\lambda} = \frac{Vs}{10\,\Delta l} \tag{2}$$

where Vs is the velocity of the S waves.

In particular, by geognostic surveys, we estimated, regarding the alluvium, a velocity ranging from 100 up to 150 m/s from which the maximum acceptable frequency is 6.6 Hz. Then the following dynamic horizontal input was applied:

$$\text{Wave} = 1.0 \cdot \sin(2.0 \cdot \pi \cdot f \cdot t) \tag{3}$$

with 2.0 Hz frequency; 1.0 m/s amplitude and 1 s duration.

6 STATIC ANALYSIS RESULTS

The results of the study confirm the general complexity of the situation and many particularities have been highlighted.

6.1 *Uphill cavity*

Even if the rock characteristics were poor by the Beniaswski's classification the results have been more than satisfactory. Indeed, the digging numerical simulation revealed millimetric displacements around the gallery and on the surface.

The digging deformed shape (Figure 3) meaningfully reflects the asymmetry of the topographical surface; indeed the maximum lithostatic loads are not on the vertical tunnel axis.

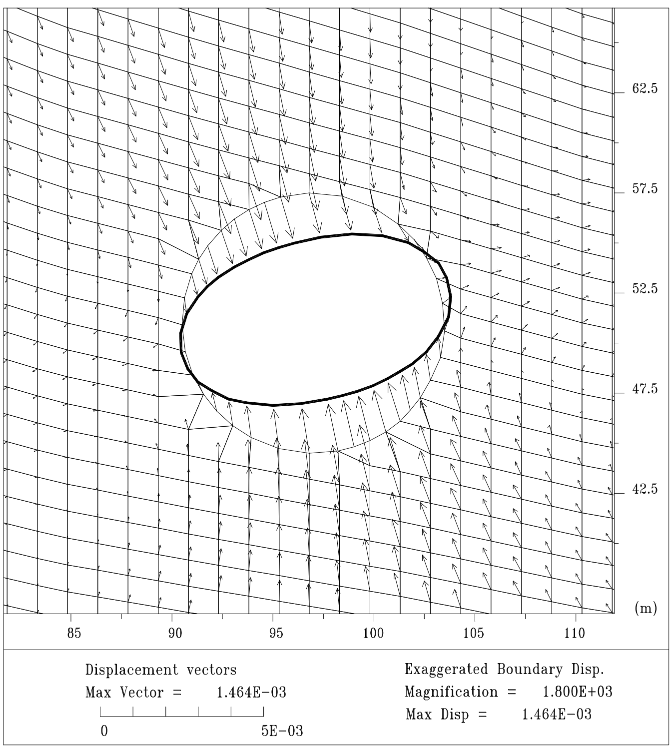

Figure 3. Displacement vectors and boundary deformations.

Observing the deformed meshes, we can argue the same considerations about the x component displacements, showing the greatest value in correspondence of the maximum thickness of alluviums. Within the tunnel we can observe a swelling of the upside-down arch and a settlement on the cap. On the surface, vertical displacements of some nodes have been recorded in order to analyze the settlements intensity (Figure 4a).

It should be pointed out that the maximum displacement at the surface is not in axis with the tunnel, but it is located downhill (F point in Figure 4b). Also, as it is displayed in Figure 4c, strain states within the tunnel are not in symmetric position regarding initial axis.

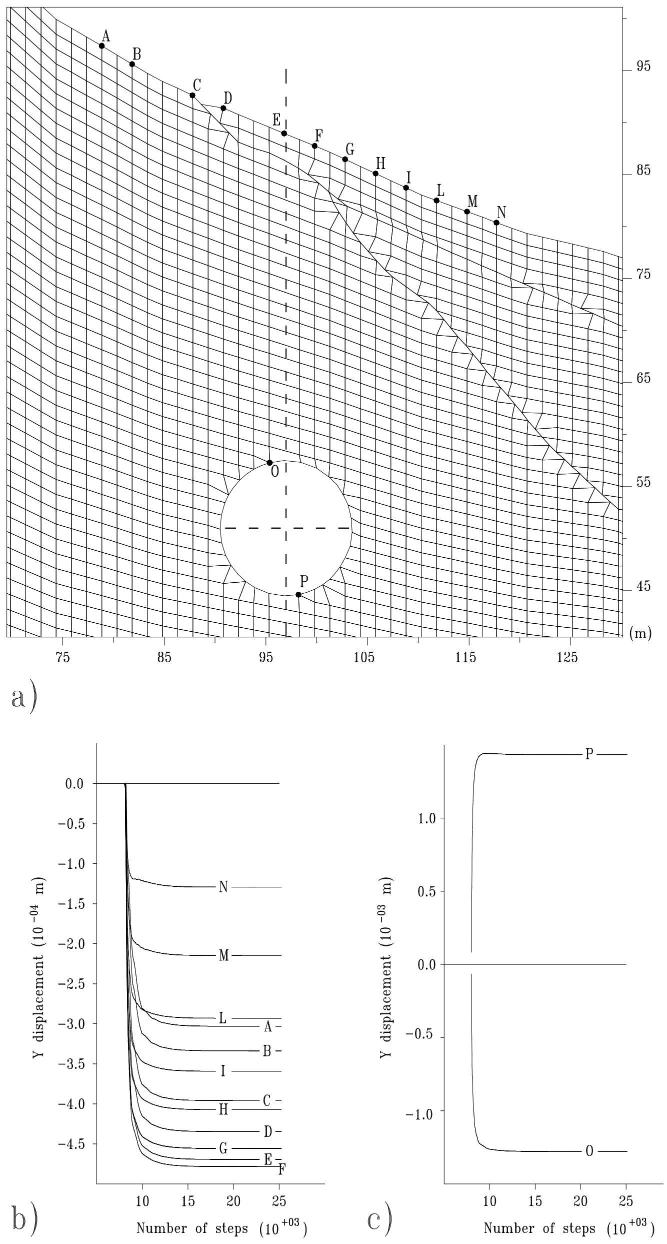

Figure 4. a) Locations of the monitored nodes; b) vertical displacements at the surface; c) vertical displacements within the cavity.

6.2 *Downhill Cavity*

The digging of the downhill cane experienced many remarkable difficulties due to the poor mechanical characteristics of the crossed soil. The assumed digging would induce the whole cap zone collapse (Figure 5), if the equilibrium tensions along the digging walls vanish.

For this reason the tensions relaxation phenomena have been studied assuming the presence of remedial works (Figure 6).

The consequence of these remedial works was to introduce local forces at the nodes related with the alluvium. In such a way the obtained maximum displacements are of the order of the millimeters.

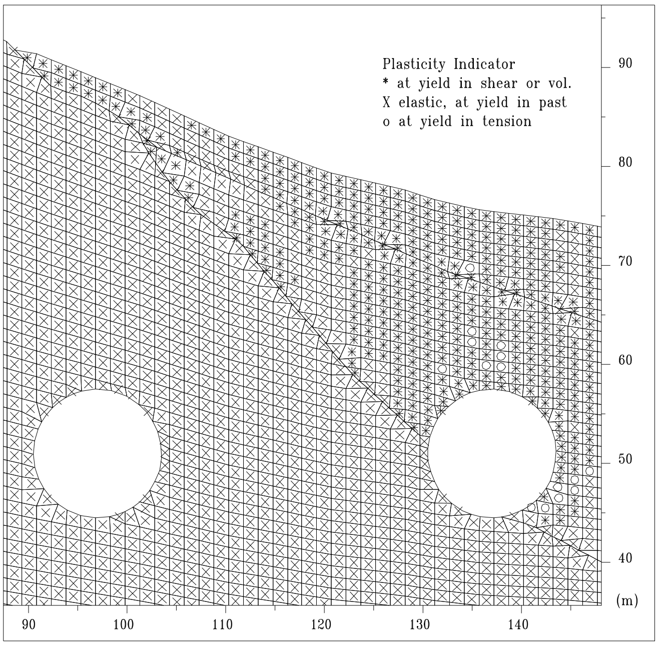

Figure 5. Plasticity indicators after the excavation of the tunnel.

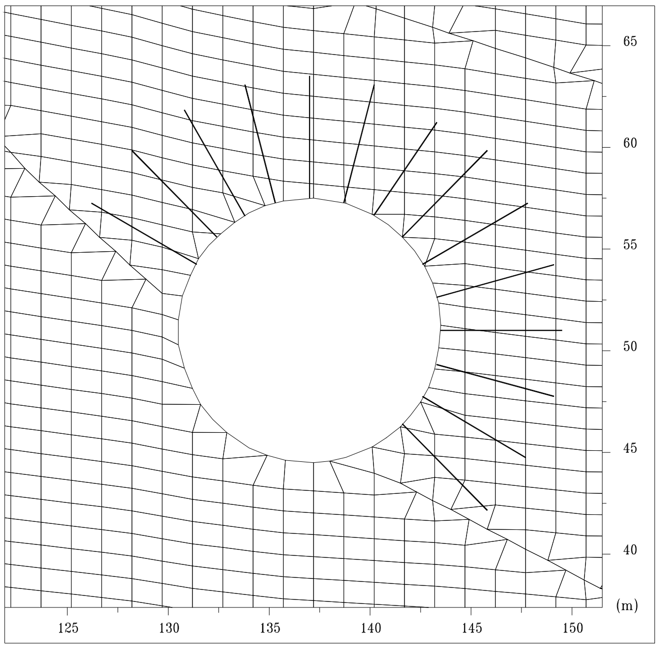

Figure 6. Remedial works position.

Also in this case the deformation of the digging is asymmetric and remarkably different regarding the uphill distortion (Figure 7). In particular we can observe a vectors displacements polarization towards right, justified by the different natural stresses distribution due to the heterogeneous geological settings. The analysis shows a shear strains increments (Figure 8) concentration along the contact surface between the two different lithologies Thus differential settlements were induced on surface, in particular in the zone in which the phyllites and the alluvium deposits outcrop.

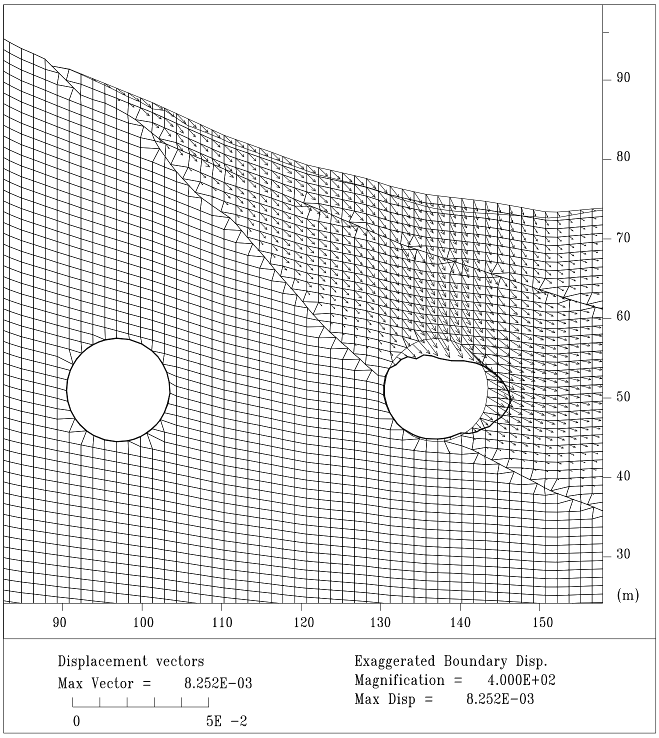

Figure 7. Displacement vectors and boundary deformation.

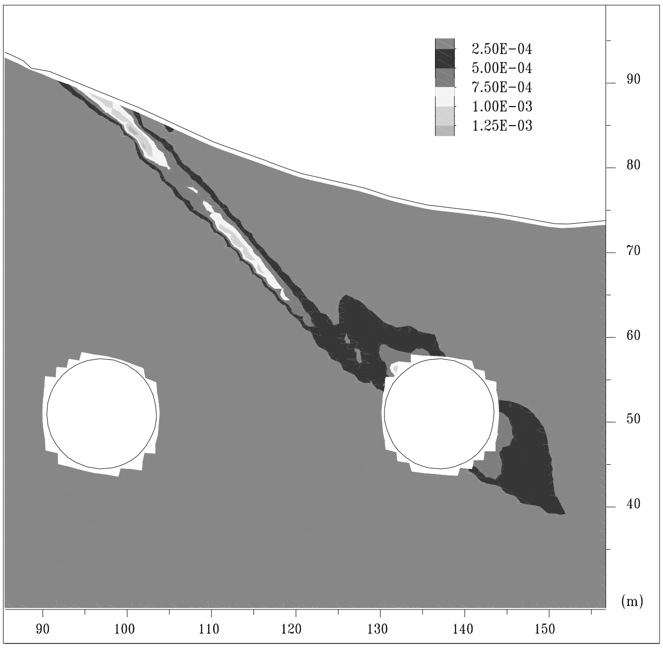

Figure 8. Maximum shear strain increment.

The monitoring of the vertical displacements of both surface and boundary gallery nodes has been carried out for this case too (Figure 9a). At the surface the maximum displacement was localized perfectly in axis with the gallery (E point in Figure 9b), like the maximum settlement (N point in Figure 9c) and the maximum swelling (O point in Figure 9c), concerning the gallery walls.

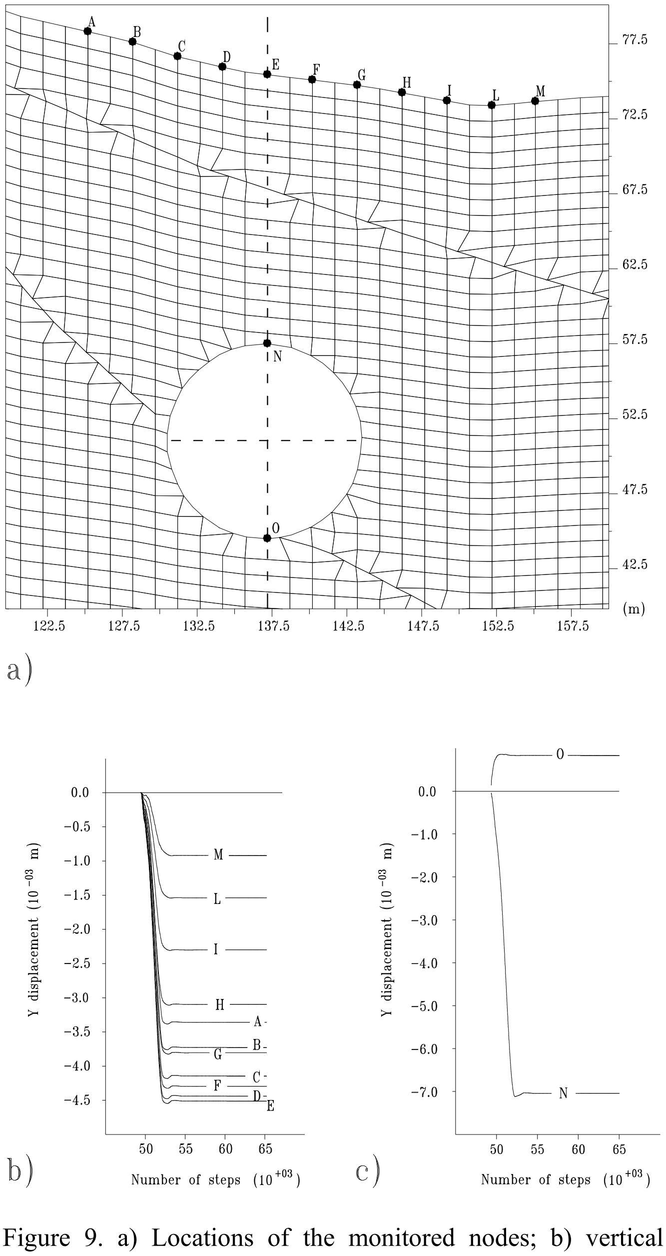

Figure 9. a) Locations of the monitored nodes; b) vertical displacements at the surface; c) vertical displacements within the cavity.

7 DYNAMIC ANALYSIS RESULTS

At the end of both simulated diggings execution a dynamical analysis has been carried out in order to verify the system behavior during a simplified earthquake. The input wave was applied at the base of the numerical model along horizontal direction.

We obtained considerable deformation essentially localized along the contact surface between the phyllites of the substratum and the moraine and alluvium deposits (Figure 10). As it is clearly showed in Figure 11, the assumed earthquake slowly influences the soil around the uphill digging; on the contrarily the soil around the downhill digging is strongly involved.

This will involve in phase of execution of the cavities the predisposition of opportune structural calculations that consider the increase of the strain states during the seismic phases.

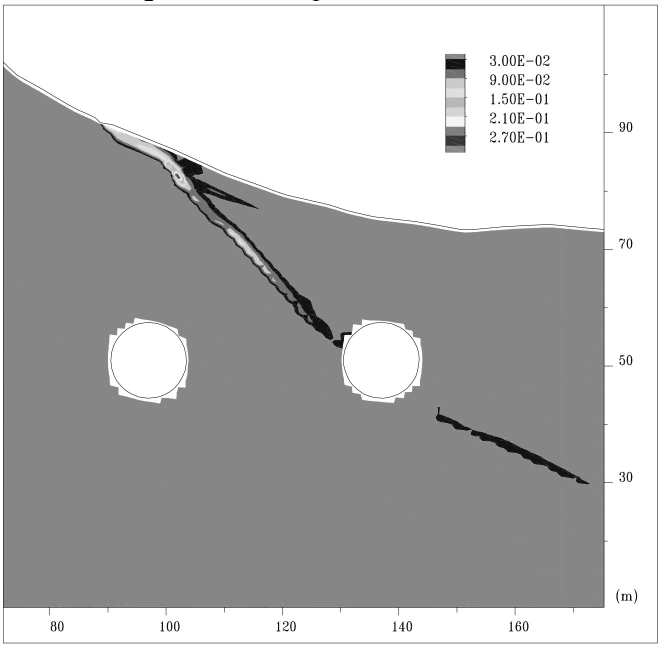

Figure 10. Maximum shear strain increment.

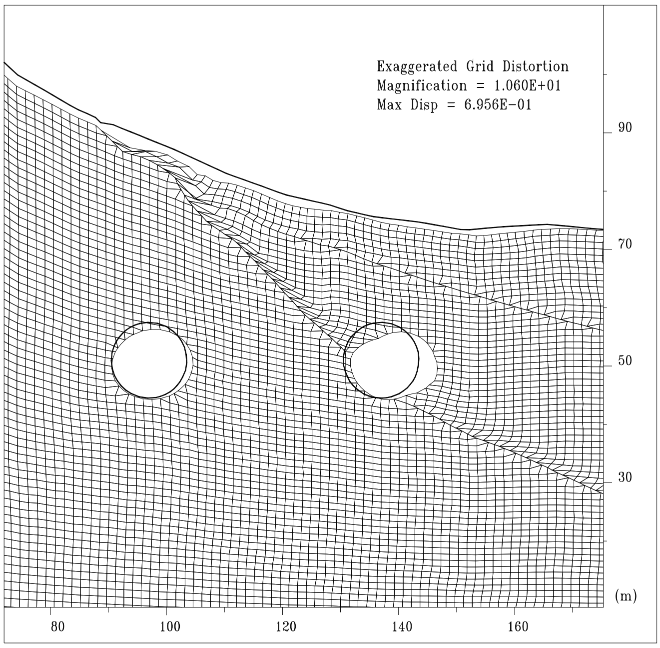

Figure 11. Exaggerate grid distortion.

8 CONCLUSIONS

In this paper it has been reported the results of a study concerning the realization of a double canes underground tunnel which crosses soils with non-homogeneous physical and mechanical properties.

In conclusion it has been evidenced:

– the analysis about the uphill cane does not show specific problems because it is sited within a homogeneous soil constituted by phyllitic rocks;
- the analysis of the downhill cane is particularly conditioned by the presence of alluvium deposits characterized by poor mechanical properties;
- for the previous considerations, remedial works were assumed around the cavity in alluvium outcroppings zones to assure the gallery stability; then it was possible to obtain millimetric settlements at the surface;
- the assumed dynamic input emphasized the vulnerability of the simulated system along the contact surface between the rock substratum and the upper lithologies with poor mechanical characteristics.

It is necessary, however, to specify that the present note has intended to study only the design feasibility of the tunnels diggings, postponing the problematic relative to the structural calculations of the retain works to the eventual executive phase.

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