

Numerical simulation of tunnel construction in volcanic rocks

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ABSTRACT: For the design of tunnels, numerical simulation plays an important role. In general 3-D analyses are required and with currently available domain based methods such as the Finite element method the effort is considerable. In this paper the numerical simulation of tunnel excavation using an alternative approach to the FEM, which results in an order of magnitude increase in efficiency and user friendliness, will be discussed. The method of analysis is the less well known Boundary Element Method (BEM), which has not been used for tunneling to date because of the inability of available programs to consider sequential excavation, heterogeneity and non-linear behavior. The new program, developed within a European research project, has the capability to deal with these aspects and can be applied to tunnel design. An example of analysis is presented where a tunnel is excavated near a preexisting cavity, a situation that can occur in volcanic rocks. It is shown that the BEM has distinct advantages over domain based methods.

1 INTRODUCTION

For the analysis of underground excavations the finite element method (FEM) is frequently used. In the case of the three-dimensional analysis of complex excavations the simulation effort can be considerable. This is because the method is not very well able to model the ground, which for all practical purposes can be considered of infinite or semi-infinite extent. Usually a large volume of material (cube) must be isolated, and discretised into volume elements. Some artificial boundary conditions have to be applied at the surfaces of the cube. It has been shown by Golser (2000) that unless these boundary conditions are placed far enough away from the excavation they can significantly influence the results. The Boundary Element Method (BEM), because it is based on a surface discretisation, on the other hand is able to accurately model the infinite domain (Beer, 2001). The effort in making a mesh and computing the results is an order of magnitude smaller than with the FEM. In addition the quality of the results is considerably better because the functions describing the variation of displacements and stresses inside the ground exactly satisfy both equilibrium and compatibility conditions.

In Figures 1 and 2 we show a comparison of the two approaches to modeling tunnel construction. The FEM mesh in Figure 1 has approx. 100 000 unknowns whereas the BEM mesh in Figure 2 has approx. 1 000 unknowns.

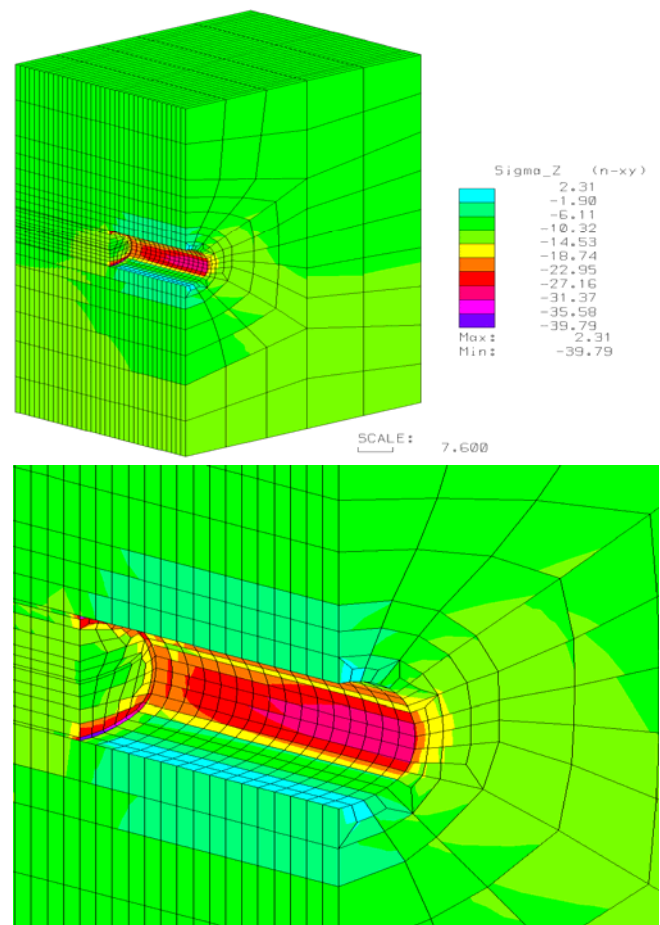


Figure 1. Example of a simulation of tunnel excavation with the Finite element method

In the finite element method usually the stresses are computed at points inside elements (Gauss points).

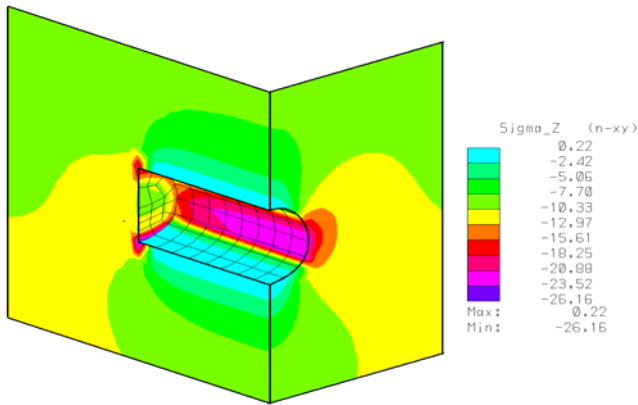


Figure 2. The problem in Figure 1 analyzed with the boundary element method.

Contours plots of stress are generated by interpolation between Gauss points. In the boundary element method no elements exist inside the rock mass. Here the stresses are computed using the fundamental solutions of the governing differential equations and therefore contours can be determined directly without interpolation. For 3-D problems result planes are specified on which the contours are painted. On the contour plots one can see clearly that for FEM analysis small discontinuities appear whereas the contours of the BEM analysis appear smooth, indicating a better quality of the results.

2 EXAMPLE OF APPLICATION

In the next example we attempt to show the advantage of the BEM for the simulation in terms of user friendliness.

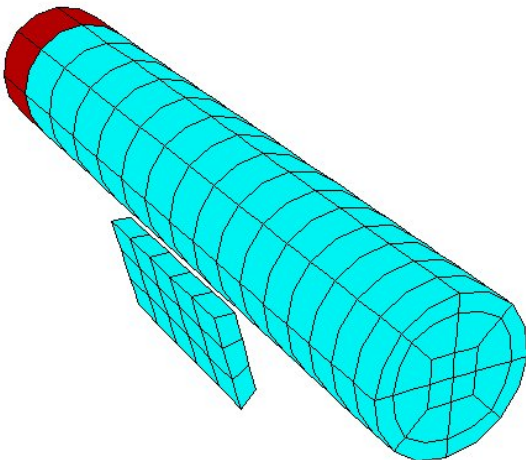


Figure 3. Boundary element mesh of a tunnel excavated near a cavity. The dark red elements are plane strain boundary elements

It is concerned with the excavation of a tunnel near an existing cavity as is may occur for example when tunneling in volcanic rocks or in carst. The aim of the analysis is to ascertain the influence of an existing cavity on the state of stress around a tunnel depending on its location relative to the tunnel.

The tunnel is assumed to be excavated in an infinite prestressed domain with a vertical stress that is twice the horizontal stress. The length of the tunnel is assumed infinite and the excavation is assumed to be made in one step.

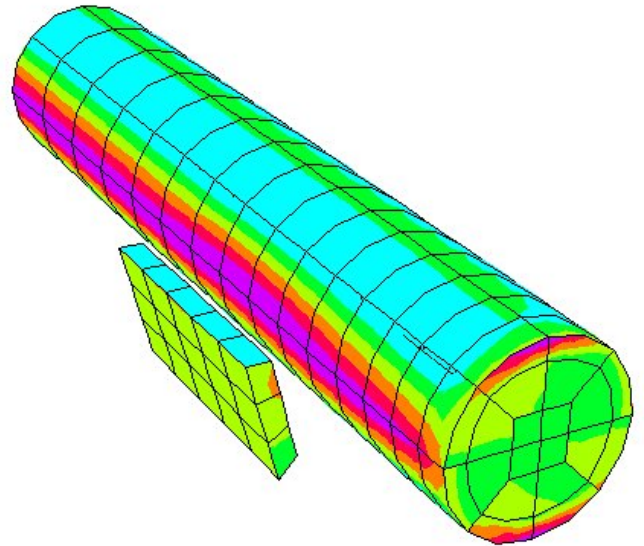


Figure 4. Contours of maximum compressive stress on the tunnel wall.

Figure 3 shows the Boundary element mesh used for a location of the cavity which is near the tunnel.

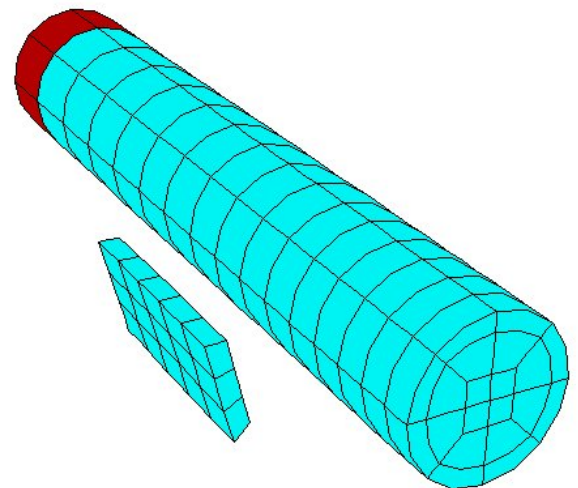


Figure 5. Required change in mesh to simulate a cavity which is further away from the tunnel

Quadratic boundary elements are used for describing the surface of the excavated tunnel and the cavity and dark red plane strain elements to accurately model the conditions where the tunnel is as-

sumed to go to infinity. One can easily see that the effort in mesh generation is considerably less than with the FEM. Figure 4 shows a result of the analysis namely the distribution of the maximum compressive stress on the tunnel wall.

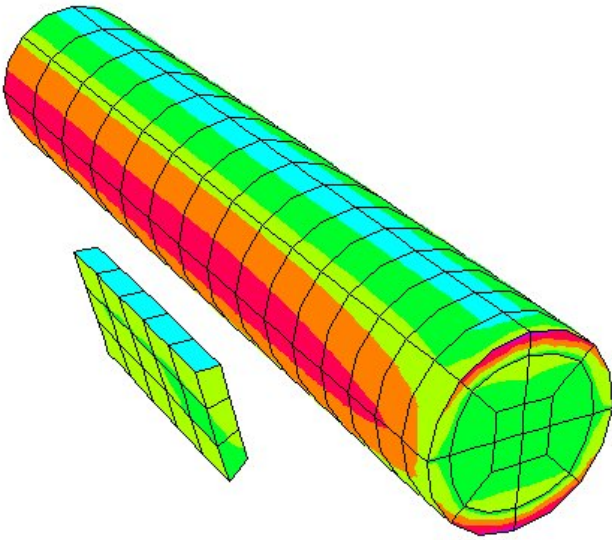
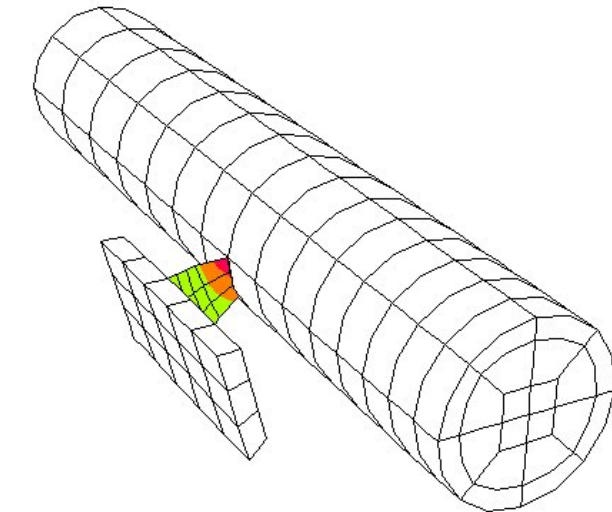
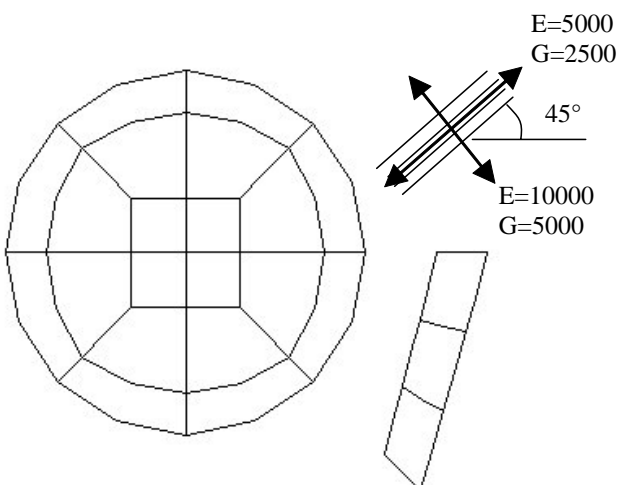


Figure 6. Effect of distance of cavity to tunnel: Contours of maximum compressive stress. Compare with figure 4.

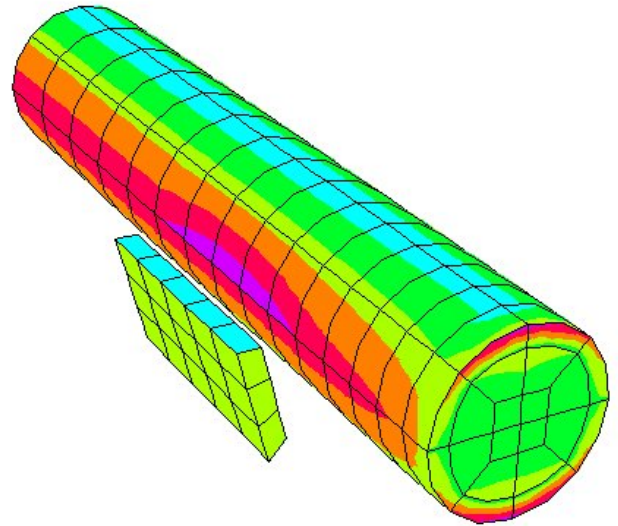
Figure 7. Distribution of maximum compressive stress



on a result plane inside the rock mass



Next we show in Figure 5 how easy the change in mesh is to analyze the effect of a cavity that is further away from the tunnel. In this case the mesh describing the cavity is simply moved to the required position. In the FEM a whole new mesh generation would have been required. The results of the second analysis are shown in Figure 6 plotted on the tunnel walls and in 7 on a result plane. It can be seen that the influence of the cavity has diminished significantly.



2.1 Anisotropic rock mass

Here we show that the BEM is also capable of considering anisotropic rock properties. For the next analysis it is assumed that the rock mass is stratified and has the properties as shown in Figure 8.

Figure 8. Definition of anisotropic material properties

Figure 9 shows that the maximum compressive stresses on the tunnel wall adjacent to the cavity have increased with respect to the isotropic case.

Figure 9. Contours of maximum compressive stress for anisotropic case

3 NONLINEAR MATERIAL BEHAVIOR

The analyses presented so far assume elastic behavior which is not a very realistic model of the real behavior. With an extension of the BEM it is possible to also consider non-linear material behavior. In this extension, volume cells have to be provided in zones that behave inelastic (Beer 2001). An example is shown in Figure 10 where the zone between the cavity and the tunnel has been discretised into volume cells. The non-linear analysis proceeds in the same way as for finite elements i.e. the stresses are

checked if they violate the yield condition after an elastic analysis. Next excess stresses are computed and these are considered as initial stresses acting on the system. The iteration proceeds until all stresses are on the yield surface. In Figure 10 we show the results of the first iteration as contours of the Mohr-Coulomb yield function plotted on the surfaces of the cells.

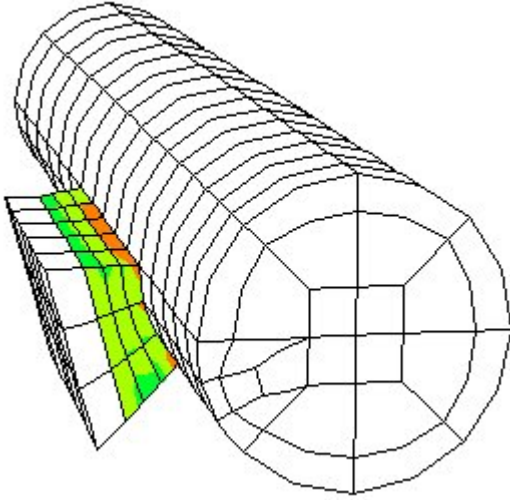


Figure 10. Nonlinear boundary element analysis of tunnel excavation. Contours of the yield function plotted on cells.

The presence of cells does not mean an additional discretisation effort by users and does not result in an increase in the system to be solved. As has been shown recently (Ribeiro, 2006) the cells may be generated automatically so from the users point of view a non-linear analysis is identical to a linear analysis.

4 SEQUENTIAL EXCAVATION/CONSTRUCTION

For the sequential excavation/construction of a tunnel with the BEM the multi-region concept can be used (Duense&Beer, 2001). The complete boundary element mesh of a tunnel consists of one infinite region which is filled with finite regions, which constitute the material removed by excavation (Fig. 11).

The whole surface of each region needs to be described by boundary elements except the surfaces on the planes of symmetry. In the example, the x-z plane and y-z plane are assumed to symmetry-planes (Fig. 12). The cross section of a tunnel is divided into top heading and bench. Figure 12 shows the complete Mesh which consists of 1 infinite region and 40 finite regions.

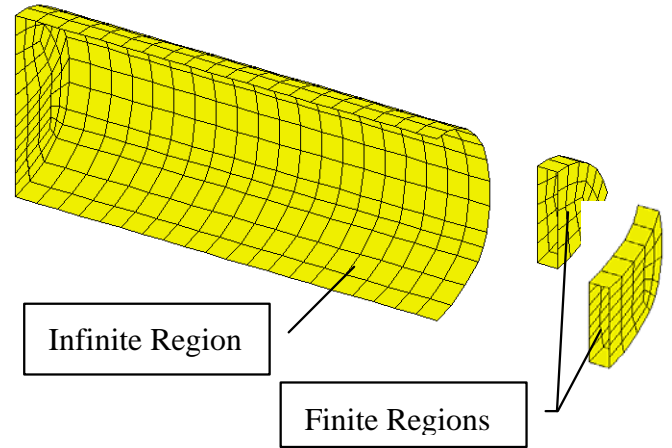


Figure 11. Regions of a BE-mesh, infinite and finite regions

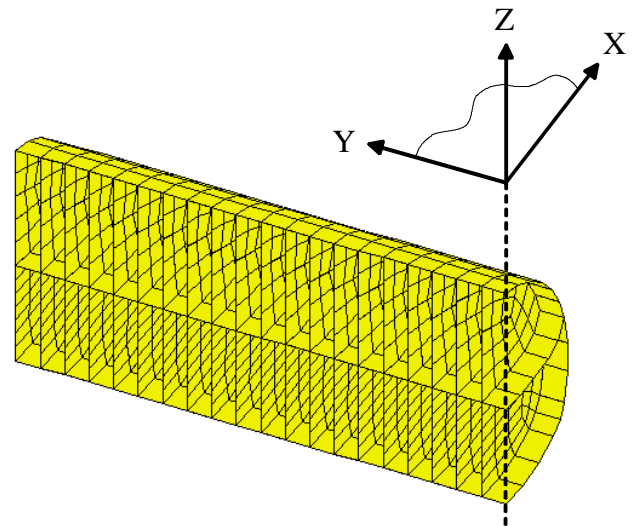


Figure 12. Complete mesh

At the beginning the whole volume of the tunnel is filled with boundary element regions. Next, the information which regions have to be excavated is supplied to the program. These regions become inactive and boundary stresses are generated due to the removal of the regions. Figure 8 shows the z-deformations on the deformed mesh in an axonometric view for a load case where 15 top headings and 5 benches are excavated.

5 CONCLUSIONS

It has been shown on an example that the boundary element method has distinct advantages over the finite element method for modeling tunnel construction. The main advantage is the user friendliness because the dimension of the problem is reduced by one. However, there are also gains to be made in the

accuracy of the results and the computing effort in the analysis of complex 3-D problems.

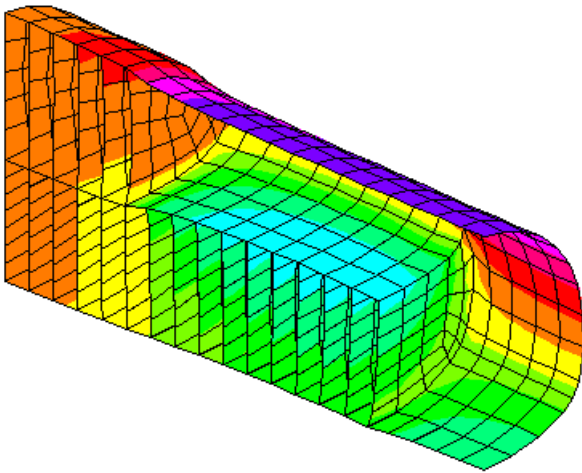


Figure 13. z-deformation of load-case 15

The main reason why this method has not found widespread use in the tunneling community is that at the moment no commercially available code exists that is able to model sequential excavation/construction, visco-plastic material behavior and ground support.

In the framework of the European project TUN-CONSTRUCT (Technology Innovation in underground construction) a computer program is being developed especially for tunneling. This program will combine the user friendliness of the BEM with the versatility of the FEM. The program capabilities are described in more detail in (Beer, 2007).

6 REFERENCES

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