Geotechnical Assessment of the Route Corridor for the Koralm Base Tunnel

A.Goricki & W.Schubert
Institute for Rock Mechanics and Tunneling, Graz University of Technology, Austria

R.Fuchs & A.Steidl
3G - Gruppe Geotechnik Graz ZT GmbH, Austria

ABSTRACT: The Koralm railway tunnel with a length of about 33 km and an overburden up to 1700 m is planned in southern Austria. To select the most economic alignment, a geotechnical assessment of the entire route corridor with an area of about 150 km² was made. It will be shown how the geotechnical parameters concerning costs and time of the planned TBM-excavation were determined and calculated. The mean value and distribution were determined for each parameter allowing statistical methods to be implemented into the analysis. To handle the extensive amount of data the results were assigned to various “layers” and visualized with a Geographic Information System (GIS). Due to the structure of the data a rating can be made by connecting the assessment parameters and layers respectively. It is, for example, possible to achieve a cost based assessment of the entire corridor by applying cost relevant weighting factors.

1 INTRODUCTION

To modernize the Austrian railway system and to improve connections to international railway networks, the HL-AG started planning the Koralm railway in the south of Austria. The Koralm railway with a length of 130 km will be part of the Trans European Network (TEN) and connects Eastern Europe via Vienna to North Italy (Hainitz 1999). The Koralm railway will also create a direct connection between the two provincial capital cities Graz and Klagenfurt, decreasing the travel time from three to one hour. This route which is named after the North Italian city Pontebba will be the eastern most crossing of the Alps.

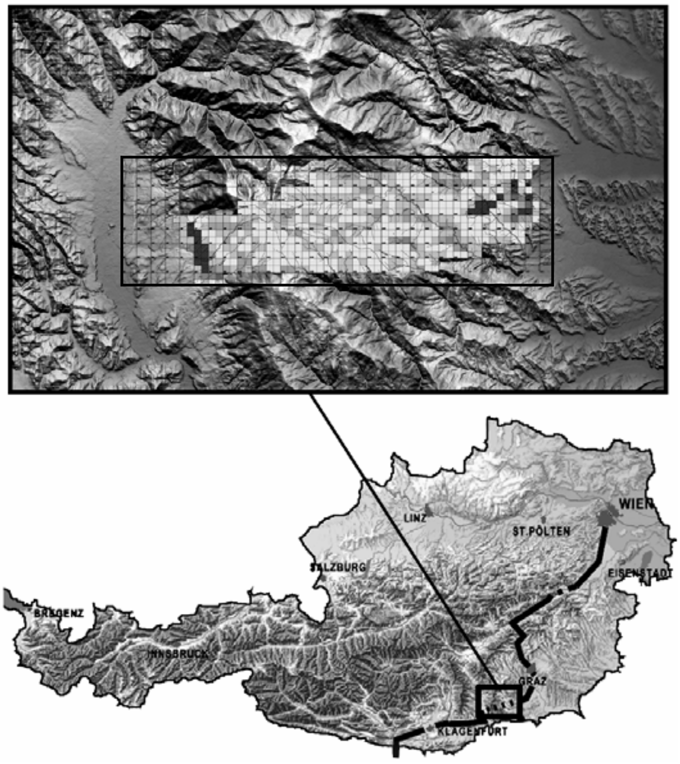

Figure 1. Geographic location of the Koralm base tunnel project.

The Koralm base tunnel with a length of about 33 km and an overburden of more than 1700 m is the key section of this railway line. This tunnel between Carinthia and Styria will be Austria’s longest tunnel.

Field investigations and laboratory tests were performed for the preliminary design and route selection. This allowed the geological and geotechnical assessment of the route corridor with an area of about 150 km².

2 GEOLOGICAL SETTING

The majority of the Koralm base tunnel is located within a polymetamorphe crystalline basement mainly consisting of paragneiss, mica schist, and secondary units including quartzite, amphibolite and marble.

Due to intensive brittle faulting at both sides of the mountain range, deep sediment basins have developed. These basins are for the most part filled with tertiary, finegrained river and marine sediments.

3 SITE INVESTIGATIONS FOR ROUTE SELECTION

To establish a rock mass model for the route corridor geotechnical investigations were performed from 1998 to 2000. The main target was to gather information on the bedrock condition as well as the characterisation and location of fault zones.

Based on this model, geotechnical risks were identified and characterised allowing the geotechnically most favourable alignment to be selected. The investigations focused on:

- detailed engineering geological characterisation of the bedrock including: lithological variations, orientation, spacing, persistency, surface properties and infillings of discontinuities
- identification of fault zones by morphological and structural appearances
- analysis of the overall stress field for the project area
- assessment of homogeneous regions and development of geotechnical models.

The investigations included outcrop studies and detailed geological field mapping in scale 1:5000 at selected, geotechnically important areas within the alignment corridor.

To complete and verify the geological picture provided from surface investigations 36 boreholes with a total length of about 6300 m were drilled and studied. Most of the boreholes were used for in situ tests, such as hydraulic fracture tests, geophysical borehole surveys and hydraulic tests. Additional information was obtained with geophysical methods consisting of reflection and refraction seismic and geoelectrical surveys.

Core samples were selected for laboratory tests to evaluate mechanical and mineralogical properties.

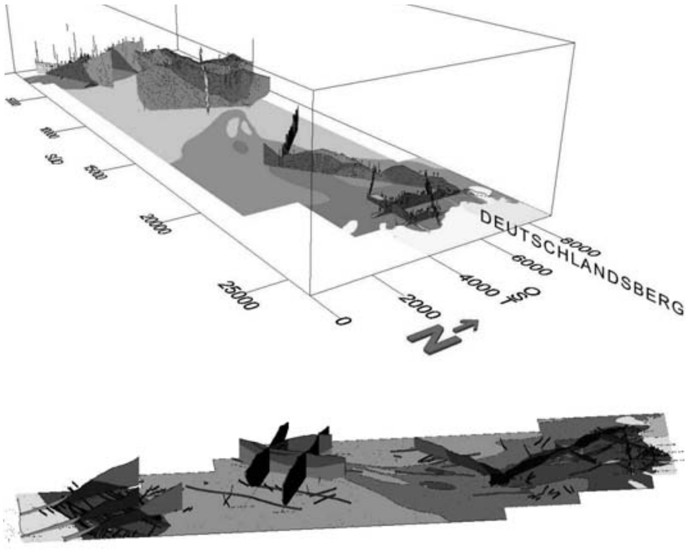

Figure 2. Geological model of the 150 km² route corridor based on the horizontal cross section in tunnel level.

4 GEOTECHNICAL ASSESSMENT OF THE ROUTE CORRIDOR

4.1 *General*

The goal was to assess the entire corridor area and to create a system to estimate time and costs for different route variants (Harer & Riedmüller 1999, Schubert et al. 2001). In that way a tool to select different routes based on geological and geotechnical conditions of the crystalline basement of the Koralm massif was given to the designer. The following procedures were used:

- Developing a geological horizontal section at the tunnel level
- Dividing the corridor into a grid of 500 m squares. This results in 586 evaluation fields covering an area of 146,5 km²
- Defining key parameters
- Calculating the distribution of the lithological units for each evaluation field
- Assigning the parameters of influence to the lithological units
- Analysis and determination of the key parameters
- Describing the information reliability
- Presenting the results in separate layers with a Geographic Information System (GIS).

In this early stage of investigation large quantities of data are collected (Riedmüller & Schubert 2001). The key parameters to assess rock mass behavior for the planned TBM excavation are: radial deformation, thickness of plastic zone, fault influence, penetration rate, abrasivity and influence of water. Some of these parameters are calculated values based on uniaxial compressive strength, rock mass fracturing, joint orientation or length and orientation of faults. To efficiently use this information the quality and relevance of each dataset must be determined.

For rock with a highly anisotropic behavior, such as gneiss (Blümel et al. 1999), the laboratory program must consider the foliation orientations relative to the loading direction as shown in figure 3. Therefore, a specific selection of specimen and a large number of tests are necessary to perform statistical evaluation.

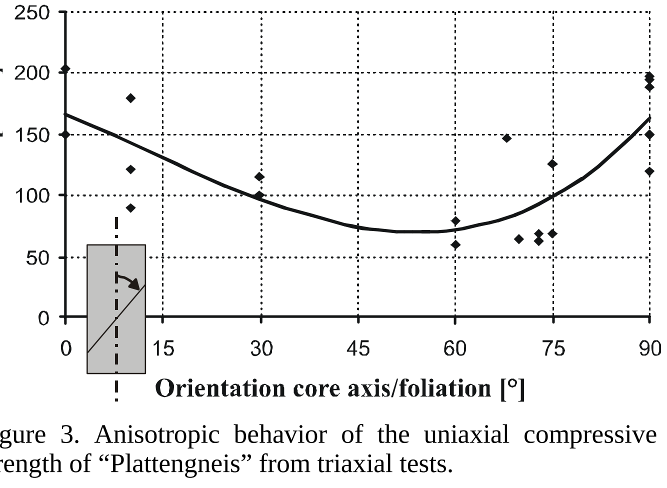

Figure 3. Anisotropic behavior of the uniaxial compressive strength of “Plattengneis” from triaxial tests.

Statistical methods were also used to analyze the key parameters. The goal was to present the parameters for the route assessment as mean values with standard deviation. An indication of the distribution and spread was obtained. The point estimate method (Rosenblueth 1975) was used to decrease the effort of calculations. With this method a continuous probability distribution can be replaced by discrete and singular probability without changing the statistical moments. So a probability distribution *f(x)* can be reduced to two points each one a standard distribution left and right of the mean value.

The aim of the probabilistical calculation is to obtain a statement about the probability for a higher or lower values than a defined one. Thus a more reliable evaluation of the results is possible.

4.2 *Determination of parameters for the route assessment*

4.2.1 *Plastic zone and radial displacement in fault free rock mass*

To estimate the depth of the plastic zone and the radial displacement for an unsupported excavation an analytical calculation (Hoek & Brown 1997, Hoek 1999) was done for areas of fault free rock masses. For each assessment square the overburden was calculated from a digital topographical model for a constant tunnel level of 380 m. The grid also contains information about intact rock like *UCS* and *mi* corresponding to the distribution of the lithological units. The influence of the anisotropic rock mass behavior was considered by reducing the *UCS* depending on the foliation orientation to the tunnel axis. The *GSI* was roughly estimated by the results of the drill core logging with values from 55 to 65 for most parts of the fault free zones of the corridor and a general standard deviation of 5. The radial displacements and the rock mass parameters calculated with the analytical model for hydrostatic primary stress conditions for a circular excavation without support, give an idea about the relative variations of rock mass behavior in different areas.

These results were calculated as mean values with a standard deviation by using the point estimate method with n+1 permutations (Zhou & Nowak 1988, Thurner 2000).

4.2.2 *Plastic zone and radial displacement in fault zones*

To determine the influence of fault zones on the radial displacement the analytical model was used with a different approach. The *GSI* value was modified depending on the excavation length in a fault zone.

To correlate the deformations with the excavation length in a fault zone the following procedure was used:

- The *GSI* was estimated for the fault free rock mass and for fault zone material based on the results of the drill hole logging
- The *GSI* value was reduced by about 10 for rock mass with very thin faults
- The *GSI* value corresponds to the fault material for excavating more than three tunnel diameters in fault zones
- A non linear correlation is assumed between the excavation length in a fault and the estimated *GSI* value based on the results of three dimensional numerical calculations (Golser 2001, Großauer 2001) as given in figure 4.

Based on this procedure, the displacements for fault influenced tunnel sections can be estimated in a simplified way (figure 5).

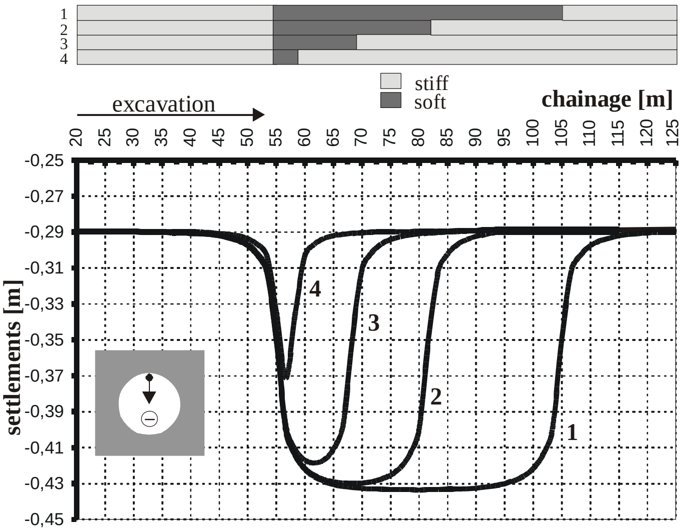

Figure 4. Final crown settlements as a results of numerical calculation with variation of fault lengths (constant primary stress condition and stiffness ratio E_{stiff}/E_{soft}).

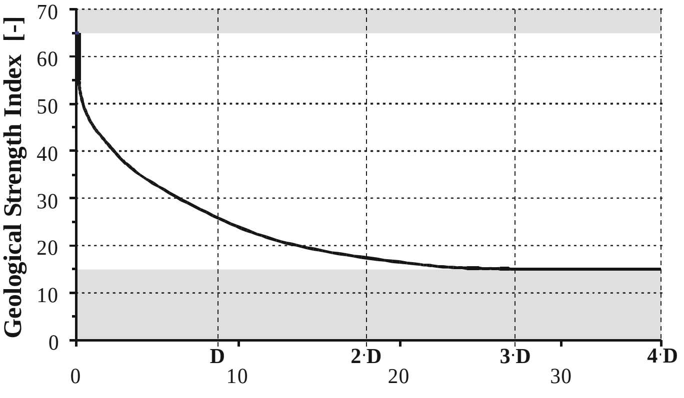

Figure 5. Example of the estimated correlation between *GSI* value and the excavation length in a fault zone; GSI_{RM} = 65 and GSI_{FZ} = 15.

4.2.3 *Fault influenced excavation length*

There are two basic types of fault data incorporated into the horizontal cross section: Lineaments from remote sensing (interpreted and projected vertically) and fault zones from field investigations, drill holes and literature (projected with the actual orientation of the faults). The fault influenced excavation length is calculated from pure geometrical conditions: fault length, fault orientation (divided into 12 classes), fault thickness, tunnel diameter and orientation of the tunnel axis. The fault influence was calculated assuming a general fault thickness of 3 m and a fault influence to the excavation at a distance of 1,5 tunnel diameters and less. After a multiplication with the probability to intersect a fault (based on orientation and length) and summing all faults in one cell the average fault influenced excavation length for each assessment square was calculated.

$$L_M = \sum_{i=1}^{12} L_M^i = \sum_{i=1}^{12} L^i \cdot P^i(St) \tag{1}$$

$$L_M^i = 3 \cdot \left(\frac{D}{\tan\alpha_M^i} + \frac{1}{\sin\alpha_M^i} \right) \cdot \frac{L_{(St)}^i \cdot \sin\alpha_M^i}{500} \tag{2}$$

L_M = average fault influenced excavation length
L^i_M = average fault influenced excavation length for one orientation class
L^i = fault influenced excavation length for one orientation class
$P^i\ (St)$ = probability to intersect a fault of one orientation class
α^i_M = average angle between fault and tunnel axis for one orientation class
$L^i_{(St)}$ = fault length of one orientation class
D = tunnel diameter

4.2.4 *Penetration rate*

To estimate the penetration rate for the planned TBM excavation a simple model was used for the performance forecast (Gehring 1995) based on the *UCS* of the intact rock. Several factors of influence like joint spacing, joint orientation and normalized machine parameters are also considered.

$$p = \frac{(k_1 \cdot k_2 \cdot \ldots\ldots\ldots \cdot k_i) \cdot F_N}{UCS} \tag{3}$$

p = penetration [mm/Rev]
F_N = force of one disc [kN]
k_i = factors of influence

With the estimated penetration per revolution (limited by disc geometry), the tunnel diameter and the maximum disc rotation speed (v_{max}) the penetration rate can be calculated as follows:

$$V_{TBM} = p \cdot \frac{3{,}6 \cdot v_{max}}{D \cdot \pi} \qquad [m/h] \tag{4}$$

To quantify the spread of the calculated values all results were presented as mean values and standard deviations.

4.2.5 *Abrasivity*

The results from the statistical evaluation of the Cerchar Abrasivity Index (CAI) tests and Abroy abrasivity tests were assigned to the lithological units of each cell. The tests showed a highly anisotropic behavior of the gneiss.

4.2.6 *Groundwater*

The following key parameters were evaluated to describe the possibility of water inflow during the excavation: permeability of different lithological units, depth of weathering zone, influence of tectonic structure. The fault zones were evaluated by their length and their orientation depending on the orientation of the foliation. At this stage of investigation numerical modeling has not been performed. So this assumption is a very rough estimation of the expected water situation during excavation.

4.2.7 *Information reliability*

The reliability of the route assessment is directly related to the quality of the input parameters. To quantify reliability of a parameter, the investigation method used to obtain a given parameter was evaluated for its information quality (Dörrer et al. 2000, Harer & Otto 2000). The different investigation methods were: core drilling, geophysical methods, field mapping and remote sensing. The subjective quantification of the investigation quality is based on:

- Quality of the result of the single investigation method
- Combination of different methods
- The vertical distance to the tunnel level.

This resulted in a classification of good, medium or low for each assessment square. This simple quantification of the information quality gives an idea about the spread of values of the geotechnical parameters. A square with a low information level has a higher probability to deviate from predicted conditions than a square with a high information level.

4.3 *GIS-based processing of geotechnical relevant data*

GIS-based spatial modeling is a process of looking at characteristics from a number of layers for locations and spatial extends to solve problems.

The GIS-System imposes a rectangular mesh or grid on selected layers. The grid cells represent an area and have a value for each map layer (figure 6). The cells from various layers are stacked to describe many parameters for each location in the project area.

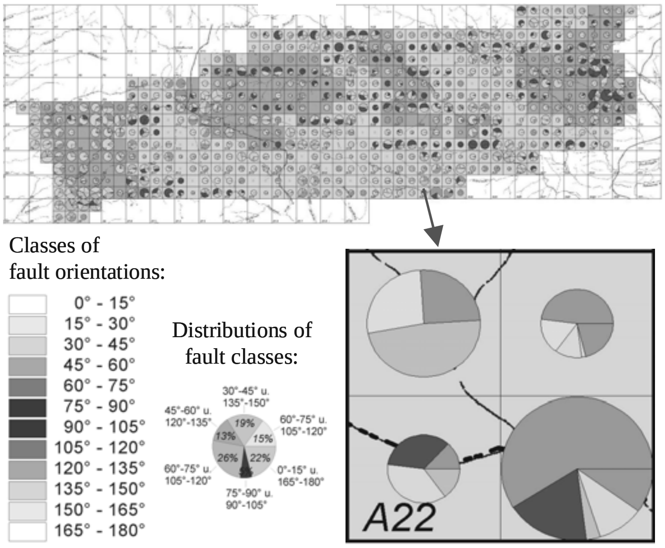

Figure 6. The fault-layer including orientation and distribution of fault classes.

The following input data were used to create layers within the model:

- Overburden (25 m DEM coverage)
- Lithology
- Orientation of discontinuities
- Faults (3D shape file)
- Hydrogeology
- Abrasivity
- Fault influenced excavation length
- Rock mass strength
- Plastic zone
- Radial displacements
- Penetration rate
- Information reliability.

Multi-layered displays comprised of several data sets (figure 7) were created. These displays are useful because they help to see relationships between the particular information. The evaluation of these input data was based on integrated vector-raster analysis.

In the model, characteristics are ranked by their suitability and combined to create a composite database of the suitability of each location based upon all features and their variables.

5 POSSIBILITIES FOR ROUTE SELECTION

5.1 *Implementation of rating systems*

For a geotechnical assessment of the route corridor it is necessary to weight and combine the relevant parameters by applying a rating system.

Due to the simple database structure a given rating system or any other mathematical function can be easily implemented. For example, if the singular values of each result layer are weighted by cost relevant factors and if the different result layers are combined together the geotechnical assessment of the route corridor can be done by comparing relative costs. The same process can be used to investigate effects of time, mechanical behavior or other required information.

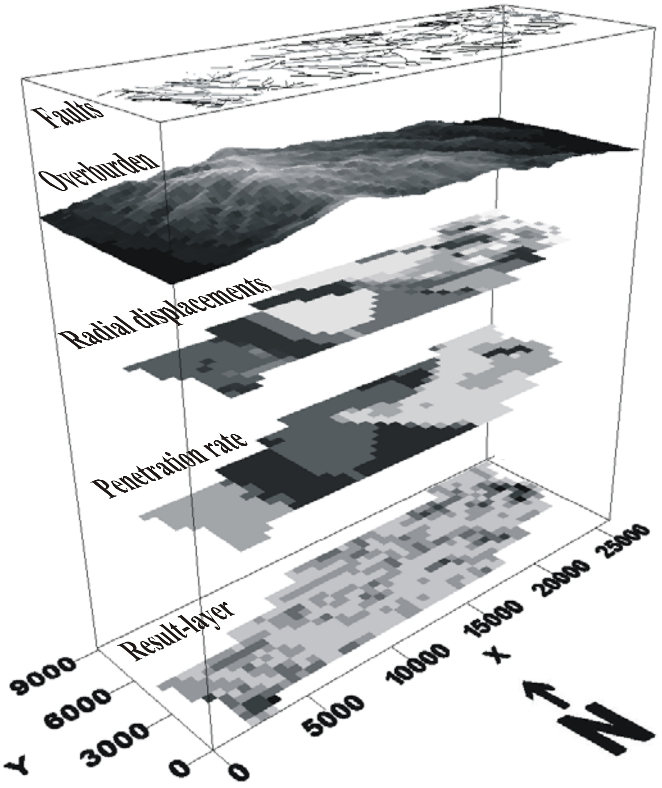

Figure 7. Example of a multi-layer display.

One of the advantages of this system is that it is simple to perform parametric studies. Due to the visualization with GIS, the effect of changing the mathematical functions that combine data-layers can instantly be evaluated.

5.2 *Route selection and evaluation*

GIS-based modeling was used to evaluate the optimal route for the Koralm base tunnel.

To assess the potential costs of different routes a cost weighted function was used to combine the layers with geotechnical key parameters. The used raster GIS network with cell-based raster data analysis and integrated vector-raster analysis defines cartographic space as a surface. The geotechnical results are represented as grid layers with values, which vary over this surface (figure 8a).

The cells of the cost weighted result layer that intersects one of the selected tunnel routes (figure 8b) leads to a 3D line with measured values like a 3D-profile graph. The results of the calculations are shown as line charts (figure 8c). These charts enabled an evaluation of the different tunnel routes by calculating a singular value (working integral). With this method the most economic route can be selected.

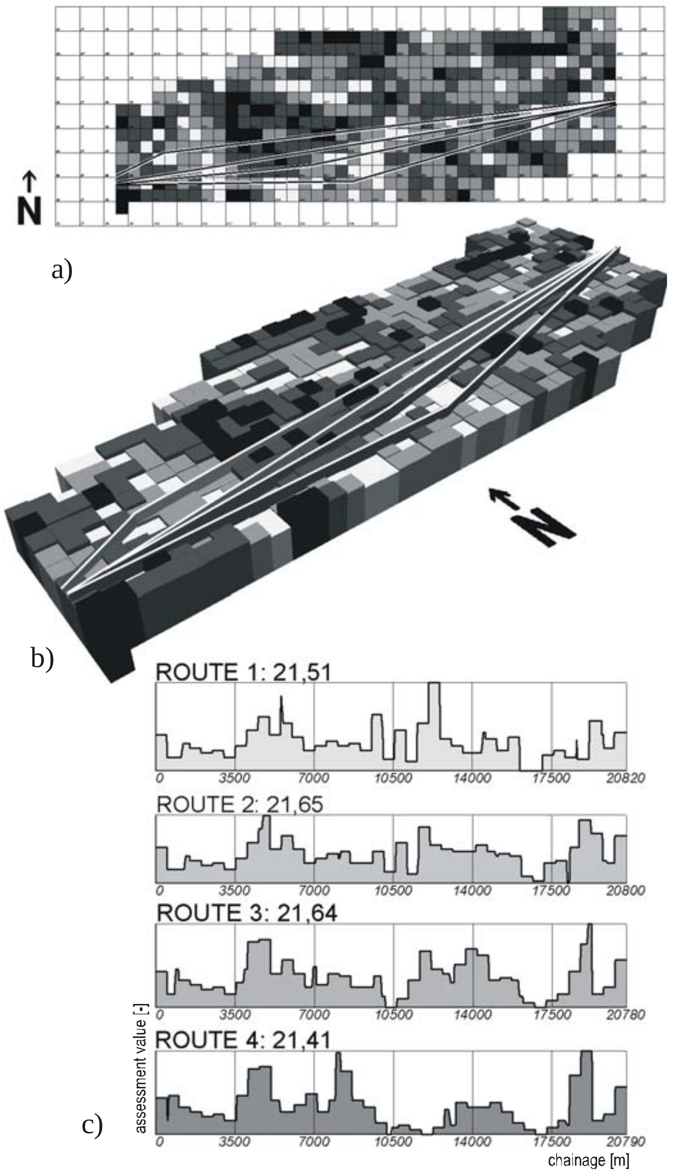

Figure 8. Visualized result layer with different routes a) plane, b) three dimensional; c) Evaluation charts to compare the different routes.

6 CONCLUSION

A geotechnical assessment was made for the route corridor of the Koralm base tunnel with an area of about 150 km². To evaluate the extensive amount of geological and geotechnical data for the entire area a clear defined procedure was used. The route corridor was divided into a grid consisting of 500 m squares. After defining and processing the key parameters the data were stacked into separate information-layers and combined with a cost relevant rating system. By using statistical methods and implementing an evaluation of the information reliability the probability and spread of the results could be estimated. A Geographic Information System was used to visualize the data and to evaluate the most favorable and economic route.

REFERENCES

Blümel, M., Brosch, F-J. & Fasching, A. 1999. Investigations on fabrics and related mechanical properties of a highly anisotropic gneiss. In G. Vouille, P. Berest (eds.), *International Congress on Rock Mechanics, Proc. intern. symp., Paris*, 1999. Rotterdam: Balkema.

Dörrer, T., Harer, G., Lehmann, B., Lux, K.-N., Riedmüller, G., Schön, J. & Seren, S. 2000. Combined Application of Geophysical Measurements, Case History Koralm Tunnel. *Felsbau* 18(4): 37-47.

Gehring, K.-H. 1995. Leistungs- und Verschleißprognosen im maschinellen Tunnelbau. *Felsbau* 13(6): 439-448.

Golser, H. 2001. The Application of Finite Element and Boundary Element Methods in Tunnelling. Doctoral Theses, Graz University of Technology.

Großauer, K. 2001. Numerical Investigation on the Influence of Fault Zones on Deformations and Stresses for Tunneling. Internal Report, Institute for Rock Mechanics and Tunneling, Graz University of Technology.

Hainitz, H. 1999. Die Entwicklung des Europäischen Eisenbahn-Hochleistungsnetzes an der Schwelle des 21. Jahrhunderts. *Felsbau* 17(5): 313-318.

Harer, G. & Otto, R. 2000. Koralmtunnel: Methodische Erkenntnisse aus der Projektvorbereitung. *Mitteilungen IAG BOKU,* Wien: 27-42.

Harer, G. & Riedmüller, G. 1999. Assessment of Ground Condition for the Koralm Tunnel during the Early Stages of Planning. *Felsbau* 17(5): 374-380.

Hoek, E. & Brown, E.T. 1997. Practical Estimates of Rock Mass Strength. *Int. J. Rock Mech. & Min. Sci. & Geomech. Abstracts*, 34(8): 1165-1186.

Hoek, E. 1999. Support for very weak rock associated with faults and shear zones. *Rock Support and Reinforcement Practice in Mining, Proc. intern. symp., Australia, Kalgoorie, March 1999.*

Riedmüller, G. & Schubert, W. 2001. Project and rock mass specific investigation for tunnels. *ISRM Reg. Symp. Eurock 2001, Espoo, Finlan,*. in press.

Rosenblueth, E. 1975. Point estimates for probability moments. *Proc. Nat. Acad. Sci.* USA, October 1975, Vol. 72(10): 3812-3814.

Schubert, W., Goricki, A., Button, E:A:, Riedmüller, G., Pölsler, P., Steindorfer, A. & Vanek, R. 2001. Excavation and Support Determination for the Design and Construction of Tunnels. *ISRM Reg. Symp. Eurock 2001, Espoo, Finland*, in press.

Thurner, R. 2000. Probabilistische Untersuchungen in der Geotechnik mittels deterministischer Finite Elemente-Methode. Doctoral Theses, Graz University of Technology.

Zhou, J. & Nowak, A.S. 1988. Integration Formulas to Evaluate Functions of Random Variables. *Structural Safety* 5: 267-284.