Geological and Geotechnical Ground Characterisation for the Koralm Tunnel Route Selection

By Arnold Steidl, Andreas Goricki, Wulf Schubert and Gunter Riedmüller

The first geological and geotechnical investigations for the Koralm tunnel were performed from 1996 to 1998. These investigations included the review and geotechnical interpretation of the existing scientific literature and geological maps, large-scale geological mapping and some geophysical studies. In addition satellite and aerial photographs were evaluated to identify faults by stereographic analyses (1, 2).

The objective of this first investigation campaign was an engineering geological assessment for a TBM excavation. Based on the parameters discontinuity orientation, overburden, lithology, faults and ground water the rock mass was classified. Due to these findings the initial route corridor was reduced by about 50 %.

This paper describes the results of the geological investigations performed from 1998 to 2000 for the geotechnical assessment of the route corridor with a total area of about 150 km^2 for route selection of the Koralm tunnel.

Site investigation concept

The objective for the site investigations during the route selection was to obtain sufficient data and knowledge to characterise the rock mass and to select the geotechnically most favourable alignment within the corridor.

The huge corridor with an area of about 150 km^2 and the limited investigation time required a special approach to the ground investigation (Figure 1). Four significant areas within the corridor were selected and a detailed investigation was carried out. The results from those investigation areas were extrapolated to the areas, which were investigated in less detail. The detailed investigations took place along the eastern and western crystalline boundaries (Hollenegg area, Westabfall Koralpe) within the Tertiary sediments, the central mountain ridge (Garanas-Glitzalm area) and the gorge of the river Schwarze Sulm (Figure 2).

General investigation targets were the

⇨ bedrock condition (lithologic variations, material properties, permeability, weathering),
⇨ discontinuities (orientation, spacing, persistency, surface properties and infillings),
⇨ assessment of groundwater conditions,
⇨ identification and characterisation of fault zones by morphological and structural appearances.

Additionally, specific investigation targets were defined for each investigation area:

➤ Hollenegg area:
⇨ identification and characterisation of the transition zone between crystalline basement and Tertiary sediments;

Geologische und geotechnische Baugrundcharakterisierung für die Trassenauswahl des Koralmtunnels

Der Beitrag beschreibt das geotechnische Erkundungskonzept sowie die Untersuchungsergebnisse für den etwa 150 km^2 großen Trassenkorridor des Koralmtunnels. Für die Beurteilung der geotechnischen Verhältnisse und als Basis zur groben Abschätzung von Bauzeit und Baukosten für die Trassenauswahl wurde ein klar definiertes und nachvollziehbares Bewertungssystem für den Tunnelabschnitt im Kristallin entwickelt. Dazu wurde in einem ersten Schritt der geologische Horizontalschnitt auf Tunnelniveau in quadratische Bewertungsfelder mit einer Seitenlänge von 500 m unterteilt. Nach Definition der für einen TBM-Vortrieb erforderlichen geotechnischen Schlüsselparameter wurden für jedes Bewertungsfeld die Parameter mit Hilfe von empirischen, statistischen und probabilistischen Methoden ermittelt. Die Ergebnisse der Analysen wurden mit GIS verarbeitet und in einzelnen „Layern" dargestellt.

This paper describes the investigation strategy for the Koralm tunnel and the results of the geotechnical investigations performed for route selection within a 150 km^2 corridor. To evaluate the extensive amount of geological and geotechnical data for the entire area of the crystalline basement a clearly 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. By using empirical and statistical methods and implementing an evaluation of the information reliability the probability and dispersion of the results could be estimated. A Geographic Information System was used to visualize the data.

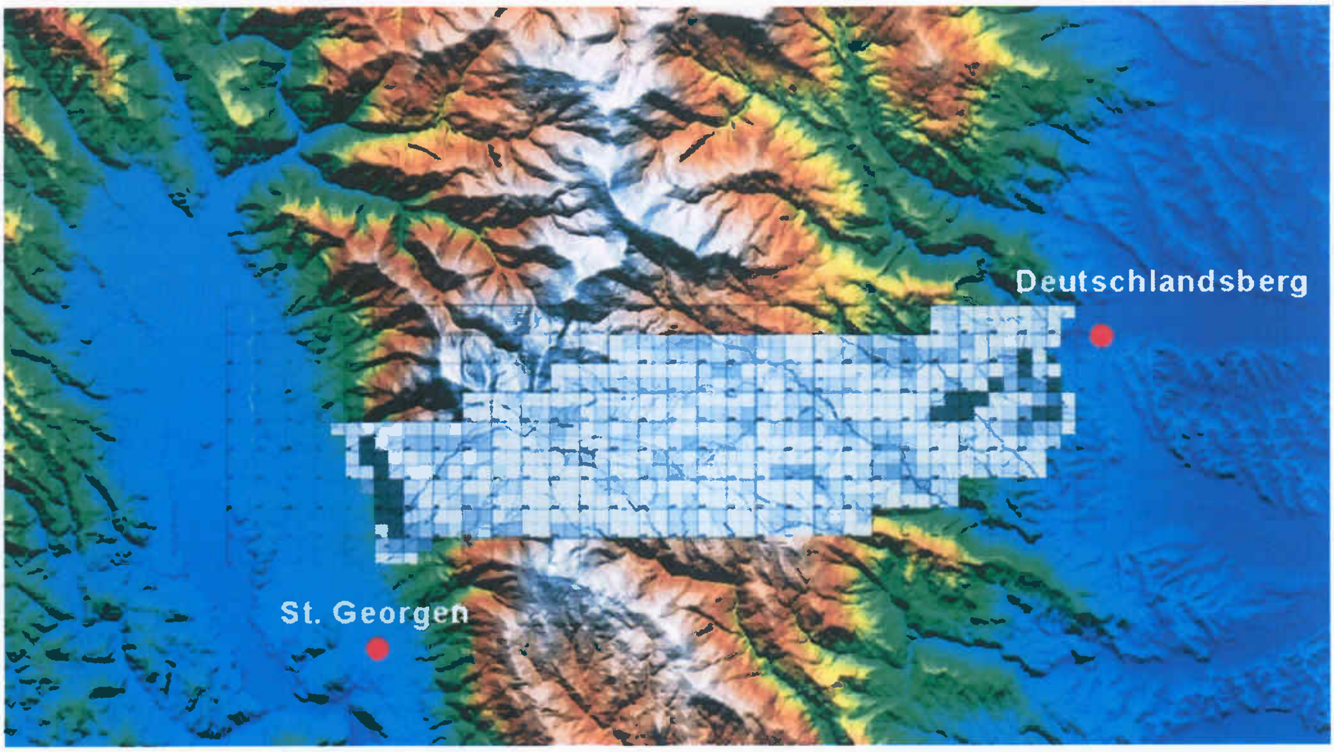


Fig. 1 Geographic location of the route corridor.

Bild 1 *Lage des Trassenkorridors.*

- Schwarze Sulm area:
  - evaluation of in-situ stress field,
  - Tertiary sediments of the Gressenberg (origin, thickness, identification of boundary to the crystalline basement);
- Garanas-Glitzalm area:
  - evaluation of in-situ stress field,
  - depth of weathering zone;
- Westabfall Koralpe:
  - detailed characterisation of the Lavanttal fault system.

Based on the results of the geological mapping a preliminary geotechnical model was developed. Core drillings and geophysical surveys at selected locations with specific geotechnical targets were used to verify that model and to establish a spatial model for each investigation area. Together with the findings of the previous site investigations the "gaps" between the investigation areas were filled and a three-dimensional geotechnical model for the entire route corridor developed (Figure 3).

Based on this model geotechnical hazards were identified and characterised allowing the geotechnically most favourable alignment to be selected. To estimate construction time and costs for different routes a GIS-based system was developed providing a tool for the tunnel designer

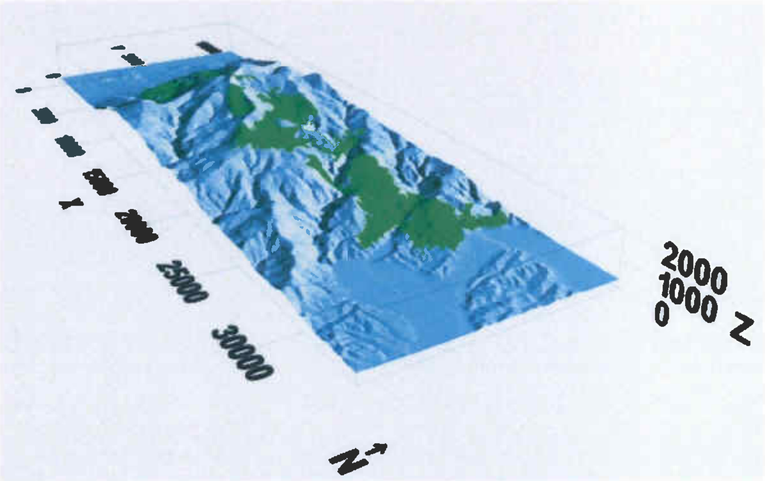


Fig. 2 Investigation areas.
Bild 2 *Untersuchungsbereiche.*

to select different routes. The selection was based on geological and geotechnical parameters. The procedure applied is shown in Figure 4.

Geotechnical investigations

The geotechnical investigations for the route selection were performed from 1998 to 2000. The investigations included outcrop studies and detailed geological field mapping in scale 1 : 5 000 at selected, geotechnically important areas within the alignment corridor. Kinematic analyses to characterise discontinuities were performed on outcrops and drill cores (3).

To complete and verify the geological picture provided from surface investigations, 34 boreholes up to a depth of 650 m with a total length of about 6 260 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 (4). Additional information was obtained with geophysical methods consisting of reflection and refraction seismic and geoelectrical surveys (5). Core samples were selected for laboratory tests to evaluate mechanical and mineralogical properties.

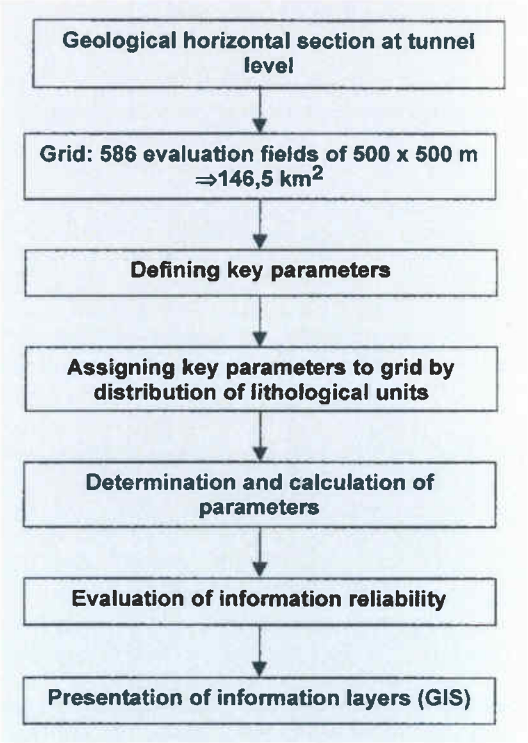


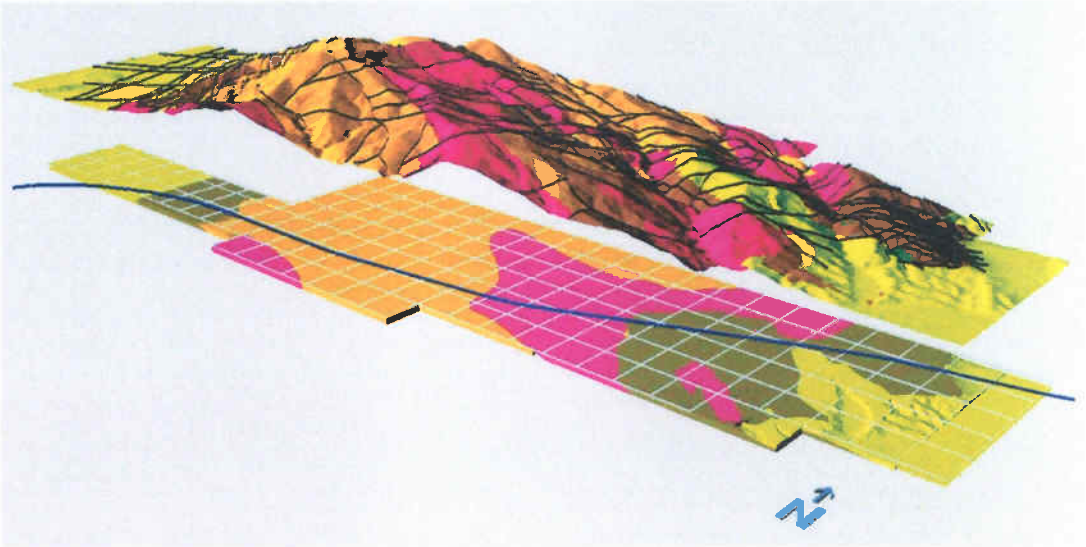
Fig. 4 Procedure for geotechnical assessment.
Bild 4 *Vorgangsweise für die geotechnische Bewertung.*

Ground characterisation

The majority of the Koralm tunnel is located within a polymetamorphic crystalline basement, mainly consisting of different types of gneisses, mica schist, and secondary units including quartzite, amphibolite, eklogite and marble. At both sides of the mountain range, tectonic basins with thick layers of Tertiary silt- and sandstones have developed.

A large-scale syncline structure trending approximately WNW-ESE dominates the central part of the mountain (Figure 5). The rocks generally are thickly bedded to massive and slightly

Fig. 3 Geological surface model.
Bild 3 *Geologisches Oberflächenmodell.*



jointed. Weathering phenomena including discoloured discontinuity surfaces, alteration of rock material resulting in rock strength reduction, open joints, etc. were generally encountered up to a depth of about 200 m.

Locally, faults or fractured zones and rock burst in sections with massive rock and high overburden may cause problems. The field investigation indicates that there is a potential for zones with elevated rock mass temperatures. Temperatures of approximately 30° are expected, and within this section the tunnel is expected to have dry to dripping conditions. Short-term water inflow rates of several 10 l/s are expected at fault zones or fracture zones.

The Koralpe is bounded on both sides by young extensional brittle fault systems. The fault system of the eastern boundary includes three major fault sets. These faults are normal to oblique slip faults and strike presumably E-W, N-S and NE-SW. The average thickness of these faults ranges from a few metres to some ten-metres.

Most critical for tunnel excavation is the Lavanttal fault system at the western boundary at the Koralpe. The entire section is characterised by a heterogeneous composition of weak fault rocks and blocks of sound parent rocks. The faults strike NW-SE and dip steeply towards the Lavanttal Tertiary basin. They are oblique slip to dextral transform faults. The entire section is characterised by a complex groundwater situation of aquifers and aquicludes. The short-term water inflows may exceed some 200 l/s.

The fine-grained sedimentary rocks in the Styrian and Lavanttal Tertiary basin are characterised by very low rock strength. These rocks are sensitive to water with a high potential of slaking. Minor water inflows are expected locally.

Geotechnical assessment of the route corridor

To handle the large quantities of data in this early stage of investigation key parameters were defined (6). The relevant parameters to assess the rock mass behaviour in the crystalline basement for the planned TBM excavation were (7):

- radial deformation,
- thickness of plastic zone,
- fault influence,
- penetration rate,
- abrasivity and
- influence of water.

Some of these parameters were 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 had to be determined.

A majority of the rocks encountered in the project area exhibit highly anisotropic behav-

Deutsches TalsperrenKomitee (DTK)

Dams in Germany

Herausgegeben von
Peter Franke

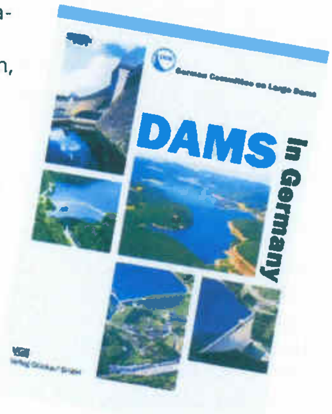
Verlag Glückauf, 2001,
DIN A4, 496 Seiten, rd. 275 mehrfarbige Abbildungen, rd. 60 Karten, rd. 60 Tabellen, ISBN 3-7739-5957-5,
98 EUR

Das Buch „Dams in Germany" beschreibt den in Deutschland existierenden, auf eine lange Tradition zurückblickenden Stand des Talsperrenbaus.

Der Entwicklung des Dammbaus vor 1890 ist das erste Kapitel gewidmet. Der Autor beschreibt die seit dem Mittelalter im deutschsprachigen Raum für die Fischzucht und den Bergbau geschaffenen Staubauwerke in ihrem technischen Aufbau. Der mit dem Namen Intze verbundene Bau von Bruchsteinmauern um 1890 kennzeichnet den Wechsel in die Neuzeit des Talsperrenbaus.

Neben der Trinkwasserversorgung und dem Hochwasserschutz ist die Nutzung der Wasserkraft ein weiterer oder zusätzlicher Grund für den Bau von Talsperren. Die aus geographischer oder topographischer Notwendigkeit heraus geborene Idee der Pumpspeicherung beschreibt ein zweiter Beitrag des Buchs. Thermisch produzierte elektrische Energie aus dem Grundlastbereich kann mit hohem Wirkungsgrad durch das in künstliche Oberbecken gepumpte Wasser in Spitzenlast veredelt oder als schnell verfügbare Leistungsreserve im Verbundnetz genutzt werden.

Den vom Umfang her größten Teil des Buchs stellt die ausführliche Abhandlung von 55 ausgesuchten Talsperren dar. Die Auswahl ist sowohl unter dem Gesichtspunkt der Beschreibung modernster deutscher Talsperrentechnologie als auch unter dem Aspekt der Ertüchtigung älterer Bauwerke an sicherheitsrelevante Anforderungen getroffen worden. Alle Beispiele werden durch bibliographische Angaben zur wissenschaftlich-technischen Fachliteratur ergänzt.



Am Ende des Buchs sind die im Weltregister der Talsperren (ICOLD World Register of Dams) nach international festgelegten Regeln aufgeführten 311 deutschen Talsperren tabellarisch zusammengefaßt.

Das Buch erscheint in englischer Sprache, um den in Deutschland erreichten Standard des Talsperrenbaus und die daran beteiligten wissenschaftlichen und administrativen Institutionen, Betreiber, Ingenieurbüros und Baufirmen der internationalen Fachwelt vorzustellen. Neben dem technisch vorgebildeten Leser, der das Buch als Nachschlagewerk und als Quelle für einzelne Fakten nutzen kann, soll es den technisch interessierten Laien darin unterstützen, sachliche Informationen für den nur im Zusammenhang zu beurteilenden Komplex des Talsperrenbaus zu erhalten.

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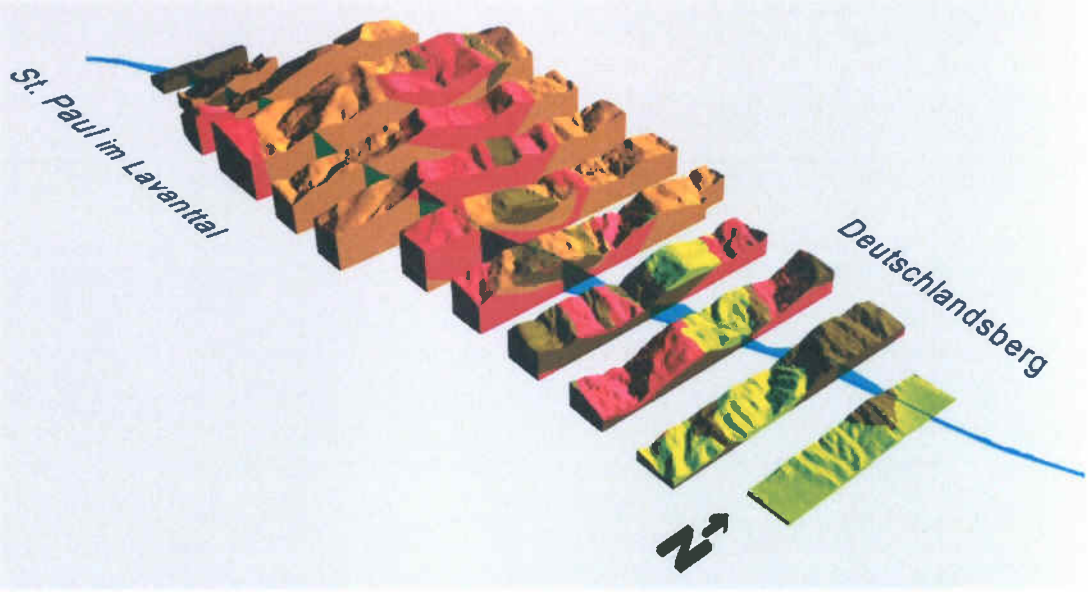


Fig. 5 Geological 3D model.

Bild 5 *Geologisches 3D Modell.*

iour. A special laboratory testing program was carried out to quantify the anisotropy (8) with the number of tests being designed to allow statistical evaluations (Figure 6)

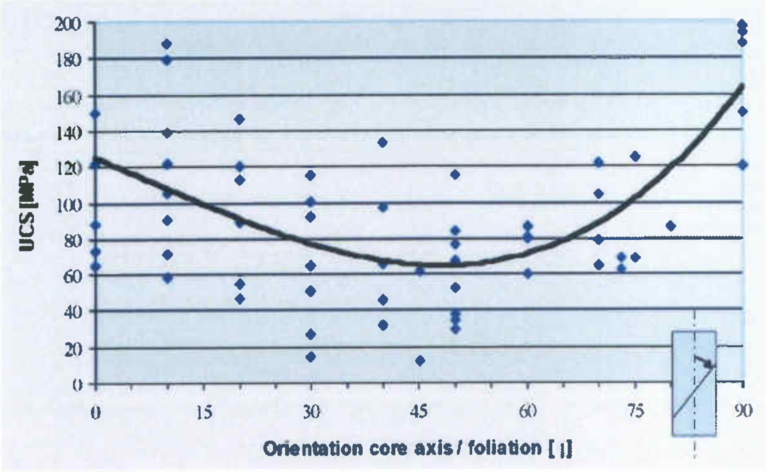
Statistical methods were also used to analyse the calculated key parameters. To decrease the effort for the calculation of these parameters the point estimate method (9) was used. With this method a continuous probability distribution can be replaced by discrete and singular probability without changing the statistical moments.

Fault influenced excavation length

The fault influenced excavation length is calculated from pure geometrical conditions: fault length, fault orientation (divided into twelve classes), fault thickness, tunnel diameter and orientation of the tunnel axis. The fault influence was calculated assuming a general fault thickness of three metres. It was assumed that a fault will influence the tunnel excavation when the distance between fault and tunnel axis is less than 1.5 tunnel diameter. Considering the probability of intersecting a fault, the fault influenced excavation length was calculated.

Fig. 6 Anisotropic behaviour of the uniaxial compressive strength of gneiss from triaxial tests.

Bild 6 *Anisotropie der einaxialen Druckfestigkeit von Gneis aus triaxialen Druckversuchen.*



$$L_M = \sum_{i=1}^{12} \frac{3L^i_{(St)}}{500} \cdot \left(D \cdot \cos\alpha^i_M + 1\right)$$

with

L_M average fault influenced excavation length,

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.

Plastic zone and radial displacement in fault free rock mass

Using analytical calculations (10, 11) the depth of the plastic zone and the radial displacements were estimated for an unsupported tunnel in fault free rock mass. The overburden, calculated from a digital topographical model and intact rock parameters like UCS and mi corresponding to the distribution of the lithological units were assigned to each assessment square of the previously defined grid. The influence of the anisotropic rock mass behaviour was considered by adjusting the UCS depending on the foliation orientation relative to the tunnel axis. The Geological Strength Index (GSI) was roughly estimated from the results of the drill core logging with values from 55 to 65 with a standard deviation of 5 for most parts of the fault free zones of the corridor.

These results of the analytical calculation were presented as mean values with a standard deviation by using the point estimate method with n+1 permutations (12, 13).

Plastic zone and radial displacement in fault zones

To calculate the plastic zone and radial displacements in fault zones the same analytical model as described before was used with a different approach. Based on the results from three dimensional numerical calculations (14, 15) a nonlinear correlation was assumed between the excavation length in a fault and the radial displacement (Figures 7 and 8). To implement this correlation into the analytical model, the GSI value was modified depending on the excavation length in the fault zone. For the practical use the following procedure was used:

- no fault: GSI value for fault free rock mass based on the results of drill hole logging,
- very thin faults: GSI value for fault free rock mass reduced by about 10,
- fault zone < three times tunnel diameter: recalculated GSI value from the results of numerical modelling,
- fault zone > three times tunnel diameter: GSI value for fault zone material based on the results of the drill hole logging.

Based on this procedure, the displacements for fault influenced tunnel sections can be estimated.

Penetration rate

To estimate the penetration rate for the planned TBM excavation, a simple model based on the UCS of the intact rock was used (16). Several factors of influence like joint spacing, joint orientation and normalized machine parameters were also considered. With the estimated penetration per revolution (limited by disc geometry), the tunnel diameter and the maximum disc rotation speed the penetration rate was calculated. Mean values and standard deviations were calculated.

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 highly anisotropic behaviour of the gneiss was considered.

Groundwater

The following key parameters were evaluated to describe the possibility of water inflow during the excavation:

- permeability of different lithological units,
- weathering zones,
- influence of faults and
- fractured zones.

Information reliability

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

- reliability of investigation results
- investigation density
- vertical distance to tunnel level.

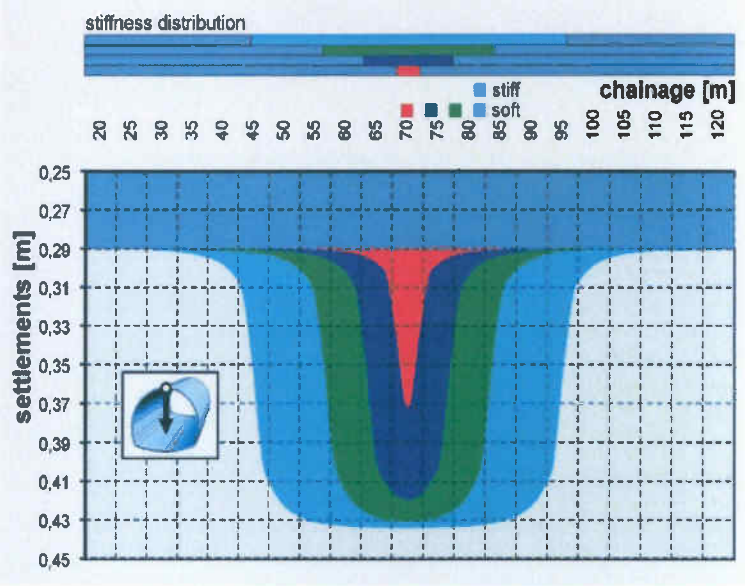


Fig. 7 Final crown settlements with variation of fault lengths (constant primary stress condition and stiffness ratio E_{stiff}/E_{soft}); Results from numerical simulations.

Bild 7 *Numerische Berechnung der endgültigen Firstsetzungen bei unterschiedlichen Störungslängen (bei konstantem Primärspannungszustand und Verhältnis der Steifigkeiten* E_{stiff}/E_{soft}*).*

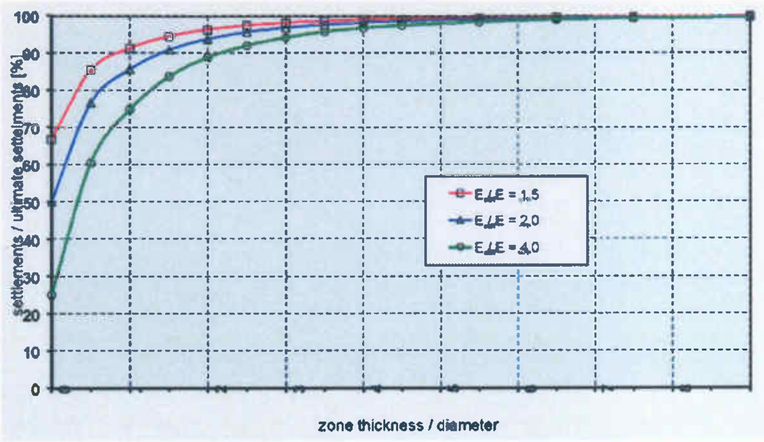


Fig. 8 Determined correlation between displacement and excavation length in a fault zones from numerical simulations.

Bild 8 *Korrelation zwischen Verschiebungen und Vortriebslängen in Störungen für verschiedene Steifigkeitsverhältnisse auf Basis numerischer Berechnungen.*

Above weighted parameters were combined and led to a classification of good, medium or low for each assessment square. A square with a low information level has a more dispersed distribution of results than a square with a high information level.

GIS-based processing of geotechnical relevant data

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 9). The cells from various layers are stacked to describe several parameters for each location in the project area.

To compile the GIS model the following parameter layers were generated :

- overburden,
- lithology,
- orientation of discontinuities,
- faults (3D shape file),
- hydrogeology,
- abrasivity,
- fault influenced excavation length,
- rock mass strength,
- information reliability,
- plastic zone,
- radial displacements,
- penetration rate.

Multi-layered displays comprised of several data sets (Figure 10) 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.

Conclusions

The extraordinary dimensions of the Koralm Tunnel, the corridor area of about 150 km² and the probable maximum overburden of up to 1 700 m, require a methodologically sound approach for rock mass characterisation to select the geotechnically most favourable route.

To optimise the tunnel design it is essential that the geological and geotechnical investiga-

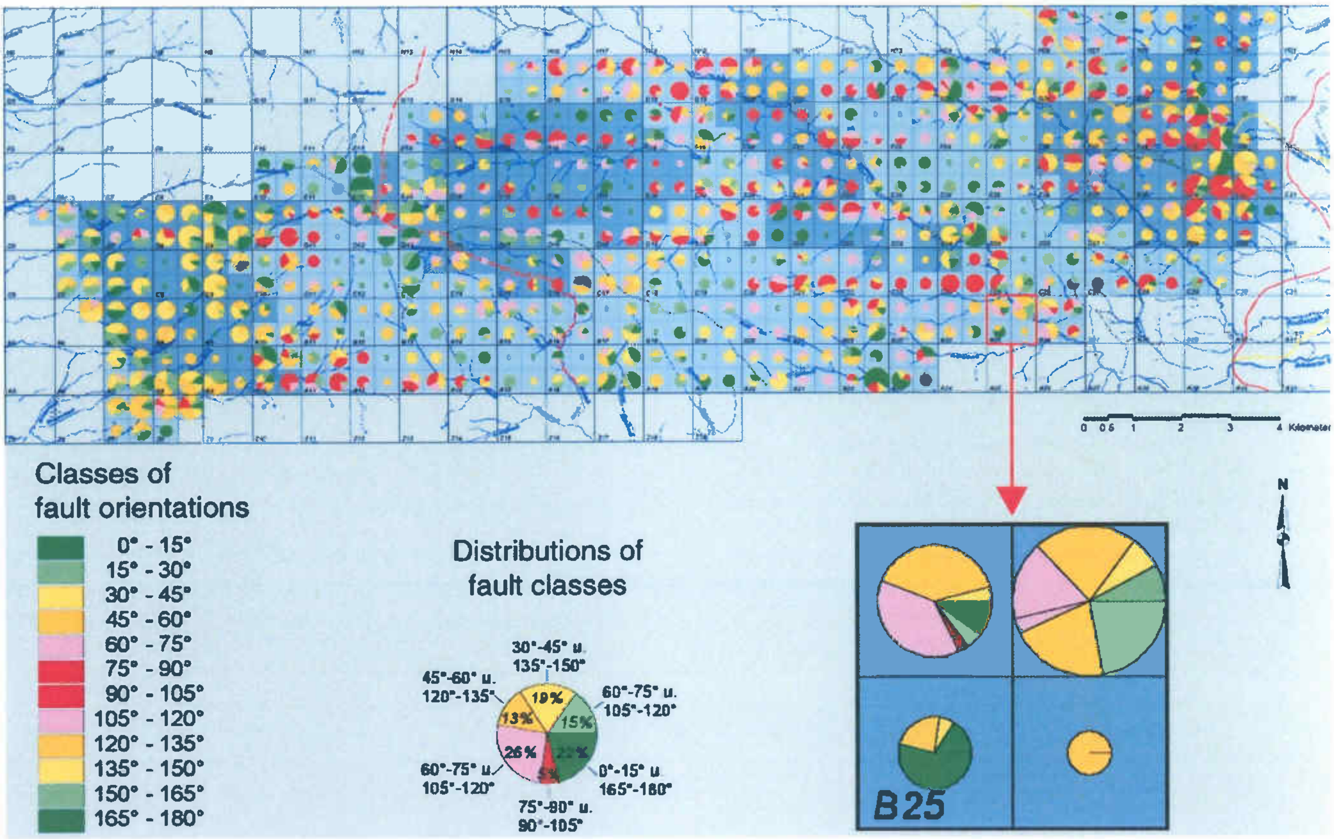


Fig. 9 The fault-layer including orientation and distribution of fault classes.

Bild 9 *Der Layer „Störungen" beinhaltet Orientierung und Verteilung der Störungsklassen.*

tions are carried out with precision and that the geotechnical model established enables an evaluation of all potential geotechnical risks. The procedure proposed to assess geotechnical parameters delivers reliable results based on empiric and probabilistic methods and allows for continuous updating the geotechnical model with gains in data availability. By using a weighted cost function the layers with the main geotechnical key parameters can be combined to enable the tunnel designer to assess the costs of different routes. This concept of site investigation and geotechnical assessment proves to be consistent and allows the most economic route to be selected.

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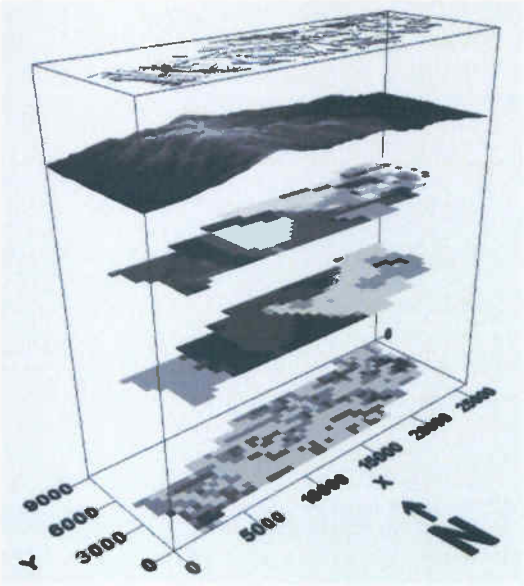

Fig. 10 Example of multi-layer display.

***Bild 10** Beispiel für eine Multi-Layer-Darstellung.*

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