Investigation Strategies for the Design of the Semmering Base Tunnel

By Gunter Riedmüller, Wulf Schubert, Andreas Goricki and Peter Pölsler

The traffic route across the Semmering mountain range is rich in tradition. It has been used as a main trading route between Vienna and the Adriatic Sea since the thirteenth century. The Semmering railway, the first European railroad crossing a major mountain range, was built during 1848 and 1854. This traditional mountain railway is still in use. Despite some improvements the Semmering railway does not meet the requirement of a modern railway and should be substituted by a base tunnel.

The Semmering base tunnel being part of Austrian‘s high speed railway project has been designed with a total length of approximately 22 km. The tunnel will connect the towns Gloggnitz in Lower Austria and Mürzzuschlag in Styria. With its east portal at Gloggnitz (km 76.636) the tunnel runs along the right slope of the Schwarza valley under shallow overburden. A cut and cover section with a length of 1 175 m is planned between the towns Pettenbach and Küb. The following mined tunnel section continues as a shallow tunnel, at first, than the crossing of the mountain range begins after km 88.5. The maximum overburden of approximately 900 m is reached beneath the Kampalpe. Continuing westwards the height of the overburden decreases gradually. After crossing the Wallersbachgraben the tunnel runs along the slope of the Fröschnitz valley beneath shallow overburden and reaches at km 98.714 the west portal at Mürzzuschlag.

In this paper the site investigation procedures for the tunnel section between chainage km 88.5

Untersuchungsstrategien für die Planung des Semmering-Basistunnels

Für den Ausbau des österreichischen Eisenbahn-Hochleistungsstreckennetzes ist die Errichtung des etwa 22 km langen Semmering-Basistunnels geplant. Für den Abschnitt km 85,0 bis 98,714 (Portal Mürzzuschlag) werden die geologisch-geotechnischen Erkundungsmaßnahmen (geologische Detailkartierung eines breiten Korridors sowie Untergrunderkundung durch Kernbohrungen, Bohrlochtests, Schürfe und geophysikalische Untersuchungen) im Verlauf der verschiedenen Planungsstadien beschrieben. Die dabei entwickelte Modellvorstellung konnte durch den Vortrieb eines 4 300 m langen Pilotstollens weitgehend bestätigt werden. Lokal mußten auch Abweichungen festgestellt werden, und ein in seiner Größenordnung unerwarteter Wassereinbruch führte zu einem Vortriebsstillstand von elf Monaten.

Der Pilotstollen bot die Möglichkeit zur Gewinnung von zusätzlichem Probenmaterial für felsmechanische und mineralogische Untersuchungen. Während des Vortriebs konnte eine Reihe von Meßdaten gewonnen werden, die mit Hilfe einer speziell für den Tunnelbau entwickelten Datenbank verwaltet und ausgewertet wurden. Gleichzeitig flossen die Ergebnisse in ein 3D-Modell auf GIS-Basis mit Schwerpunkt auf einer detaillierten Analyse der Störungskinematik ein.

Für die Ausschreibungsprojektierung konnten aus dem breiten Spektrum auftretender Gesteinsarten auf der Grundlage von Lithologie, Schieferung/Anisotropie, Blockgröße, Trennflächencharakteristik sowie felsmechanischer Parameter und Datenbankauswertungen 21 Gebirgsarten definiert werden. Unter Berücksichtigung von zusätzlichen Einflußfaktoren wie Festigkeits- und Deformationseigenschaften, Trennflächenorientierung zur Tunnelachse, Primärspannung, Ausbruchsquerschnitt und Bergwasserführung sind daraus 14 Gebirgstypen ableitbar. Diese werden zehn generellen Verhaltens- beziehungsweise Versagenstypen zugeordnet.

The Semmering base tunnel, part of Austrias high speed railway project, has been designed with a total length of approximately 22 km. The site investigation procedures for the tunnel section between km 88.5 and km 98.714 (the west portal at Mrzzuschlag), are described here. A preliminary geotechnical model was created. This model corresponded quite well to the actual conditions encountered, during the excavation of a 4 300 m long pilot tunnel. Some discrepancies were discovered, including an unexpected high water inflow which caused a cessation of the excavation lasting eleven months.

The excavation of the pilot tunnel was used to collect additional rock samples. These samples were then tested to determine both their mechanical and mineralogical properties. The evaluation of the logging and mapping results, from the excavation of the pilot tunnel, was aided by a newly developed electronic data management system along with GIS applications. The main focus was on the detailed analyses of fault kinematics.

These investigations resulted in 21 different rock mass types being identified. The key parameters used for their classification were lithology, anisotropy, block size, discontinuities and mechanical intact rock properties. 14 types of rock mass behaviour were distinguished on the basis of strength and deformational characteristics, the orientation of discontinuities towards the tunnel axis, primary stresses, tunnel geometry and groundwater situation. Ten typical categories of failure, possible during the excavation, were assigned to the different types of rock mass behaviour.

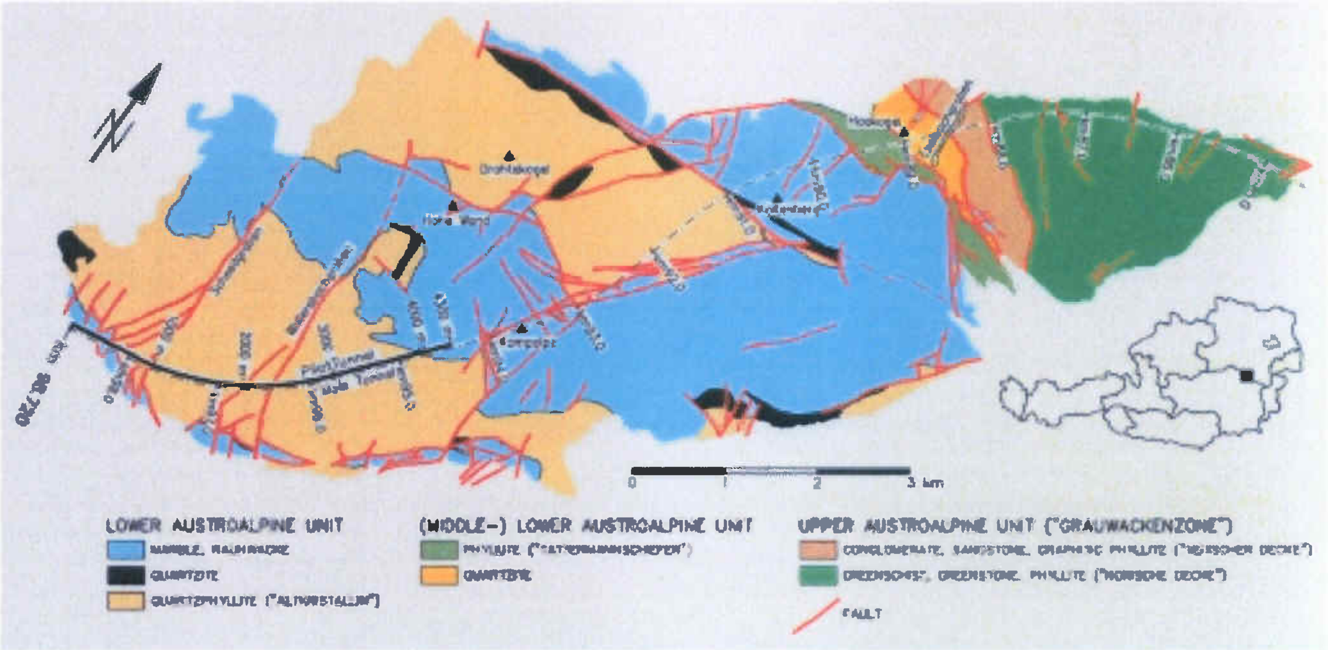

Fig. 1 Geological sketch map of the investigated area of the Semmering base tunnel.

***Bild 1** Geologische Übersicht des bearbeiteten Abschnitts des Semmering-Basistunnels.*

and the west portal at Mürzzuschlag are described. Cost-benefit aspects along with geotechnical considerations have largely determined the investigation procedures.

Geological Setting

The alignment of the Semmering base tunnel transects various major geological units at the north-eastern spur of the Eastern Alps. Proceeding from north to south, these units are the nappes of the Upper East Alpine Grauwacken zone, consisting of early and late Paleozoic, very low-grade metamorphosed sediments and volcanic rocks, as well as the nappes of the Lower East Alpine unit, consisting of a polymetamorphic basement with an Alpine metamorphic Permo-Mesozoic sedimentary cover (Figures 1 and 2).

The crystalline basement of the Lower East Alpine unit consists mostly of quartzphyllite. Its Permomesozoic sedimentary cover includes phyllite, quartzite, marble and rauhwacke. The Paleozoic sequence of the Upper East Alpine "Grauwackenzone" contains quartzconglomerate, meta-sandstone, greenstone, chloritic and graphitic phyllites with intercalations of anhydrite and gypsum (1, 2).

Imbrication and folding appear as local features within the large-scale pile of nappes. Site investigations between 1988 and 1989 have indicated the existence of two large thick-skinned, basement involved, thrusts within the Lower East Alpine tectonic unit. Each thrust sheet includes a thick inverted sequence of the sedimentary cover in the foot-wall and tectonically reduced, isolated remnants of the sedimentary cover in the hanging wall.

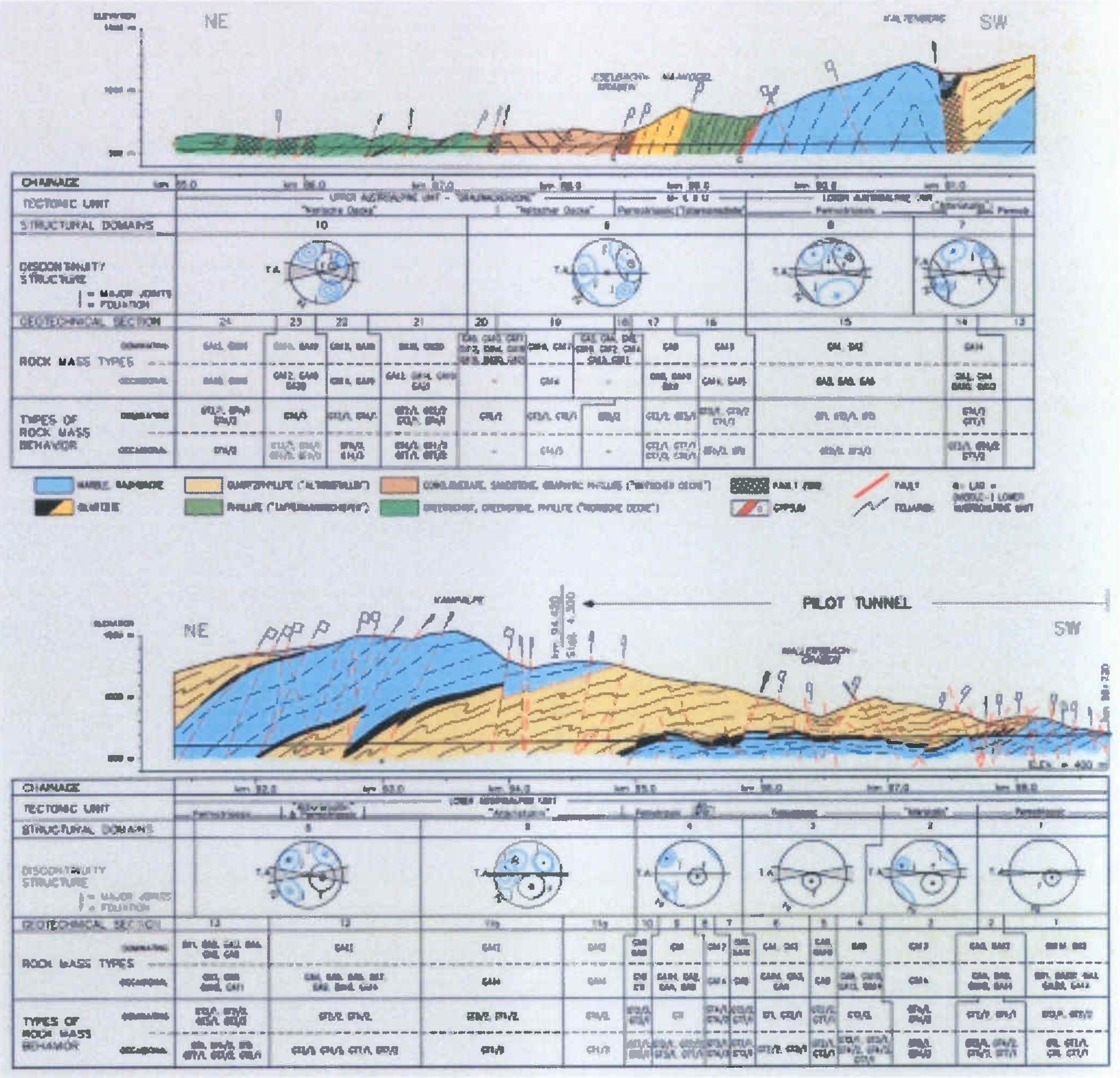

Fig. 2a and b Geotechnical longitudinal section of the Semmering base tunnel from the portal at Mürzzuschlag to chainage km 85.0 with the expected distribution of the rock mass types and the types of rock mass behaviour.

Bild 2a und b *Geotechnischer Längenschnitt des Semmering-Basistunnels vom Portal Mürzzuschlag bis km 85,0 mit der erwarteten Verteilung von Gebirgsarten und Gebirgstypen.*

The transport of the upper thrust sheet occurred along a northerly dipping, low-angle, shear zone which is dominated by clayey gouge, crushed quartzite, marble and rauhwacke.

Of great importance in view of the tunnel project are brittle high-angle faults which have generated gouge and intensely fractured rocks. Site investigations coupled with satellite images have shown that the pattern of brittle faults consists of strike-slip duplexes trending NNE-SSW, NE-SW and E-W. The youngest faults seem to be N-S striking extensional oblique-slip faults. Geometry and kinematics of the young brittle faults comply with the Neogene eastward extrusion of the Central Alps (3, 4, 5, 6).

The project area was not glaciated during the Pleistocene. The slopes were formed by periglacial solifluction. Weathering during the Tertiary and interglacial periods caused deep reaching karstification and the development of residual soils.

Site Investigation

Reconnaissance of the project area including geological, hydrogeological and geomechanical investigations began in 1988. The various investigation stages consisting of desk studies, surface and subsurface investigations correspond with the design stages from route selection to tender design.

Route Selection

Investigations for the route selection study began in 1988 (7, 8, 9, 10). The investigations were mainly based on desk studies which primarily included the evaluation of aerial photographs and the review of existing geological maps and data.

WBI -PRINT

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The excavation of a tunnel leads to stress redistributions. Stresses, which are transferred through the ground in the area of the opening before its excavation, have to be diverted around the opening after its excavation. Even at medium heights of overburden, this cannot be achieved by the support alone, if the latter has to be economically designed. Thus, the soil or bedrock is the main load-carrying element, whereas the support has a supporting function. Consequently, stability analyses in tunneling must, above all, consider the load-carrying behaviour of the ground and thus also its stress-strain behaviour. Aim of the given book is to represent the basis of advanced stability analyses for tunnels fulfilling the above mentioned requirements.

Because of the generally complex ground conditions and the three-dimensional states of stresses and deformations occuring during the stages of construction, only numerical analysis procedures are suitable for such types af analyses. The most known and widespread procedure is the finite element method. Simpler analysis procedures, such as applying forces on the tunnel's lining, the methods based on the modulus of subgrade reaction or analytical solutions, are only applicable to special cases and therefore, as a rule, not suitable for stability analyses for tunnels.

A characteristic of tunnel design is the stepwise approach. If required, selected steps of the design are even carried out several times. A tunnel's design is mainly based on

- the results of an extensive geotechnical ground investigation,
- stability investigations, which are adapted to the encountered ground conditions and to the construction method,
- the careful control of the stability by means of in-situ measurements during and after construction.

It also is an essential principle to adapt the design to the ground conditions encountered during construction. Also, backanalyses of measurement results are carried out to adapt the design to changed ground conditions. Further analyses during and after construction certainly increase the tunneling experience in certain ground conditions.

The authors of the given volume WBI-PRINT 4 have many years of experience in applying numerical analysis procedures to tunneling. During their work, they found out that numerical analysis is an extremely useful aid for a tunnel design.

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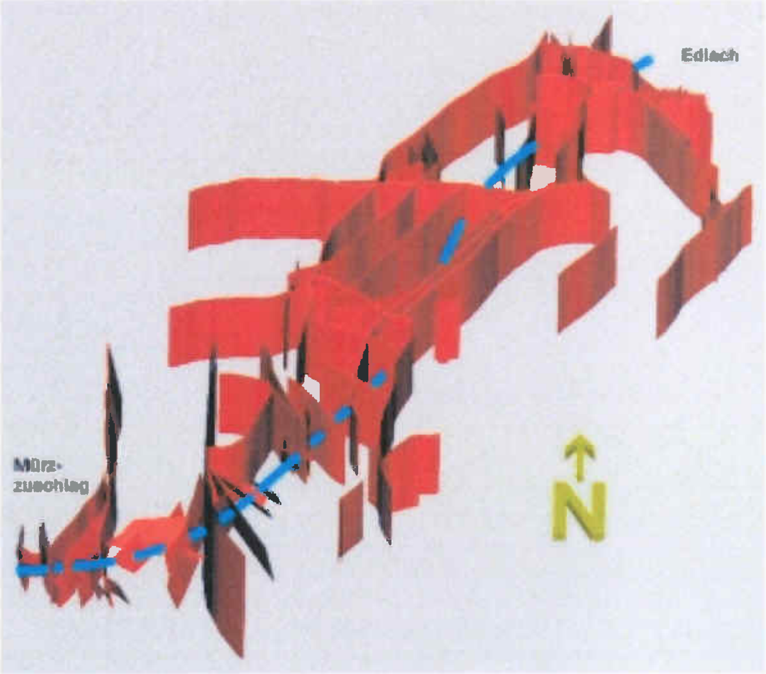


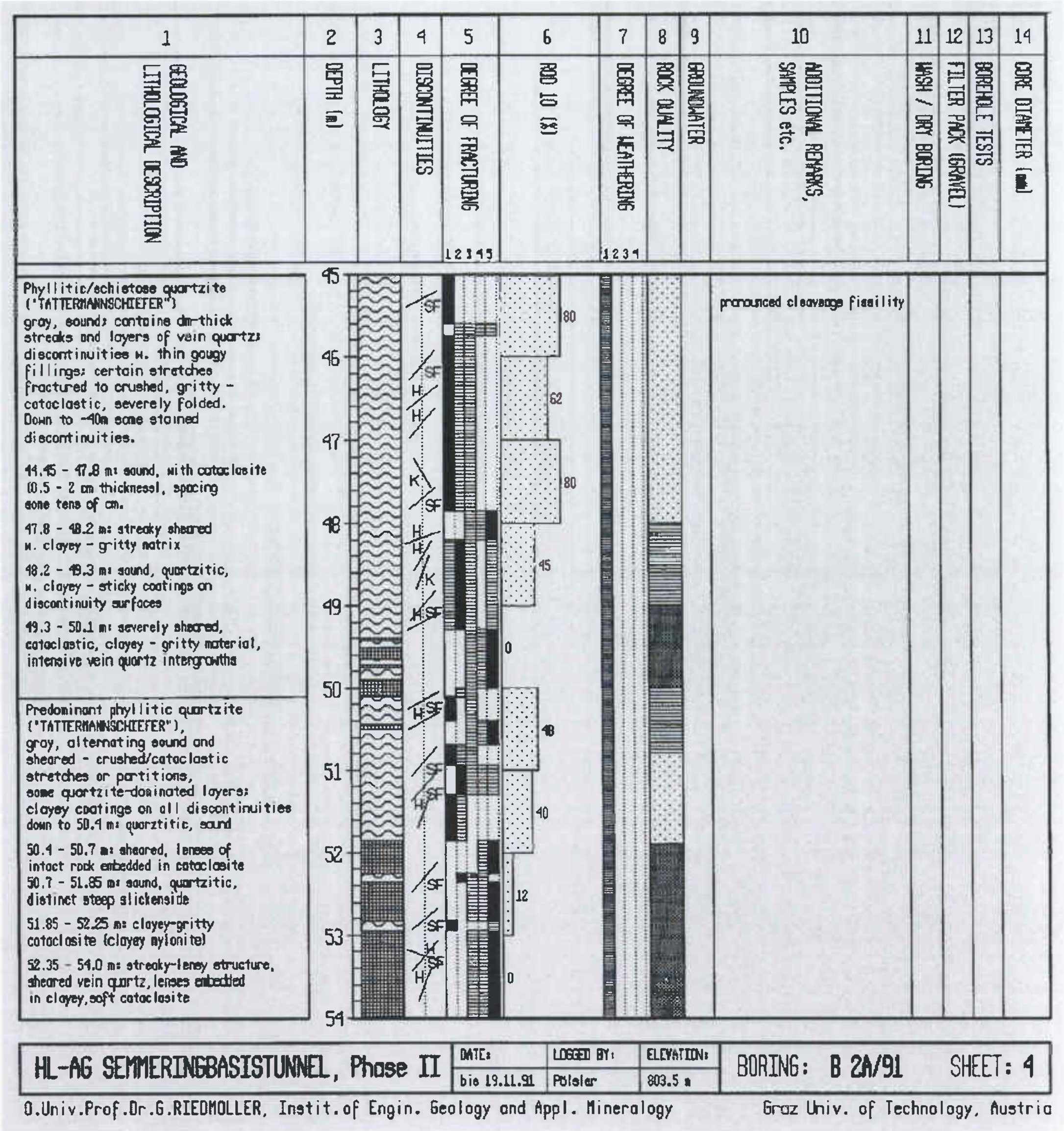
Fig. 3 3D-modelling of the fault system along the axis of the tunnel.

Bild 3 *3D-Modellierung des Störungsmusters entlang der Tunnelachse.*

The generalized geological picture of the project area was supplemented by outcrop studies and geological mapping of selected areas. These studies resulted in a geological map with a scale of 1 : 25 000. The map showed lithological units with geotechnical relevance, a first generalized assessment of faults and the differentiation of the alignment into structural domains with the orientation of the discontinuity structure.

Subsurface investigations consisting of core drilling and a geophysical survey were focussed in some crucial areas, such as faults, the crossing of valleys under shallow overburden and sensitive hydrogeological zones. Drill hole installations and tests consisted of groundwater standpipes, inclinometers and water pressure tests.

The comparison and selection of tunnel alternatives was mainly based on environmental, in particular hydrogeological aspects to appease public debates, along with criteria from traffic, safety, construction management as well as construction time and costs.



Phyllitic/schistose quartzite
("TATTERMANNSCHIEFER")
gray, sound; contains dm-thick streaks and layers of vein quartz; discontinuities w. thin gougy fillings; certain stretches fractured to crushed, gritty - cataclastic, severely folded.
Down to -40m some stained discontinuities.

44.45 - 47.8 m: sound, with cataclasite (0.5 - 2 cm thickness), spacing some tens of cm.

47.8 - 48.2 m: streaky sheared w. clayey - gritty matrix

48.2 - 49.3 m: sound, quartzitic, w. clayey - sticky coatings on discontinuity surfaces

49.3 - 50.1 m: severely sheared, cataclastic, clayey - gritty material, intensive vein quartz intergrowths

Predominant phyllitic quartzite
("TATTERMANNSCHIEFER"),
gray, alternating sound and sheared - crushed/cataclastic stretches or partitions,
some quartzite-dominated layers;
clayey coatings on all discontinuities down to 50.4 m: quarztitic, sound

50.4 - 50.7 m: sheared, lenses of intact rock embedded in cataclasite
50.7 - 51.85 m: sound, quartzitic, distinct steep slickenside

51.85 - 52.25 m: clayey-gritty cataclasite (clayey mylonite)

52.35 - 54.0 m: streaky-leney structure, sheared vein quartz, lenses embedded in clayey, soft cataclasite

pronounced cleavage fissility

HL-AG SEMMERINGBASISTUNNEL, Phase II

DATE:	LOGGED BY:	ELEVATION:
bis 19.11.91	Pölsler	803.5 m

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O.Univ.Prof.Dr.G.RIEDMOLLER, Instit.of Engin. Geology and Appl. Mineralogy Graz Univ. of Technology, Austria

Fig 4 Core log (partly) with the key parameters of the rock mass.

Bild 4 *Ausschnitt aus einem geologischen Bohrprotokoll mit den wesentlichen dokumentierten Gebirgsparametern.*

The final report on the plausibility of tunnel alternatives as a basis for the route selection was submitted, according to schedule, in May 1990. Investigations for the environmental impact assessment and the preliminary design of the selected tunnel alternative could begin without cessation the following summer.

Environmental Impact Assessment Preliminary Design

The investigation target in this planning stage was the establishment of a preliminary geotechnical model which included the characterisation of the rock mass, the detailed assessment of the groundwater situation and the estimate of primary stresses.

The site investigation consisted of detailed geological mapping (scale 1 : 5 000) of the whole alignment corridor and subsurface investigations by geophysical survey, trenches, core drilling and borehole tests. The main focus was on the detailed analyses of the fault kinematics (Figure 3). Laboratory tests, including mechanical and mineralogical analyses aided in the description of the intact rocks (8).

It is pointed out that the maximum depth of drill holes was approximately 200 m, even in the alignment sections with high overburden. Drill hole locations arranged due to the geological structure allowed, in accordance with detailed geological mapping, the extrapolation of drilling results down to the level of the tunnel and the establishment of a realistic three dimensional geological model.

The logging of drill cores was primarily aimed at the assessment of rock mass qualities (Figure 4). Apart from basic information such as number, location, elevation, groundwater table, tests etc., the drill core log included a geotechnically relevant description and the differentiation of the various lithologies. Furthermore, the key parameters of the rock mass, such as degree of fracturing and weathering, RQD, orientation of discontinuities toward the drill core axis, surface properties of discontinuities, infilling, secondary mineralisation and solution phenomena were specified. A genetic categorisation of the discontinuities i.e. foliation, slickenside, extensional joint was also determined.

Borehole in situ tests included dilatometer tests, which were performed mainly on sheared phyllite, and hydraulic tests (water pressure, pumping and seepage tests). Mineralogical and mechanical routine analyses on drill core samples were used to characterise intact rock properties.

By summarizing the results of investigations, from detailed outcrop studies through subsurface investigations to laboratory analyses, geotechnical relevant rock mass types were defined. These are characterized by intact rock properties and discontinuity structures.

Typical sections were selected and the depth of failure zone and magnitude of radial displacements calculated with a simple analytical model (11). Based on the depth of failure zone and the range of expected displacements different types of rock mass behaviour were distinguished.

The influence of structural features on the development of gravity falling or sliding blocks, defined by intersecting discontinuities, was analysed by spherical projection techniques (12).

The groundwater situation was investigated by the "Institut für Geothermie und Hydrogeologie der Forschungsgesellschaft Joanneum, Graz". Their prediction was based on hydrochemical and isotopic analyses, on the long term observation of springs, wells and borehole standpipes, and on the evaluation of hydraulic borehole tests in combination with tracer techniques (13).

The interpretation of investigation results were displayed in a geotechnical longitudinal section showing the lithological units, different structural domains, the groundwater situation, a schematic differentiation into geotechnical sections with an estimate of rock mass types and types of rock mass behaviour, roughly grouped into the categories "standfest" (stable), "gebräch" (gravity controlled failure dominating) and "druckhaft" (stress induced squeezing rocks).

Uncertainties remained due to the complicated geological and hydrogeological situation. This required the excavation of a pilot tunnel as an

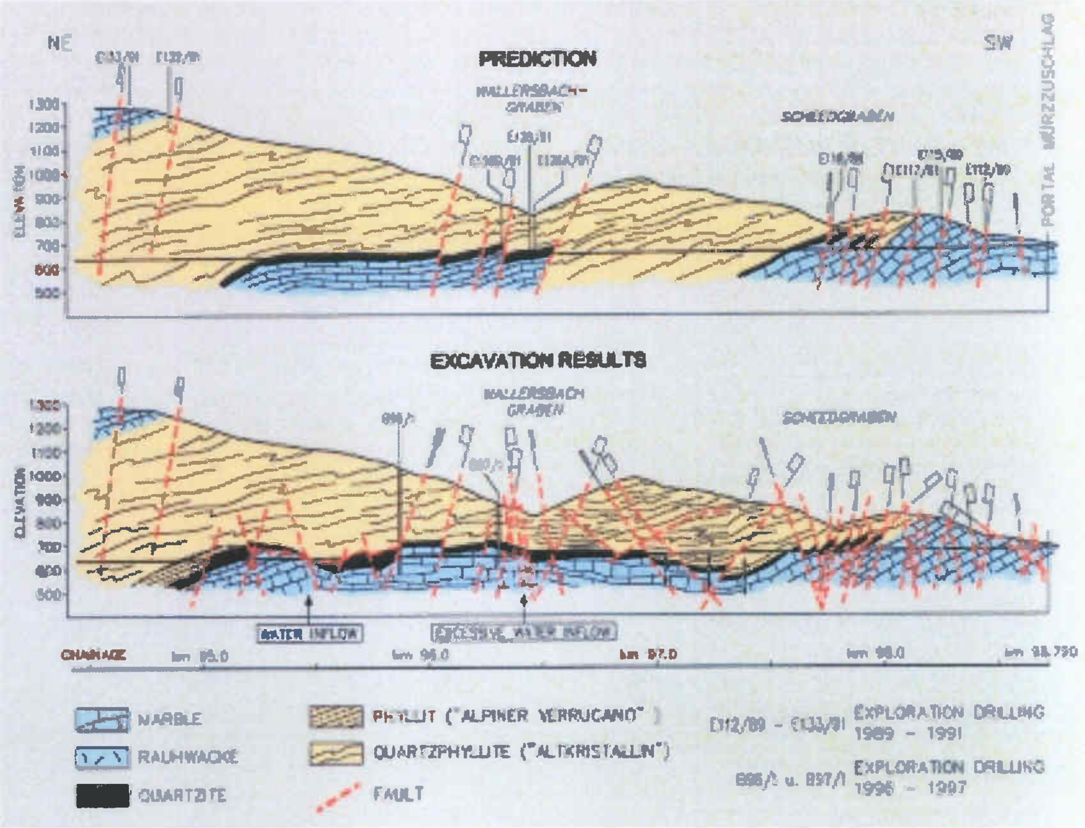


Fig. 5 Comparison between the predicted and actual conditions as encountered during the excavation of the pilot tunnel, based on the documentation of J. Kaiser.

Bild 5 *Gegenüberstellung von Prognose und tatsächlich angetroffenen Verhältnissen beim Auffahren des Pilotstollens auf Grundlage der Stollendokumentation von J. Kaiser.*

Table 1 Geological parameters, laboratory test results and calculated rock mass parameters for the rock mass types using number 12 as an example.

Tabelle 1 *Geologische Einflußparameter, Ergebnisse aus Laborversuchen und errechnete Gebirgskennwerte der exemplarisch dargestellten Gebirgsart 12.*

	Rock mass type 12
Lithology	Phyllit
Foliation/Anisotropy	flaky to platy, highly anisotropic
Block size	< 20 cm
Joint properties	coated with clay
Persistence	dominating low
Aperture	dominating closed
	Intact rock
Parameter	average, standard deviation, number of samples
UCS [MPa]	28,2 / 13,6 / 19
c [MPa]	10,8 / 3,1 / 3
φ [°]	31,7 / 1,5 / 3
E [GPa]	26,7 / 19,1 / 18
Cerchar Abrasivity Index	no value
ν [ ]	0,43 / 0,18 / 2
Hoek Constant m_i [ ]	14,5 / 6,0 / 3
	Rock mass
Parameter	average, standard deviation
Geological Strength Index	40 / 5*
UCS [MPa]	3,9 / 2,0
c [MPa]	1,1 / 0,5
φ [°]	31,3 / 3,6
E [GPa]	3,0 / 1,0
	Joint properties
Parameter	average, standard deviation, number of samples
Friction angle [°]	33,7 / 6,3 / 15
Residual friction angle [°]	28,5 / 5,6 / 23

*estimated values

essential support for the tender design of the main tunnel. Monitoring results and experiences from the excavation of the pilot tunnel should help to minimize the ground risks for the client. The tender of the pilot tunnel was based on the existing results from the site investigation. Uncertainties and geotechnical problems which had to be clarified by the pilot tunnel were primarily the long term deformational behaviour of phyllite under high primary stresses, rock mass condition and behaviour in fault zones, the depth of karstification and the hydraulic properties of both aquifers and aquitards.

Detail/Tender Design

It was intended to investigate in detail the complicated geological conditions between Mürzzuschlag in the west (km 98.720) and km 85.0 in the east by a pilot tunnel with a diameter of 14.9 m². The pilot tunnel was located 30 m north of the axis of the main tunnel. The pilot tunnel could later, after completion of the main tunnel, be used as a rescue and service tunnel.

The construction of the pilot tunnel began in December 1994 with downgrade heading from the west portal at Mürzzuschlag. The actual conditions encountered during excavation of the pilot tunnel corresponded quite well with the predicted model. Major discrepancies with the model were a highly fractured section of rock mass, approximately 60 m longer than predicted, between the portal and km 97.620, a syncline structure between km 97.620 and km 96.620 2 100 m, which caused the occurrence of sheared quartzite at the level of the tunnel and an unexpected high water inflow at km 96.617 on October 1996 (Figure 5), (14).

The water inflow, with a yield of 300 to 350 l/s, caused the pilot tunnel to flood and a stoppage of the excavation ensued lasting until September 1997. Additional investigations consisting of core drilling from the surface as well as from the tunnel, including pumping tests and monitoring of groundwater standpipes, were required to guarantee a safe continuation of the excavation.

The pilot tunnel came to a final halt at km 94.420. The upgrade heading from the east is disallowed due to political reasons, at present. As a consequence, a discrepancy of information quantity and quality exists between the alignment section which was in detail investigated by the pilot probe and the section without a pilot tunnel between km 94.420 and km 85.0.

The evaluation of logging and monitoring results from the excavation of the pilot tunnel was essentially supported by a newly developed electronic data management system in combination with GIS applications. The data evaluation system (DEST) facilitated unbiased evaluation of geological, mechanical and hydrogeological data, as well as excavation and support related information (15, 16).

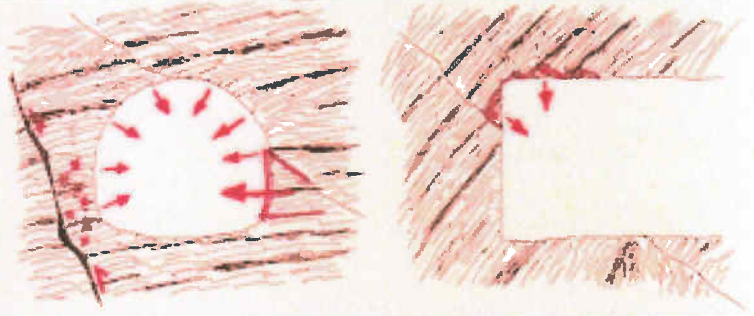
Rock mass types and types of rock mass behaviour as defined during the investigation for the preliminary design stage were improved by the additional data. 21 different rock mass types were specified. The key parameters were lithology, foliation/anisotropy, block size, discontinuity parameters such as persistence, surface properties and aperture as well as mechanical intact rock properties (UCS, c, n, E, CAI) (Table 1). The strength characteristics of rock mass types were estimated on the basis of the Geological Strength Index (17). The GSI value was determined by back calculation from monitoring results of the pilot tunnel excavation.

Considering the variation of the rock mass parameters, primary stress conditions and different support categories, the range of expected displacements was determined analytically along the line of the planned tunnel.

Table 2 Influencing parameters and the estimated rock mass behaviour of the exemplary rock mass behaviour type 3/2.

Tabelle 2 *Einflußparameter und abgeleitetes Gebirgsverhalten des exemplarisch dargestellten Gebirgstyps 3/2.*

Parameter	Rock mass behaviour
Rock mass type	Rock mass type12 and 13
Main discontinuity orientation	The foliation strikes normal to the tunnel axis and dips 45 to 75°
Rock mass description	Thinly foliated rock mass with clayey coatings on foliaion planes
Stress conditions	The stress redistribution is governed by steeply dipping foliation planes. Due to relatively high rock mass strength parallel to the foliation only shear failures develop
Groundwater conditions	Very little to no groundwater inflow
Rock mass behaviour (excavatability, failure mechanisms, long term behaviour)	Highly anisotropic rock mass with relatively homogeneous deformations. Small block failures occur due to the foliation and excavation induced fractures. For foliation dipping into the excavation block slide towards the excavation, for foliation dipping away from the excavation the face stability is relatively good
Deformation characteristics	The deformations are relatively rapid. Radial deformations with the given overburden are expected to be 10's of centimeters
Recommended excavation method	Drill and blast, roadheader
Support recommendation	Systematic bolting with medium length and density to control and minimize overbreak and stress induced failures. If necessary use ductile support elements within gaps in the shotcrete lining to allow for large deformations. To avoid excess overbreak in the crown forepoling can be required



Symbolic diagram for Quartzphylitte (excavation towards NE)

Scale and stress effects with respect to displacements and overbreak were studied for blocky material and squeezing rock with the help of numerical analyses. Appropriate support sys-

Table 3 Typical categories of the types of rock mass behaviour.
Tabelle 3 *Einteilung typischer Kategorien von Gebirgsverhalten.*

	Type	Description
1	Stable	Stable rock mass with small local gravity induced falling or sliding of blocks
2	Stable with the potential of discontinuity controlled block fall	Deep reaching discontinuity, gravity controlled falling and sliding of blocks, occasional local shear failure
3	Shallow shear failure	Shallow stress controlled shear failure in combination with discontinuity and gravity controlled failure of the rock mass
4	Deep seated shear failure	Deep seated, stress induced shear failure and large deformation
5	Rock burst	A sudden and often violent failure of the rock mass, caused by highly stressed rock and the rapid release of accumulated strain energy
6	Shear failure under low confining pressure	Potential for excessive overbreak and progressive shear failure with the development of dead loads, caused mainly by a deficiency of side pressure
7.1	Ravelling ground	Cohesionless dry flow
7.2	Flowing ground	Wet flow with low friction
8	Swelling	Time dependent volume increase of the rock mass, caused by physical- chemical reactions of rock and water in combination with stress relief, leading to inward movement of the tunnel perimeter
9	Changing rock mass behaviour	Rapid variations of primary stresses and deformations, caused by block-in matrix situation of a tectonic melange (brittle fault)

tems were developed for squeezing ground (18, 19).

The factors and parameters used to assess the rock mass behaviour were strength and deformational characteristics of the rock mass types, orientation of discontinuities towards the tunnel axis, primary stresses, tunnel geometry and groundwater situation. 14 types of rock mass behaviour including remarks on excavation methods and support were classified (Table 2). The different types of rock mass behaviour were assigned to 10 typical categories of failure during excavation (Table 3).

Conclusion

The construction of the Semmering base tunnel is a great challenge for engineers and geologists. The investigation strategy used for this project can be described as a systematic, geotechnically relevant assessment of the rock mass, as well as estimates of the primary stresses and the groundwater situation. The characterisation of rock mass properties, the calculation of rock mass behaviour and consequently the determination of support types require an intimate collaboration of engineering geologists, hydrogeologists, geotechnical engineers and designers.

The investigation results testify that no environmental, technical or economical argument can be found to prevent the construction of the Semmering base tunnel from going ahead. This tunnel is imperative to the upgrading of the European railway network. It is hoped that the completion of this important tunnel project is no longer hampered by the interests of regional politicians.

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