Project and Rock Mass Specific Investigation for Tunnels

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ABSTRACT: Deficiencies in site investigations for the construction of tunnels have been recognized. Investigations are typically performed to collect data for empirical models without considering individual rock mass characteristics and design stage specific requirements. We propose an investigation procedure initially based on simple key parameters specifically chosen for each rock type. As the design proceeds and investigations continue models are developed which are updated through all design stages to the construction. To optimize construction, especially in complex geological situations, support and excavation sequences are finalized during the tunnel excavation based on the results of face mapping and geotechnical monitoring. We demonstrate this procedure with case studies from Taiwan and Austria.

1 INTRODUCTION

The difficulty in performing a quality site investigation for a tunnel project is often underestimated. In addition to characterising the ground conditions for assessing methods, together with costs and scheduling of the tunnel construction, geological and geotechnical investigations should increasingly be considered in terms of cost-benefit analysis and the sharing of contractual risks between the client and contractor. This is particularly important for ”Build-Operate-Transfer (BOT)“ and/or ”Public-Private-Partnership (PPP)“ models.

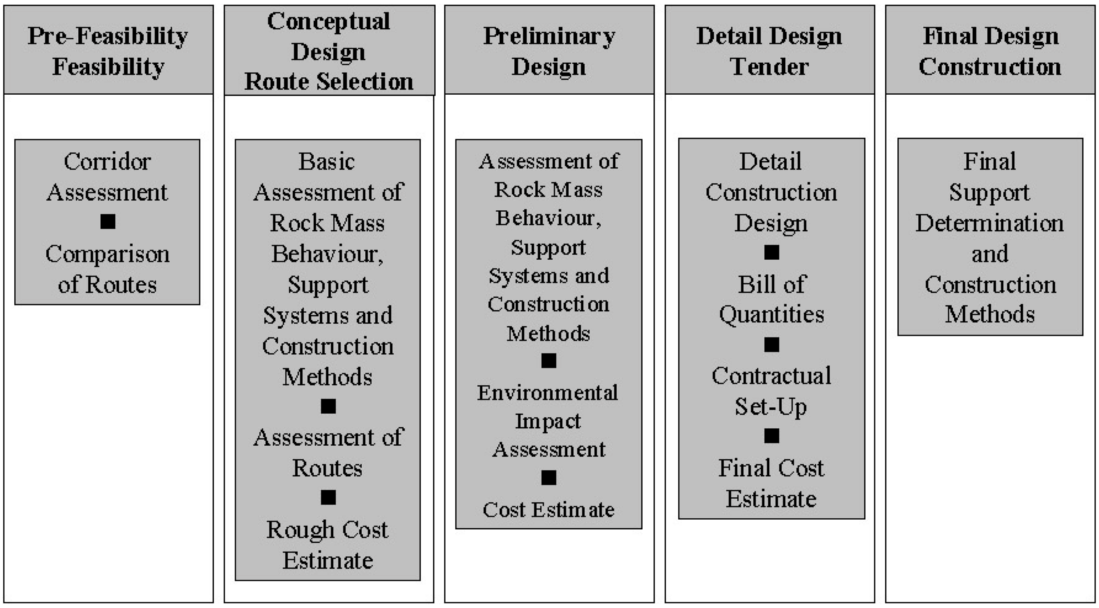
A number of concepts and guidelines have been developed in recent years to evaluate appropriate methods for ground investigation and testing (Dumbleton & West 1976, Anon 1981, Clayton et al. 1982, Head 1986, Anon 1987, Oliveira 1992, Bell 1993). It is demonstrated by cases all over the world that high standards and quality for a site investigation lead to an economical and technical successful construction. However, despite this understanding situations still will occur where the knowledge of ground conditions is inadequate. Currently site investigations are primarily aimed to collect rock mass parameters for the application of quantitative classification systems, such as the widely used RMR-system of Bieniawski and the Q-system of Barton, which are based on only a few universally applied classification parameters (Barton et al. 1974, 1998, Bieniawski 1973, 1974, 1989). These methods are usually applied, without any modification, for all design stages including final design and construction. Major shortcomings of quantitative classification systems for tunnels have been recognized (Daller et al. 1994, Riedmüller & Schubert 1999a, Riedmüller & Schubert 1999b).

On the other hand, extensive investigations which focus on collecting vast amounts of data without considering the specific rock types and the phase of the project also have disadvantages. Data evaluation and interpretation becomes cumbersome and important information may easily be overlooked.

Contrary to common methods we believe a more efficient investigation and characterisation process should be governed by the necessary objectives of each project phase, as explained below.

2 INVESTIGATION APPROACH

Investigation items and quantities depend largely on the complexity of the geological situation and the requirements of the project. In general, the investigations are conducted in stages commencing with fast and simple investigation methods and moving progressively towards more expensive and time-consuming techniques. A combination of cost constraints and the necessary information will determine the most suitable investigation programme. We recommend to optimize the investigation programme by performing cost-benefit analyses, particularly for cost-intensive subsurface investigations (Swoboda 1999).



Pre-Feasibility Feasibility	Conceptual Design Route Selection	Preliminary Design	Detail Design Tender	Final Design Construction
Corridor Assessment ■ Comparison of Routes	Basic Assessment of Rock Mass Behaviour, Support Systems and Construction Methods ■ Assessment of Routes ■ Rough Cost Estimate	Assessment of Rock Mass Behaviour, Support Systems and Construction Methods ■ Environmental Impact Assessment ■ Cost Estimate	Detail Construction Design ■ Bill of Quantities ■ Contractual Set-Up ■ Final Cost Estimate	Final Support Determination and Construction Methods

Table 1. Design phases and investigation objectives

The basis for our approach to tunnel site investigations is a geotechnical rock mass characterisation procedure which aims to correlate rock mass properties with rock mass behaviour through key parameters during the early design. During later design stages rock mass models are developed and updated.

Table 1 outlines the phases of tunnel design from the feasibility to the final design and construction. It must be considered that different design phases have different objectives. Accordingly, geotechnical tasks and investigation methods differ during each phase. This leads to increasing quantity and quality of information as the design process proceeds.

Defining key parameters allows for a first qualitative assessment of potential geotechnical problems related to the tunnel construction in the most efficient and economic way. The key parameters in combination with factors such as stresses, groundwater, kinematic conditions and construction process result in predictions of ground behaviour. For example, key parameters for estimating the behaviour of phyllites during tunnel excavation are the surface properties of the foliation and its orientation relative to the direction of drive, whereas for a massive conglomerate key parameters are grain size, degree of cementation, strength properties and the ratio of matrix to coarse-grained fragments. Table 2 shows examples of key parameters for basic rock types. The assessment of these parameters is based on experiences from various tunnel projects.

It is our experience that for a pre-feasibility and feasibility study the rock mass characterisation can usually be based on the key parameters revealed by desk studies and the geological reconnaissance of selected areas. The geological surface investigation may be supported by inexpensive geophysical surveys. The rock mass characterisation in this design stage is aimed to achieve the general geological architecture of the tunnel corridor, to assess basic rock types, rock mass qualities mainly defined by fracture frequency, fault pattern, and to estimate roughly the influencing geological factors.

Route selection and conceptual design studies require a more accurate assessment of the rock mass behaviour. The establishment of a preliminary geotechnical model enables the interaction between different support systems, construction methods and the ground behaviour to be analysed. Investigation methods in this stage include detailed engineering geological mapping of the tunnel corridor as well as subsurface investigation by core drilling and geophysical surveys. An important task is the detailed examination of fault zones to clarify their orientation, thickness, kinematics and strength properties. Comprehensive laboratory testing and basic geotechnical analyses have to be performed. The strength and deformation characteristics of the rock mass may be based in this stage on the Hoek-Brown procedure (Hoek 1998a, Hoek 1998b).

The preliminary and detailed design require improved geological, mechanical and hydraulic models, which are achieved by intensified surface and subsurface investigations in combination with laboratory and in situ testing. Tunnel corridors with complex, heterogeneous geological and hydrogeological situations may call for the investigation by a pilot tunnel. Geotechnical modelling includes numerical simulations and detailed structural and kinematic analyses. Main objectives of these design stages are the environmental impact assessment, construction design, bill of quantities and contractual set-up.

Basic Rock Types	Key Parameters																			
	Intact Rock Properties													Discontinuities						
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Volcanic Rocks				G	#	#						#	#		#	#		G	#	G
Plutonic Rocks		#	#	#		G						#			#	#		G	#	G
Fine-Grained Clastic Rocks (massive)			#				#	#	#		#	G			G	G				
Fine-Grained Clastic Rocks (bedded)	#		#				#	#	#		#			#			#			G
Coarse-Grained Clastic Rocks (massive)		G	#	G	G			G			#	#	#		G	G		G	G	
Coarse-Grained Clastic Rocks (bedded)	#	G	#		G			G			#	#	#	#			#			
Carbonatic Rocks		#								#		#			#	#		G	#	G
Sulfatic Rocks		#							#	#		G								
Metam. Rocks (massive)		#	#	#		G						#			#	#		G	#	
Metam. Rocks (foliated)	#	#	#	#		G						#		#			#			#
Brittle Fault Rocks		G				G	#	#	#		#	#	#							

LEGEND
Significant Parameter
G Less Important Parameter
1 Anisotropy
2 Mineral Composition
3 Grain Size
4 Texture
5 Porosity
6 Secondary Alteration
7 Clay Mineral Composition
8 Clay Content
9 Swelling Properties
10 Solution Phenomena
11 Cementation
12 Strength Properties
13 Ratio Matrix/Coarse-grained Fragments
14 Orientation of Dominant Set
15 Number and Orientation of Sets
16 Fracture Frequency
17 Roughness/Shear Strength
18 Persistence
19 Aperture
20 Infilling

Table 2. Examples of key parameters for basic rock types

If the investigation reveals highly complex and difficult geological ground conditions, we have to bear in mind that despite an utmost intensive ground characterisation programme uncertainties will remain. These conditions require a flexible construction contract which allows for modifications to the support and excavation methods. The geotechnical model of the pre-construction phase has to be checked and revised in order to technically as well as economically optimize the construction. The final updating of the geotechnical model as well as short-term predictions during construction have to be continuously performed by evaluating the results of geological face mapping and displacement monitoring (Schubert & Steindorfer 1996, Steindorfer & Schubert 1997, Steindorfer 1998).

3 CASE STUDIES

The project and rock mass specific investigation we have developed is demonstrated by two case studies. The first explains the investigation procedure in the early design stages for several tunnels for an expressway project in Taiwan. The second case study illustrates the whole process of investigations, from route selection to the detail design, for the Semmering base tunnel.

3.1 *Hualien - Taitung Expressway Project*

The expressway connects the cities of Hualien and Taitung in Eastern Taiwan. The crucial sections of the alignment are five tunnels with lengths ranging from 800 m to 4740 m. The maximum overburdens vary between 140 m and 440 m. Our tasks were to review site investigation studies and to assist in the engineering planning of the tunnels for feasibility and route selection studies[1].

The tunnel alignments traverse three major geological units, the eastern metamorphic belt of the Central Range (”Yüli Belt“), the Coastal Range, and the Longitudinal Valley. The Longitudinal Valley is a tectonic trough at the boundary between the Eurasian continental plate and the Philippine oceanic plate separating tectonically the Coastal Range from the Central Range (Ho 1988, Wu et al. 1997, Lallemand & Tsien 1997, Chang et al. 2000). The various lithological units include a melange complex, greenschist, slate, phyllite, quartzite, volcanic, volcanoclastic and clastic rocks. These lithological units are severely tectonically deformed. Active faulting occurs in this region indicated by the offset of young morphological features, high seismicity and ground displacement during major earthquakes (Angelier et al. 2000).

The site investigation included the evaluation of satellite images and aerial photographs, general geological mapping along the alignment, limited core drilling at portal areas, some hydraulic tests and mechanical laboratory analyses.

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[1] For this project G.Riedmüller (Geotechnical Group Graz) and J.Daller (iC-Consulenten) were consultants for China Engineering Consultants, Inc.

		ANISOTROPY		DISCONTINUITIES									STRESSES						GROUNDWATER			
	Rock Mass Types			ORIENTATION			BLOCK SIZE			ROUGHNESS												
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Phyllite	RMT1		G	#					G		G	G	#			#			#			
	RMT2		G	G	#				G		G	G	#				#		#			
	RMT3		G	G					G		G	G										
	RMT4		G		#				G		G	G		#			#		#			
	RMT5																			G	#	#
Quartz-phyllite	RMT6		G	#			G	G			G	G	#			#			#			
	RMT7		G	G	#			G			G	G	#				#		#			
	RMT8		G	G	#		G	G			G	G		#			#		#			
	RMT9		G			#		G	G		G	G	#					#	#			
	RMT10																			G	#	#
Quartzite	RMT11	G		#	G		#			G	G		#			#			#			
	RMT12	G			#			#		G	G		#				#		#			
	RMT13	G					G	G		G	G			#			#		#			
	RMT14	G			G	#		G	#	G	G	G	#					#	#			
	RMT15																				#	#
Meta-Sandstone	RMT16	G		#			#			G	G		#			#			#			
	RMT17	G			#			#		G	G		#				#		#			
	RMT18	G			#		G	G		G	G			#			#		#			
	RMT19	G			G	#		G	#	G	G	G	#					#	#			
	RMT20																			G	#	#
Slate	RMT21		G	#					G			#	#			#			#			
	RMT22		G	G	#				G			#	#				#		#			
	RMT23		G		G	#			G			#	#					#	#			
	RMT24																			G	#	#
Shale	RMT25		G	#	G				G			#	#			#			#			
	RMT26		G		#				G			#	#				#		#			
	RMT27		G			#			G			#	#					#	#			
	RMT28																			#	G	
Fault-Rocks	RMT29	G	G	G	G	G	G	G	G			#	#					#	#			
	RMT30	G	G	G	G	G	G	G	G			#			#			#	#			
	RMT31																			#	#	#
Conglo-merate	RMT32	G					#			#			#			#			#			
	RMT33	G					G	#		#			#				#		#			
	RMT34																			G	#	#
Conglom. poorly cemented	RMT35	G											#			#			#			
	RMT36	G											#				#		#			
	RMT37	G											#					#	#			
	RMT38																			#	#	
Sandst. poorly cement.	RMT39	G											#				#		#			
	RMT40	G											#					#	#			
	RMT41																			#	#	
Sand/Silt consolid	RMT42	G											#				#	#				
	RMT43																			#	#	

Table 3. Rock mass types defined by key parameter and influencing factors

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Significant classification parameter
G Classification Parameter

1 Isotropy
2 Anisotropy
3 Favourable orientation
4 Fair orientation
5 Unfavourable orientation
6 Large block size
7 Medium block size
8 Small block size
9 Rough (JRC>15)
10 Slightly rough (JRC 9-15)
11 Smooth (JRC <9)
12 $\sigma_v > \sigma_h$
13 $\sigma_v >> \sigma_h$
14 $\sigma_v < \sigma_h$
15 Rock mass strength / stress < 0,3
16 Rock mass strength / stress = 0,1-0,3
17 Rock mass strength / stress < 0,1
18 Dry conditions
19 Conductivity < 10^{-7}m/s
20 Conductivity < 10^{-4}-10^{-7}m/s
21 Conductivity > 10^{-4}m/s

With a limited amount of finalized results available, because investigations were still ongoing, we were required to assist in the route selection, to develop support concepts, and to assess preliminary construction time and costs.

To cover all possible scenarios of rock mass behaviour during excavation of the tunnels 43 rock mass types were defined (Table 3). The large number of rock mass types, defined by key parameters, were established due to the many different lithological units and varying geological environments together with a deficiency of adequate investigation results. The rock mass parameters selected for each lithological unit were anisotropy, discontinuity orientation and roughness, as well as block size. Influencing factors included a rough estimate of the ratios vertical stress to horizontal stress and rock mass strength to maximum principal stress, and the potential for groundwater problems, expressed by the conductivity of the rock mass.

Next we grouped the rock mass types into three rock-support-interaction-categories according to their anticipated behaviour, defined by displacement magnitudes and failure mechanisms. The allocation of rock mass types to rock-support-interaction categories was based on experiences from tunnel projects in comparable ground and was supported by analytical calculations (Hoek 1998, Hoek & Brown 1997, Feder 1997, Sulem et al. 1987). Due to the simplifications of input parameters and boundary conditions the accuracy of such calculations is limited. However, the displacement magnitudes and the development of plastic zones could roughly be determined.

The rock-support-interaction categories provided the basis to define eight support classes which took into account the anticipated behaviour of the rock mass during excavation, as well as required support and length of round. It is emphasised that a simple geomechanical model such as the rock-support-interaction category requires different support classes according to the type of rock mass and failure process.

Additionally to the rock-support-categories, which were primarily established on basis of strength-stress relationships, unfavourable ground conditions, such as low side pressure ($\sigma_v >> \sigma_h$), swelling clays and water inflow in heavily jointed or weakly cemented rocks were considered for special ground treatment and/or support measures.

3.2 *Semmering Base Tunnel*

The Semmering base tunnel is part of Austria‘s railway modernization project. The tunnel will connect the towns Gloggnitz in Lower Austria and Mürzzuschlag in Styria, having a length of approximately 22 km. The maximum overburden is about 900 m.

The alignment of the Semmering base tunnel transects various major geological units in the northeastern spur of the Eastern Alps. The polymetamorphic crystalline basement and the Paleozoic as well as Permo-mesozoic lithological units include quartz phyllite, phyllites with local intercalations of anhydrite and gypsum, quartz conglomerate, metasandstone, greenstone, quartzite, marble and rauhwacke.

The metamorphic lithological units were subjected to severe tectonic deformation by thrusting and folding. Of great importance in view of the tunnel project are high-angle faults which have generated gouge and intensely fractured rocks (Neubauer & Genser 1990).

Reconnaissance of the project area began in 1988 and included geological, hydrogeological and geomechanical investigations (Riedmüller et al. 1992, Riedmüller 1995, Riedmüller et al. 2000). The various investigation stages correspond with the design stages from route selection to tender design.

Initial investigations for the route selection were mainly based on desk studies which included the evaluation of aerial photographs and the review of existing geological maps and data. The generalized geological model of the project area was supplemented by detailed outcrop studies and selected geological mapping. These studies resulted in a first generalized assessment of faults and differentiated the corridor into structural domains based on the orientation of discontinuity structures.

Subsurface investigations consisting of core drilling and geophysical surveys were focussed on crucial areas, such as fault zones, the crossing of valleys under shallow overburden and sensitive hydrogeological regions. Drill hole installations and tests included groundwater stand pipes and water pressure tests, as well as inclinometers in the portal areas.

The comparison and selection of tunnel alternatives was mainly based on a preliminary assessment of environmental impacts, in particular to the hydrogeological system, to appease public debates. Other criteria included safety, traffic, construction management as well as construction time and costs.

The final report on the plausibility of tunnel alternatives, as a basis for the route selection, was submitted in early 1990. Investigations for the detailed environmental impact assessment and the preliminary design of the selected tunnel route could begin without delay the following summer.

The information collected in this investigation stage was aimed at establishing 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.

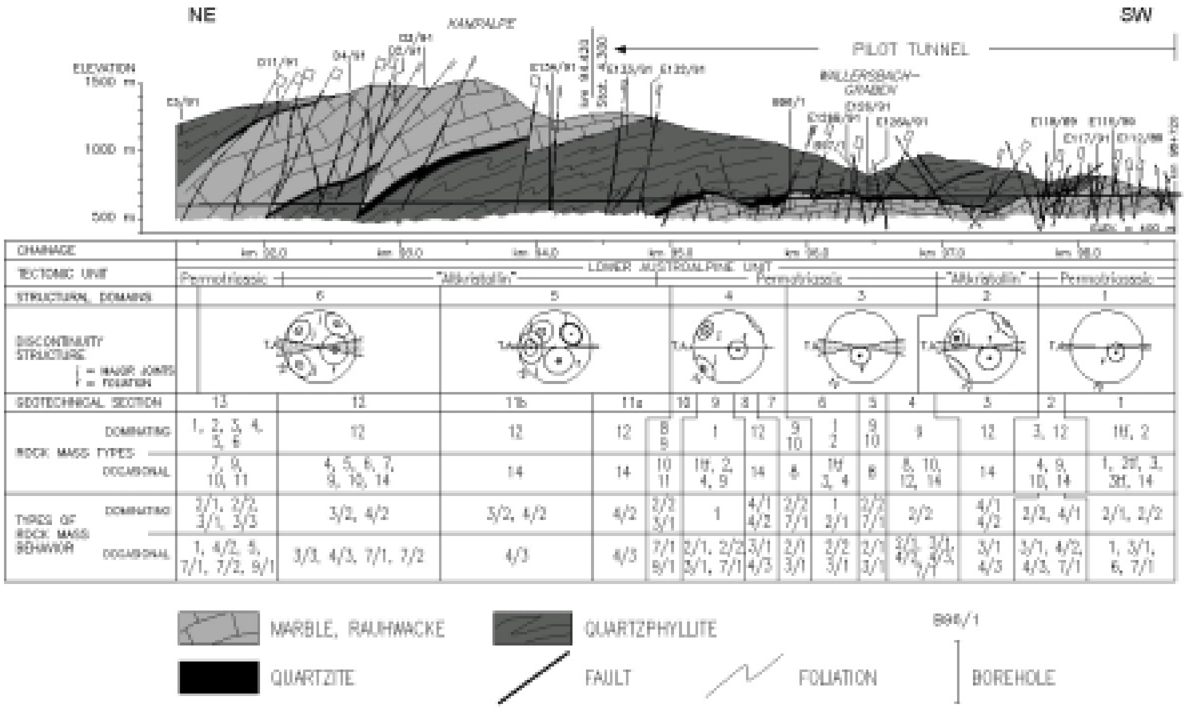

Figure 1. Predicted geotechnical longitudinal section

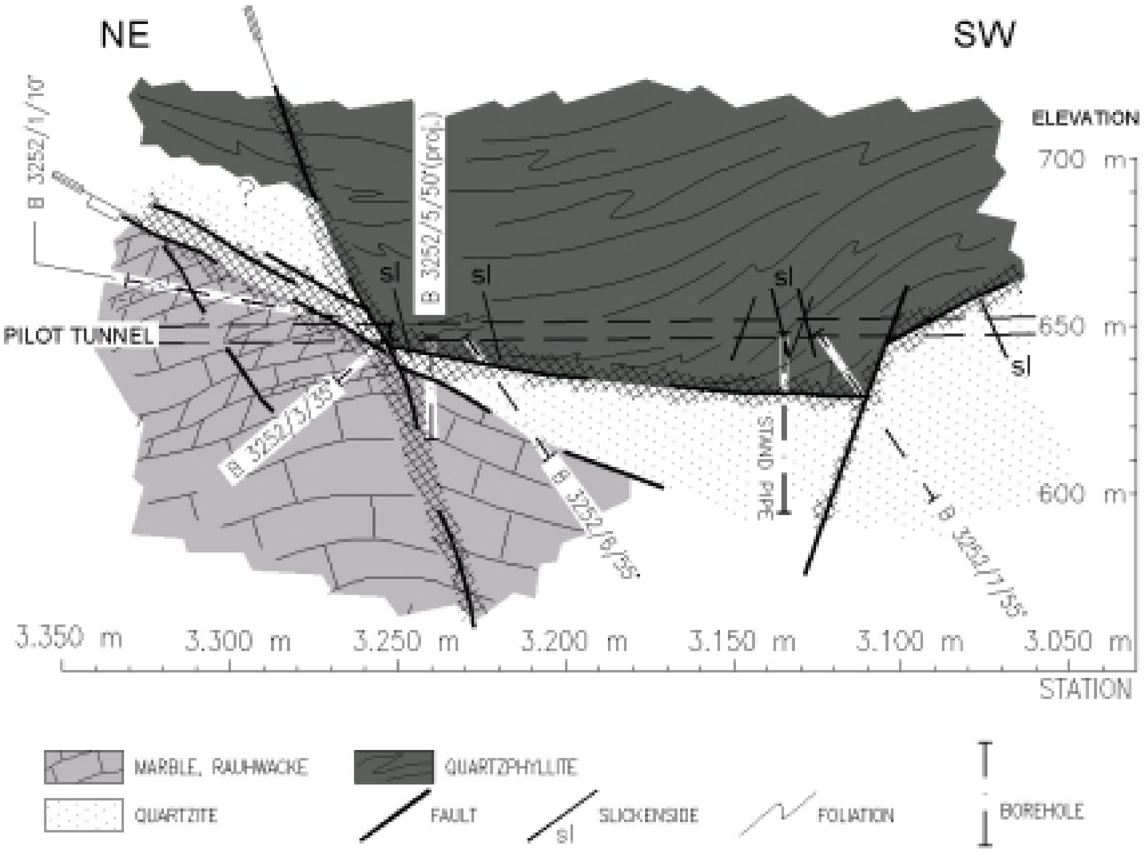

Figure 2. Detail investigation by pilot tunnel and additional drilling

The site investigation consisted of detailed geological mapping (scale 1:5000) of the tunnel corridor and extensive subsurface investigations including geophysical surveys, trenching, core drilling and borehole testing. The main focus was on the detailed analyses of the fault kinematics. Laboratory tests included mechanical and mineralogical analyses of intact rocks.

Drill hole locations were arranged due to the geological structure. The borehole layout combined with geological surface mapping allowed the extrapolation of drilling results down to the level of the tunnel and the establishment of a realistic three dimensional geological model.

Rock mass types, defined by significant geotechnical properties, were established and their distribution along the alignment at the level of the tunnel was estimated. They were grouped according to their estimated behaviour, defined by failure mechanism, depth of plastic zone and the magnitude of radial displacement (Sulem et al. 1987).

The interpretation of the investigation results are 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 (Figure 1).

Due to the complicated geological and hydrogeological situation uncertainties remained. In order to optimize the design of the main tunnel and to quantify environmental risks a pilot tunnel with a diameter of approximately 5 m was excavated (Pölsler 2000). Monitoring and mapping results as well as additional core drilling from the pilot tunnel helped to reduce uncertainties and risks for the client (Figure 2). The experiences gained from the excavation of the pilot tunnel allowed for optimization of supports and construction methods based on a better understanding of the rock mass structure and behaviour.

In order to handle and quantify the large amount of data acquired during the excavation of the pilot tunnel the evaluation of logging and monitoring results were supported by an electronic data management system (DEST) in combination with GIS applications. The data evaluation system allowed for unbiased evaluation of geological, mechanical and hydrogeological data, as well as excavation and support related information (Liu et al. 1999).

4 CONCLUSION

We have outlined a reasonable investigation process for tunnel design. This process is based on the information necessary for each design phase. The investigations should begin step-by-step with the assessment of the general geological architecture of the tunnel alignment and the definition of geotechnically relevant key parameters selected according to the type of rock as well as influencing geological factors. Then initial models are developed and updated as results are gained from more comprehensive investigations. Geological, geotechnical and hydraulic modelling continue through all design stages to the construction. The selection of the optimal support and excavation sequence is determined from the results of face mapping and observed displacements combined with short-term predictions.

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