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THE APPLICATION OF AN EXPERT SYSTEM FOR THE BASIC DESIGN OF TUNNELS

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Abstract. *To successfully complete a tunnel project a coherent and transparent geotechnical design procedure is required.*

Following general steps have to be followed:

- *Definition of a route corridor*
- *Geological/geotechnical investigation*
- *Rock and rock mass characterization*
- *Assignment of parameters to the route corridor*
- *Determination of ground behaviours along each selected alignment*
- *Allocation of possible construction methods and costs to behaviour types*
- *Comparison of different alignment and construction method options in terms of feasibility, risk and costs*

To allow an objective and unbiased assessment of the optimal combination of alignment and construction methods, a consistent procedure has to be followed. The process proposed here uses a combination of analysis and expert knowledge for the determination of key parameters, the assessment of ground behaviour types, and the assignment of construction measures to the different ground behaviours. Also the natural scatter of the rock mass parameters can be considered in the procedure, using probabilistic methods.

The contribution shows the basic procedure of the design process. The application is demonstrated using a case history of a 23 km long water conveyance tunnel in Thailand, where different excavation options were analyzed.

1 INTRODUCTION

The purpose of the investigations shown in this paper was to optimize the tunnel alignment with respect to the technical and environmental risks. During the planning of the water conveyance tunnel a comprehensive geological/geotechnical investigation program was conducted [1]. Different options for the construction of the project were evaluated, including NATM and open, as well as shielded TBM excavations, with a maximum of 5 headings from two access tunnels and one portal. After establishing the geological model and characterizing the rock mass, the response of the rock mass to the excavation was analysed along the entire alignment. For this purpose the rock mass was divided into slices of 50m width each and the ground behaviour due to the excavation determined. Depending on this behaviour excavation and support methods, as well as auxiliary measures were selected. Time and costs were assigned to each activity.

In addition to the variation in construction methods, the geological risk was assessed by using expected, optimistic and pessimistic rock mass parameters. This evaluation showed a variation in excavation time of up to 8 months depending on the construction methods chosen. A comparison of construction costs revealed that due to the relatively low labour costs in Thailand the option with the greatest share in drill and blast excavation is the most economical one.

2 BASIC DESIGN PROCEDURE

According to the procedure outlined in the Austrian Guideline for Geomechanical Design of Underground Structures [2], the information gained by the field investigation, drilling, and laboratory testing is used to define Rock Mass Types in a first step.

After establishing the Rock Mass Types, their distribution along the alignment is determined. For each section of the tunnel then the relevant factors influencing the rock mass behaviour are established. Influencing factors are primary stresses, tunnel size, ground water conditions, and relative orientation of the rock mass structure to the tunnel axis. The rock mass behaviour is defined as the ground reaction to the excavation, without of consideration of any support or other construction measures. After analysing the rock mass behaviour for each slice of the tunnel, the single behaviours can be grouped into basic behaviour categories, so called Ground Behaviour Types (GBT). Rock mass behaviours can be determined empirically or analytically using closed form solutions, block analyses, or numerical simulations as appropriate.

Excavation and support methods are then determined based on the rock mass behaviour in a way to meet the requirements, like constructability, stability, serviceability, and economical aspects. Finally the costs and time required will be allocated the each investigated rock mass slice.

3 ROCK MASS CHARACTERISATION

During several design phases of the water conveyance tunnel geological field and subsurface investigations were conducted. The subsurface exploration, including the drillings for the feasibility study, consist of:

- 28 core drillings in total
- water pressure tests carried out in selected boreholes
- refraction seismic profiling and resistivity sounding
- laboratory tests (point load tests, uniaxial compressive strength tests, triaxial tests, tensile strength tests (Brazilian Test), direct shear tests on discontinuities, Cerchar abra-

sivity tests, thin sections on outcrop and core samples), qualitative clay mineral analysis using X-Ray Diffractometry

Based on the results of the field, subsurface, and laboratory investigations the alignment of the tunnel was selected in a way to minimize excavation in poor rock masses. Figure 1 shows the simplified longitudinal section as chosen for the further investigations. The most crucial alignment section is a thrust fault with a considerable thickness in the central part of the project [3].

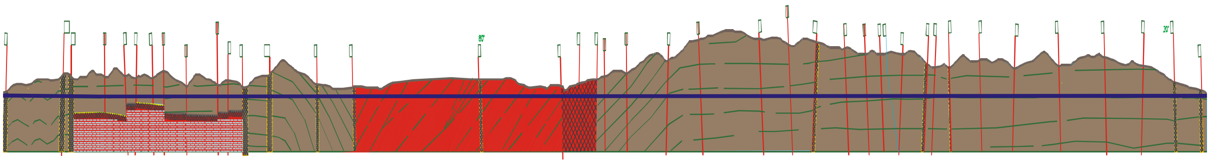

Figure 1: Simplified longitudinal section along the tunnel

3.1 Determination of Rock Mass Types

The information gained from the aforementioned investigations was used to define Rock Mass Types. These Rock Mass Types are defined as groups of rock masses with similar geotechnical properties. Table 1 shows an excerpt of the 17 Rock Mass Types determined during the investigations. The classification parameters used were:

- Rock type
- Bedding thickness
- Joint persistence
- Fracturing
- Joint roughness
- Karstification
- intact rock strength

RMT	rock type	bedding thickness			fracturing		joint persis-tence		joint roughness			karstification			intact rock strength			
		>60 cm	60-20 cm	20-2 cm	low	high	high	low	v. r.	r.	sm.	none	small cav	large cav	<10 MPa	10-50 MPa	50-150 MPa	150-250 MPa
RMT 1	limestone (marble)	X			X		X			X			X				X	
RMT 2	limestone	X			X		X			X				X			X	
RMT 5	siltstone			X	X			X			X	X				X		

Table 1: Excerpt of Rock Mass Types and classification parameters

For each Rock Mass Type rock mass properties were determined using the upscaling procedure proposed by Hoek [4], Hoek & Brown [5] and Hoek et al. [6] with some minor modifications.

Both the intact rock properties and the rock mass properties in the project area vary in a wide range. Sandstones have been tested with a strength up to 250 MPa, while weaker fault rocks have a strength of a few MPa only. The rock mass strength properties accordingly vary in the range of around 1 MPa up to a maximum of about 100 MPa.

3.2 Distribution of Rock Mass Types along the alignment

Based on the geological model derived from the results of the geological investigation the previously defined rock mass types were allocated to the tunnel alignment (Figure 2, compare to the geological longitudinal section shown in Figure 1). As already mentioned in the introduction, the rock mass along the tunnel alignment was cut into sliced with 50m thickness and the Rock Mass Types allocated. This allows the further processing and comparison of the various construction methods considering the specific mechanical parameters, ground water and stress conditions for each slice.

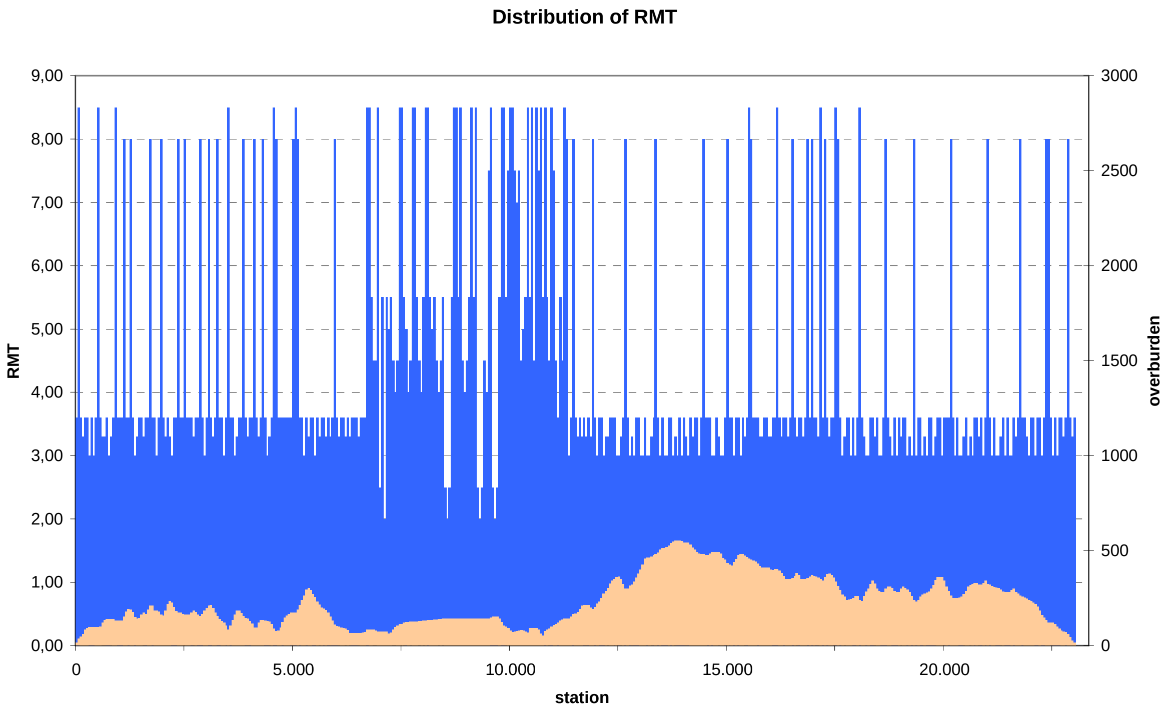

Figure 2: Distribution of the allocated Rock Mass Types (blue bars) and the overburden (brown area) along the tunnel alignment.

4 DETERMINATION OF ROCK MASS BEHAVIOUR

The Rock Mass Behaviour is defined as the ground reaction to the excavation without of the influence of construction measures or any support. The purpose of the determination of this ground reaction is to identify potential failure modes and thus providing a basis for the selection of appropriate excavation and design methods.

After assigning the appropriate rock mass types with their relevant physical parameters to the individual sections along the alignment, the analysis is performed under consideration of the influencing factors, like primary stresses, size of tunnel, and relative orientation of main discontinuity sets to the tunnel axis. In a first step, an analytical procedure is used to determine the rock mass behaviour for each rock mass segment in a hierarchical way. The result of the analysis is checked against the criteria established (delimiting criteria) to distinguish the single behaviour categories. Systematically the results are checked against each criterion. The dominating failure mode then is shown in the output.

In addition the magnitude of displacements is assessed based on closed form solutions [7, 8]. The basic procedure of the determination of Behaviour Types is shown in the flow chart (Figure 3).

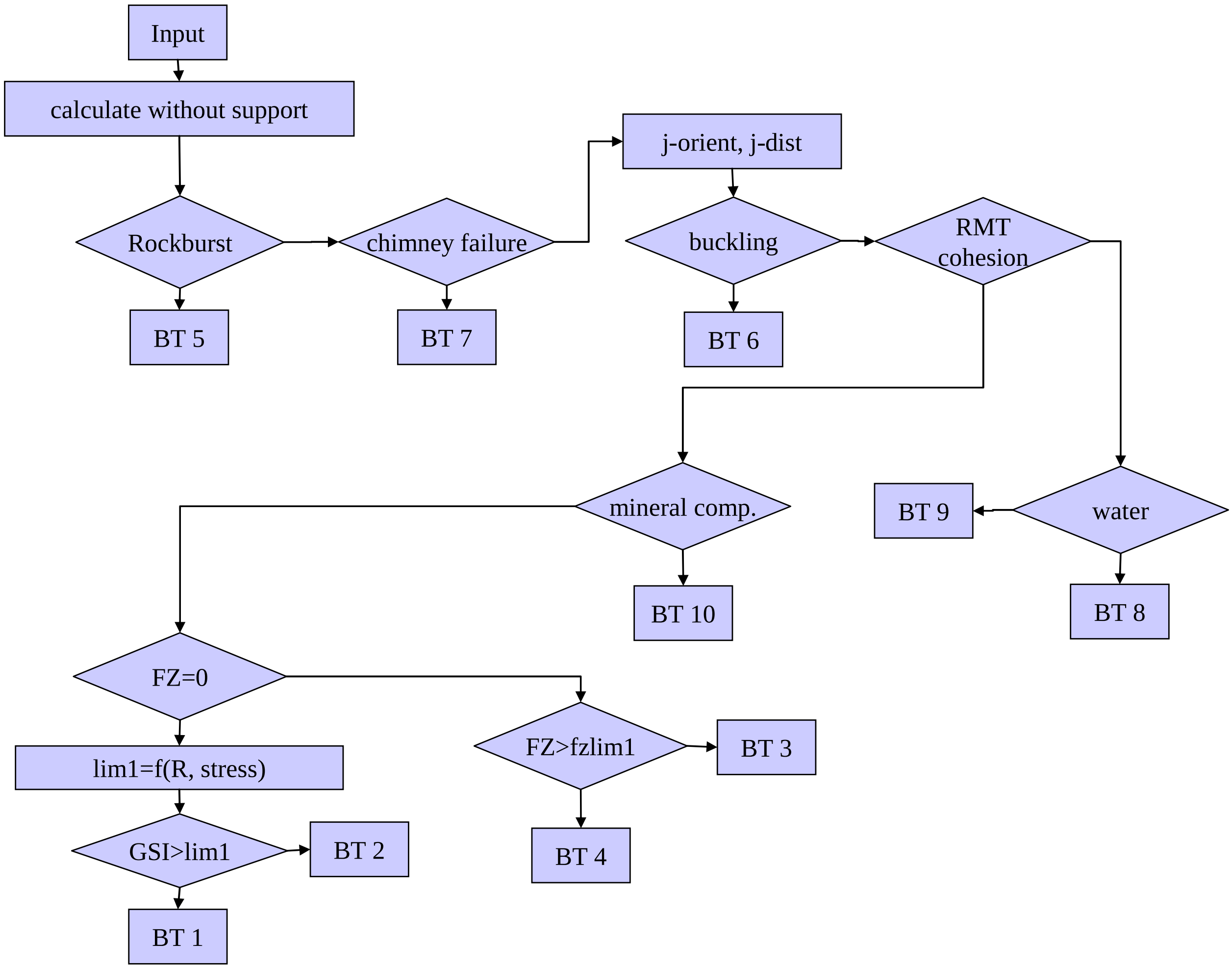

Figure 3: Flow chart of the basic procedure to determine the different Behaviour Types (BT)

For three different sets of rock mass parameters this evaluation was done for the whole alignment. The dominating Behaviour Type for all conditions evaluated is within category 2, which represents discontinuity controlled overbreak. For a minor length also Behaviour Type categories 3 (shallow stress induced failure) and 4 (deep seated stress induced failure) was identified. Due to the intense fracturing of the rock mass, stable conditions without support are expected on a length of a few hundred meters only. Subcategories have been defined for the categories 2, 3 and 4 for an appropriate allocation of construction measures to the single behaviours.

The delimiting criteria play the crucial factor within the BT determination. They are established based on experience and on theoretical considerations. The application of these criteria allows for an unbiased and coherent design procedure and hence allows for consistently comparing different tunnel options in terms of construction method.

5 COMBINATION AND EVALUATION OF CONSTRUCTION METHODS

Three options for construction have been studied. With option 1 the major part of the tunnel is excavated by drill and blast with conventional shotcrete and rock bolt support, while from the outlet a TBM excavation on a length of approximately 11 km was foreseen. For this option both adits are required for construction. With option 2 a second TBM was foreseen to excavate from adit 6 towards the intake, while drill and blast was considered from adit 6 towards the outlet. With this option, adit 5 is required for depletion of the tunnel only. Option 3 finally consisted of two TBM excavations, one from adit 5 towards the outlet, and the other one from the outlet towards the intake. With this option the adit 6 would not be required.

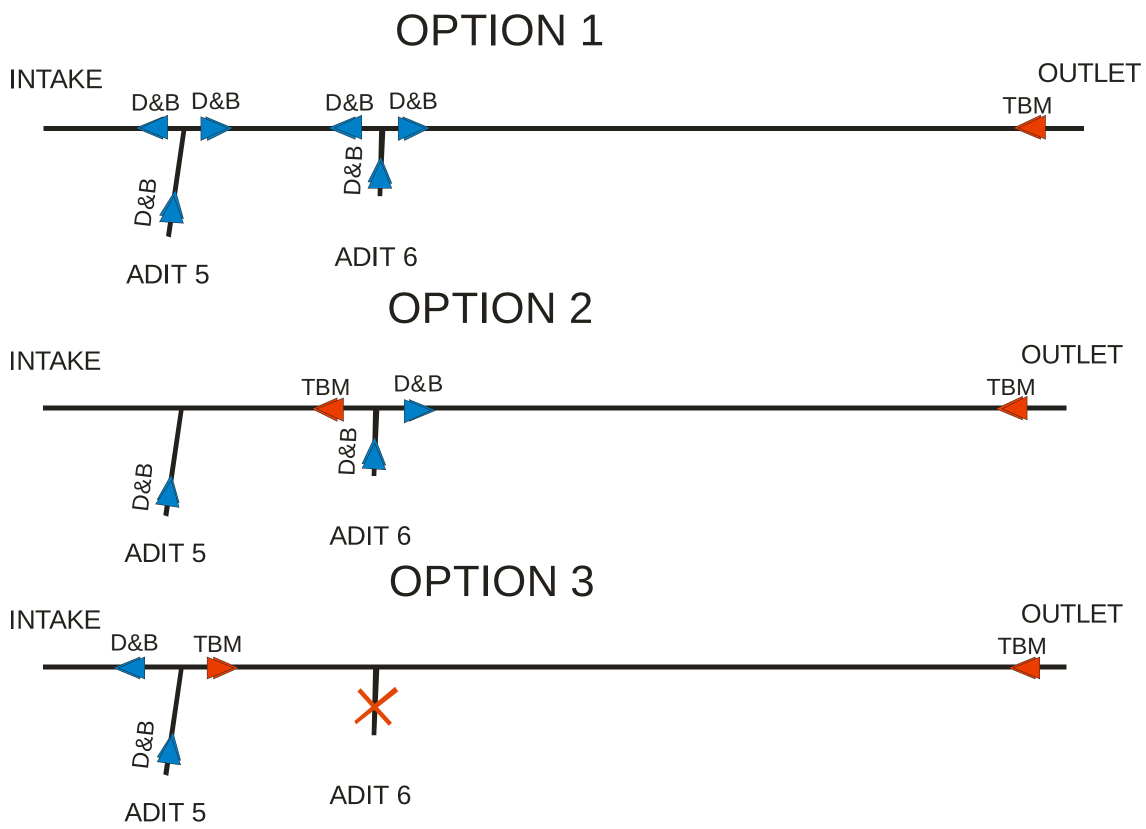

Figure 4: Options for construction methods studied

Due to the requirement of a smooth inner surface for the TBM sections a continuous segment lining was foreseen and a double shield TBM chosen for excavation. For the drill and blast sections a final concrete lining with a minimum thickness of 25cm was chosen.

Geotechnical criteria are used to assign excavation and support type to each Ground Behaviour Type (see Table 2). Four excavation and support classes have been designed for the drill & blast excavation, and two segment types have been allocated to the TBM excavation. In the drill & blast sections the supports consist of a roof protection by shotcrete and spot bolting to prevent blocks from falling into the opening for the better rock masses, while a continuous shotcrete lining and systematic bolting, as well as steel arches are provided for the low quality rock masses. The difference between the two types of segments is in the concrete quality and amount of reinforcement.

Excavation rates D&B 2,8m dia			Support	round length
GBT	m/d	d/m	type	m
1,0	12	0,08	A	3
2,1	10	0,10	A	3
2,2	9	0,11	B	2,5
3,1	7	0,14	B	2,5
3,2	7	0,14	C	2
3,3	6	0,17	C	2
4,1	5	0,20	C	1
4,2	4	0,25	D	1
4,3	4	0,25	D	1
5,0	9	0,11	B	3
6,0	8	0,13	D	1
7,0	4	0,25	D	1
8,0	4	0,25	D	1
9,0	n.a	n.a	n.a.	n.a.
10,0	6	0,17	C	2
11,0	3	0,33	D	1

Table 2: Listing of the Ground Behaviour Types (GBT) and the associated support types, including the expected excavation rates, respectively

After assignment of construction methods, the compatibility of the supports with the requirements is checked, and in cases of insufficient agreement the support modified.

Once excavation and support methods have been fixed for the whole tunnel, construction time and costs are evaluated. Construction time includes cycle times for the different excavation and support classes, as well as delays due to treatment of water and other activities, like probing ahead, etc. This again can be linked to the evaluated Ground Behaviour Types, respectively Rock Mass Types.

In terms of construction time for option 1 the time evaluated for the main civil works (excavation and support, and inner lining) was around 40 months after award of contract (see Figure 5). For option 2 the required time for the main works would be very similar to that of option 1, while option 3 showed to be the fastest with a time requirement for the main works of around 30 months (see Figure 6 and Figure 7).

It shows that the total construction time with varying rock mass strength does not change significantly. The reason is that with higher rock mass strength the penetration rate of the TBM decreases, while the more favourable rock mass conditions allow a faster drill and blast progress due to a higher share of “better” excavation classes. This slightly changes the breakthrough location, but has a minor influence on the total construction time.

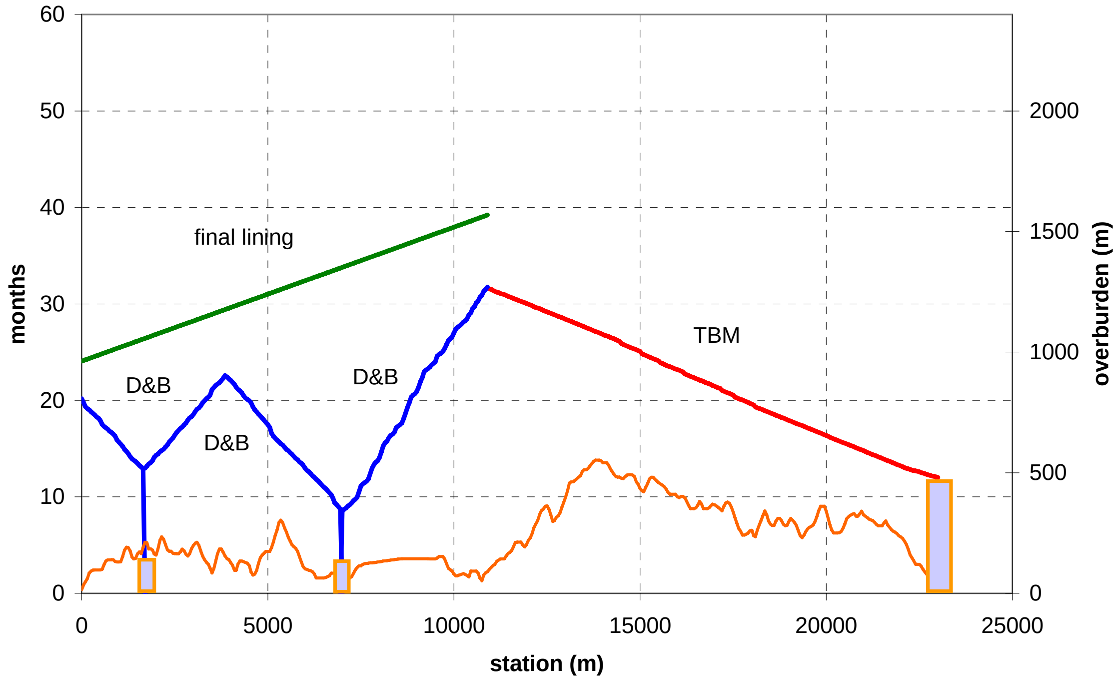

Figure 5: Rough construction time schedule for option 1 with medium rock mass quality

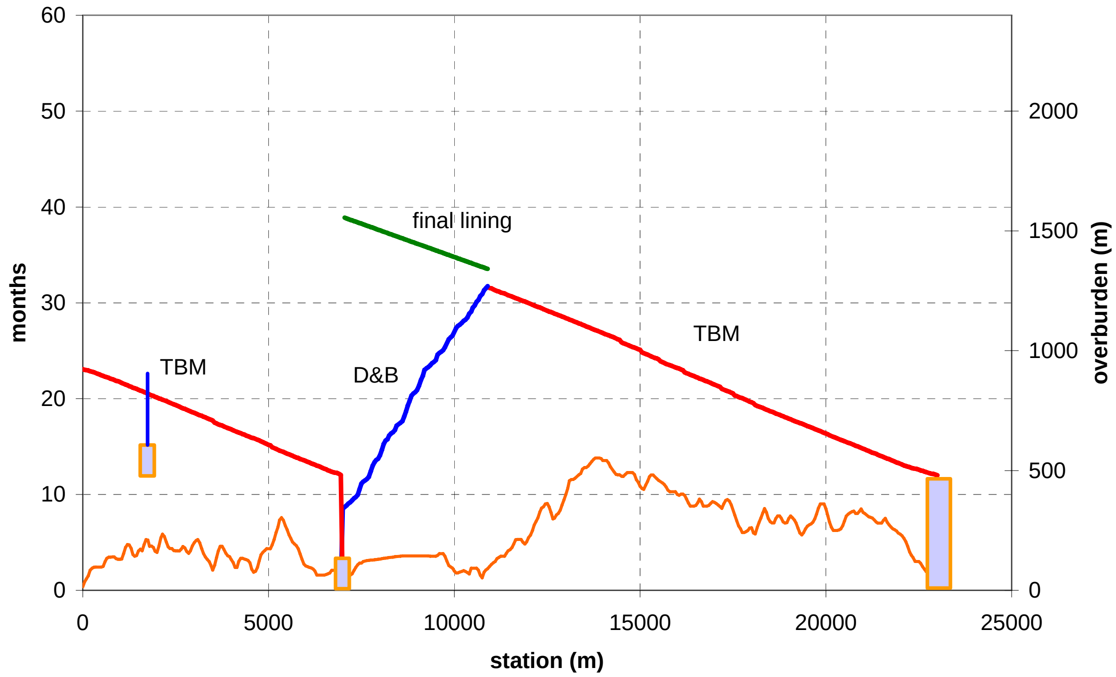

Figure 6: Rough construction time schedule for option 2 with medium rock mass quality

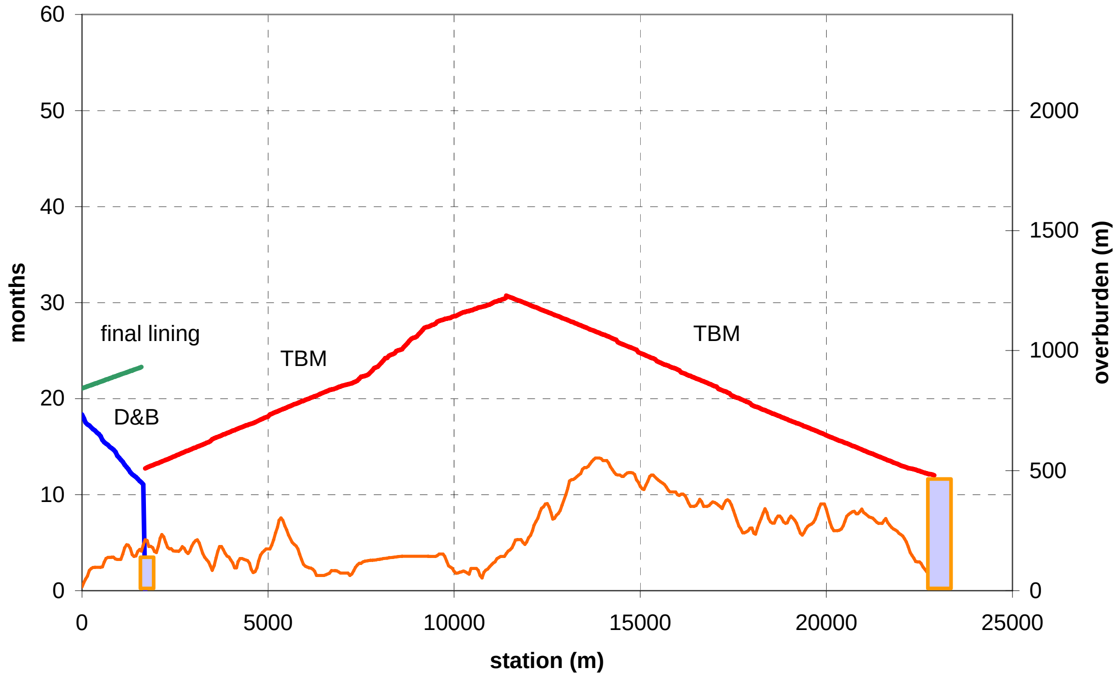

Figure 7: Rough construction time schedule for option 3 with medium rock mass quality

A preliminary evaluation of the construction costs due to the relatively low labour costs in the project area showed that option 1 with a higher share in labour intensive drill and blast would be the most economical one (see Figure 8). The difference in tunnelling costs between the most expensive option 2 with low rock mass quality and option 1 is in between 12% to 17%. The evaluation also clearly shows that the rock mass quality does not influence the costs of a TBM excavation considerably. This is attributed to the low degree of variation in support in relation to the rock mass quality. With the drill and blast method better rock mass quality reflects in lower costs, as progress rate increases, while support demand decreases.

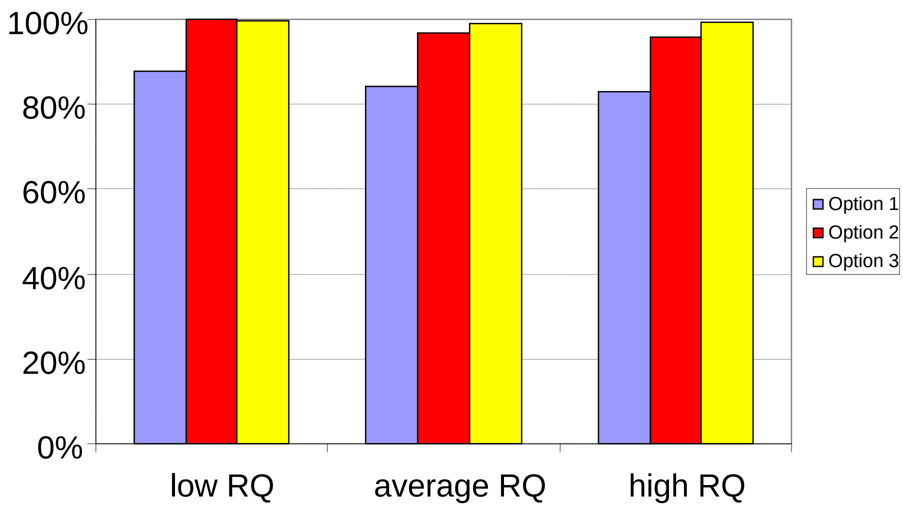

Figure 8: Comparison of the relative costs of the options investigated

6 CONCLUSIONS

When comparing several options in terms of construction method for a project, a consistent procedure is required to arrive at an unbiased result. In the case of the water conveyance tunnel shown, a comprehensive rock mass characterization was followed by an evaluation of the ground behaviour. Assigning construction methods and auxiliary measures to the different ground behaviour types allows an objective evaluation of construction costs and time for different excavation options. The consideration of the spread in rock mass parameters allows evaluating the spread in construction time and costs.

Even with the in-depth evaluation of different alignments and construction methods, residual risks with respect to construction costs and time remain. This particularly is attributed to the complex geological conditions, and the uncertainty in the evaluation of realistic ground water conditions. The study therefore has considered delays due to effects of the ground water on the excavation on the safe side. A big advantage of the chosen option 1 with total 5 headings is the fact, that in case of a problem in one of the headings requiring a longer stop, the other heading can proceed further, thus reducing the impact on the total construction time.

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