Rock Characterisation, Modelling and Engineering Design Methods – Feng, Hudson & Tan (Eds)

Applying the observational approach for tunnel design

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ABSTRACT: The inherent uncertainties in the ground model and influencing factors, in most cases, do not allow a reliable direct design of a tunnel. Empirical tunnel design methods do not allow proofing stability or serviceability, thus are not acceptable according to common understanding.

To allow for construction of safe and economical tunnels, the uncertainties have to be dealt with by observing the behaviour of the structure, and adjust construction measures to the real ground conditions and behaviours ("observational method").

After characterizing the ground, potential hazards are identified, the possible range of behaviours is assessed and appropriate construction measures to the expected behaviours are assigned. A monitoring plan needs to be established together with a safety management plan including contingency measures for inacceptable predicted behaviour deviations.

The paper with the help of a few worked examples illustrates the influence of the rock mass structure and fault zones on the system behaviour.

1 INTRODUCTION

Optimization of underground structures design has been a topic widely studied by researchers and the industry. New approaches, guidelines and techniques have been developed replacing standard classification systems which tried to simplify/generalize the ground conditions with the inherent shortcomings (Daller et al. 1994, Palmström & Broch 1996, Riedmüller & Schubert 1999a, Riedmüller & Schubert 1999b). New approaches attempted to consider biases and uncertainties that arise from the multiple influencing factors which govern the ground behaviour and focus on achieving an appropriate technical and economical design (Radoncic et al. 2009a, Clayton et al. 1982, Head 1986, Oliveira 1992). Yet each design phase entails uncertainties that have to be considered during construction (Einstein 2001).

This paper presents a description on how to achieve a proper design and connect it, through the observational approach, to the construction phase. The first part deals with the design stage and how to attain expected system behaviours and tunnelling classes based on ground types, boundary conditions, and influences. The second part presents some examples showing how to link the work done during the design stage with the observational approach during construction.

The approach presented in this paper allows tunnel engineers to complete a technical, economical and safe construction in spite of uncertainties which are difficult to detect during the design stage.

2 DESIGN STAGE

A clear scope and objectives should be set depending on the projects stage, project size, geological complexity, and cost-benefit analysis among other factors (Riedmüller & Schubert 2001).

2.1 *Investigation stage*

Under this stage the main goal is to assemble a high standard geological/geotechnical model which, at the same time, helps with the definition of a technical and economical alignment for the project (Schubert et al. 2001).

The model is continuously updated throughout the design and construction stages and constitutes a key element for the evaluation of system behaviours and tunnelling classes. Thus evaluation and interpretation of data that is used within the investigation stage as well as discarding useless or inaccurate data is important.

2.1.1 *Office data collection*

The first approach to the geological model comes from existing information which has a low cost and gives valuable information regarding geological features (Hoek 1992, Boyce 2010). From this information a first model "draft" can be assembled.

Common sources of information for assembling the model are literature, aerial photographs, satellite images, seismicity data, land slide records, geological maps and hydrological data.

2.1.2 *Field survey*

Based on the first "draft", assembled with existing information, field survey takes place on the project area along a given corridor or in the influencing area of the project (Goricki et al. 2001, Hoek 1982).

Field survey is mainly made by engineering geological mapping. This task requires experience in order to identify relevant morphological features, study of outcrops, identification and characterization of fault zones, fault activity and assessments on hydrogeological conditions.

Through field survey on the one hand a refinement of the geotechnical/geological model can be derived, but certain features are difficult to locate or quantify (e.g. magnitude of faults, properties of the ground, recharge areas for springs, flow direction of underground water). Supplementary techniques help reducing these uncertainties.

2.1.3 *Subsurface exploration*

The most common methods for the exploration are geophysical methods, drilling and coring. Though a large number of tools and methods are available (Anon 1987), it is important to previously acknowledge the applicability and limitations to help in the selection of the method.

Subsurface investigation is cost intensive and time consuming. Therefore the implementation of a cost-benefit analysis can help to optimize the exploration program (Swoboda 1999).

At this point a refined and accurate model should be achieved, displaying magnitude, orientation and any relevant geological/hydrogeological features, yet quantification of material properties is still to be added into the model.

2.1.4 *Laboratory/In-situ testing*

The information gained from laboratory and in-situ testing represents the primary basis for the geotechnical design. With it different ground types can be determined and rock parameters, discontinuity parameters as well as rock mass parameters (caution with homogenization!) assigned which have significant influence on the ground behaviour. Therefore it is clear that the results of laboratory and in-situ tests have to be checked for their accuracy and plausibility. Furthermore it should be taken care when averaging values from similar tests (e.g. uniaxial compressive strength). The test specimen may appear to be the same but when closely checking each test result, essential differences for example in the orientation and formation of the texture or in the failure mechanism can be located. Due to this fact the results are often not comparable (Kluckner 2012).

In order to obtain information which is useful for the geotechnical design a cooperation of geotechnical engineers, geologists and laboratory staff is required right from the beginning of the project. This applies with regard to laboratory and in-situ testing as well as to investigations generally.

2.2 *Geotechnical design*

Based on adequate investigations and a realistic geological model (Riedmüller & Schubert 2001) at which the amount of information depends on the project phase (see Section 2) the engineer has to characterize the ground and specify an appropriate tunnelling method (excavation and support type) for the expected ground behaviour.

The Austrian Society for Geomechanics published a guideline (OeGG 2010) with the aim of providing the engineers a general concept for the geomechanical design of underground structures. The guideline is widely used especially in combination with the so-called New Austrian Tunnelling Method (NATM).

The concept is composed in a hierarchical and logical way (see Figure 1) in order to ensure a transparent design which is of utmost importance. In particular for large projects the design process may take a long time and the responsible engineer may be reassigned during the design and construction stage.

In the following subsections the main points of the geotechnical design according to this guideline are briefly described.

2.2.1 *Ground types*

Reliable intact rock properties and discontinuity properties that will likely have the most influence on the ground behaviour (e.g. uniaxial compressive strength of the intact rock, discontinuity spacing and properties) have to be designated. With these quantifiable/measurable "key parameters" different ground types (GT) can be delimited. For this purpose ground volumes with similar physical/mechanical and hydraulic properties are merged into one ground type, regardless of the lithological unit (Radoncic et al. 2009a).

The already defined ground types enable the engineer to previously make assumptions about geotechnical hazards (Riedmüller & Schubert 2001).

2.2.2 *Ground behaviour and behaviour types*

Taking the influencing factors such as primary stress state, ground water level and spatial orientation of the ground structure into consideration the tunnel alignment has to be divided into segments whereat one segment represents a ground volume with the same type of ground (GT) and similar influencing factors and requirements. For each segment the ground behaviour (response of the rock mass to the excavation) and possible failure mechanisms or hazards need to be determined. It should be noted that for the determination of the behaviour neither the support nor a partial excavation shall be considered.

Afterwards the identified mechanisms have to be allocated to behaviour types (BT). The most common types are illustrated in the geotechnical guideline (OeGG 2010). For behaviour deviating from the illustrated examples additional types or subtypes have to be defined.

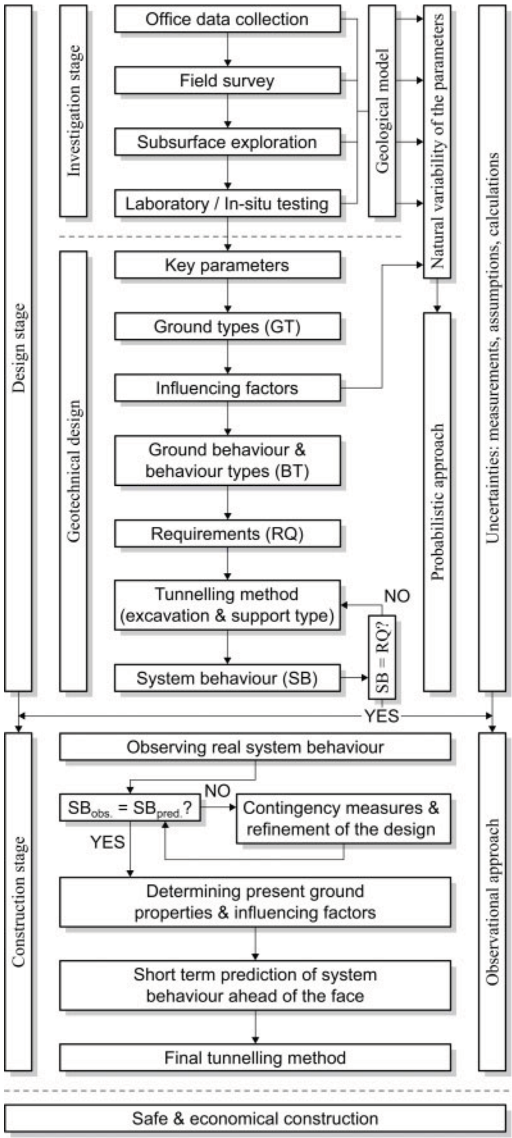

Figure 1. Schematic procedure of the design stage and the construction stage.

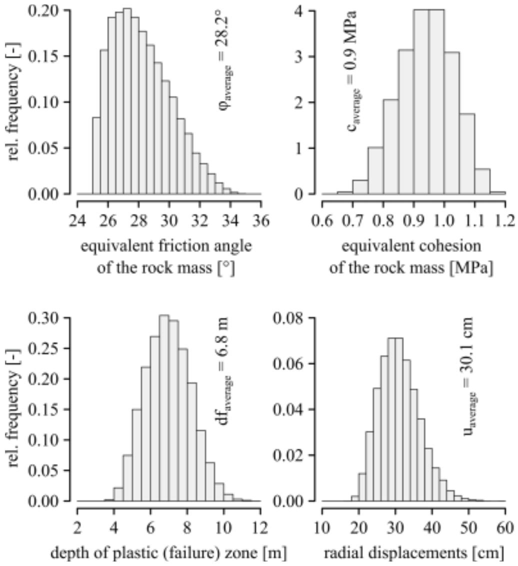

Figure 2. Natural variability of design parameters (upper diagrams) and the effect on results (lower diagrams).

2.2.3 *Tunnelling method and system behaviour*

The next step is to establish a tunnelling method for each type of behaviour (BT). Such a method comprises the excavation method (continuous or conventional), the excavation sequence (full face, top heading, round length, etc.), support or pre-support and other additional measures.

The excavation and support methods have to be established in a way that the system behaviour meets the project specific requirements (RQ) such as limited displacements, limited surface settlements or an upper limit for the utilization of the lining. Tunnel design in fault zones with high overburden means a special challenge, as displacements will exceed the strain limit of conventional supports. In such cases ductile linings can be provided (Radoncic et al. 2009b).

After the tunnelling method has been defined for different ground behaviour types the system behaviour (SB) needs to be analysed. If the system behaviour does not satisfy the requirements a modification of the chosen tunnelling method is necessary.

At the end the final system behaviour represents the "normal behaviour" or the "predicted behaviour" respectively.

2.2.4 *Natural variability of input parameters*

Contrary to structural engineering, where loads and material properties are known with enough accuracy, these parameters are showing a natural variability in geotechnical engineering. During the design stage it is the engineer's responsibility to take this variability into account. In Figure 2, the upper diagrams show a feasible distribution of the equivalent friction angle and the equivalent cohesion of the rock mass.

Considering the mean values only would lead to a depth of failure zone of df = 6.8 m and to radial displacements of u = 30.1 cm using a closed form solution for isotropic and homogeneous material (Feder & Arwanitakis 1976).

Though the results are those with the highest probability the radial displacements can for example vary from 18 cm to 54 cm, shown in the lower right diagram. Therefore, while defining the ground types and determining possible hazards a probabilistic approach (e.g. Monte Carlo method) or at least the use of optimistic and pessimistic values in addition to the mean value has to be carried out. Otherwise it may occur that the design and thus the contract does not provide for conditions outside of the average, leading to an increase of risk and at the end to additional time and cost (Goricki et al. 2006).

2.2.5 *Remaining uncertainties*
Regardless of the amount of investigations and how detailed the design is accomplished uncertainties will always remain. Due to limited time and financial resources investigations especially subsurface explorations can only be executed pointwise (Kluckner 2012). Additionally in most cases the ground is heterogeneous with a complex structure. Hence, some important geological features may not be encountered during the investigations. To proper dealing with these shortcomings following tasks corresponding to the guideline (OeGG 2010) should be performed:

(1) Defining warning criteria to identify whether the observed system behaviour is within the predicted range;
(2) Defining contingency measures for circumstances if the observed system behaviour deviates from the predicted one in the particular tunnel section and which does not fulfil the requirements. This could require a modification of the tunnelling method or additional measures (e.g. additional support, decreased advance rate, etc.).

3 CONSTRUCTION STAGE

Besides the common practice to map the geological structure at the tunnel face and at the tunnel wall, and producing a geological model in a representative volume around the tunnel, the system behaviour has to be monitored continuously during construction. Besides this, additional observation measures have to be applied depending on the project boundaries (e.g. limitation of surface displacements during the excavation of a shallow tunnel). Therefore, a monitoring plan has to be established already in the design stage. According to the monitored data the engineers have to decide how to proceed at the tunnel site. The "observational approach" is the combination of the monitoring of relevant information, its interpretation and the adjustment of the tunnelling method to fulfil the requirements.

It is needless to say that an observational approach requires experienced personnel on site and an appropriate contractual setup to efficiently allow for modifications of the construction method.

4 EXAMPLES

Computational software was used to demonstrate the shortcomings of homogenizing the ground and to display the advantages of the observational method.

4.1 *Influence of discontinuity orientation*

Numerical simulations were done with the software Flac3D (Itasca). To simulate the discontinuities the ubiquitous joint constitutive model was used.

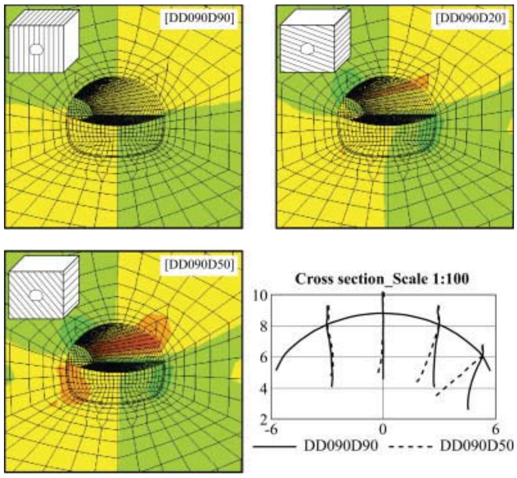

Figure 3. Displacement vector orientation and influence of discontinuity orientation.

Nowadays it is common practice to homogenize the ground through rock mass characterization systems such as GSI (Hoek & Brown 1998), thus losing the discontinuities influence for support and tunnelling class considerations. The following example aims to display the importance of involving discontinuities during the design stage and for the interpretation of monitoring data during construction.

Several numerical simulations were performed in order to study the influence of the discontinuities orientation with respect to the tunnel axis. Figure 3 clearly displays the influence of different discontinuity orientation on displacements and stress distribution.

The displacement vector constitutes a convenient tool for the observational approach recording changes as the one displayed in Figure 3. A correct interpretation of changes in the vector trend allows identifying changing ground conditions ahead of the excavation (Großauer & Schubert 2009).

Displacement development is highly influenced by the discontinuities as seen in Figure 4. The figure displays a change on the percentage of displacements behind the face (pre-displacements) depending on the dip and dip direction of discontinuities. An optimal design should consider this situation for the support systems and during construction a complete understanding of the influence of discontinuities helps the interpretation of monitored data.

4.2 *Shallow tunnel in weak rock*

The following example presents a tunnel with 20 m overburden in a BIMrock (block in matrix) ground.

4.2.1 *Geotechnical design*
A relevant feature of the design is the characterization of such material, key parameters such as volumetric proportion of blocks in connection to the size of the excavation, not common for the characterization of

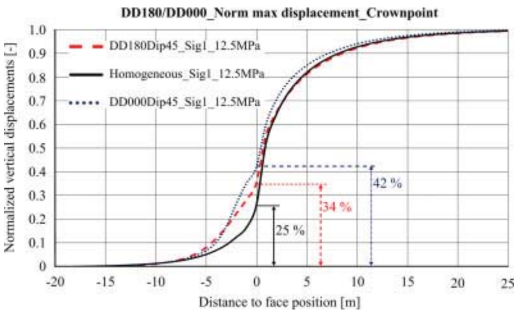

Figure 4. Longitudinal displacement development and influence of the discontinuity orientation.

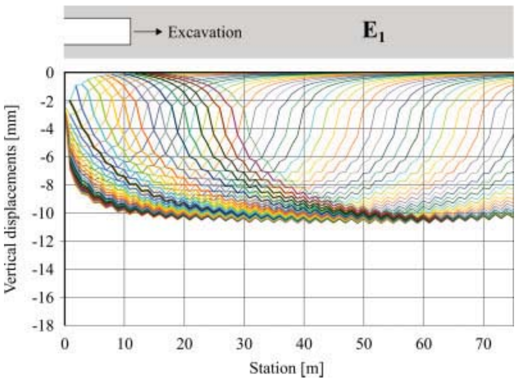

Figure 5. Crown displacement for the tunnel class "BIMRock".

Table 1. Summary: Shallow tunnel example.

Shallow tunnel / Mohr-Coulomb (FLAC3D)					
Numerical model geometry L/H/W (m):			90/60/54		
Ground properties (* 1):			500/0.2/0.035/38/4		
Tunnelling class "BIMRock"		Shotcrete (cm)	Umbrella pipes (* 2)	Steel ribs (* 3)	Round length (m)
	Top heading	15	2/0.25/0.35	HEB100/2	2
	Bench	15		HEB100/2	4
	Invert	20			6

*1: E-Modul (MPa)/poisson ration (-)/coh. (MPa)/fric. angle (°)/dilat. angle (°)
*2: # of rows/distance between rows (m)/distance between umbrellas (m)
*3: Profile type/longitudial spacing (m)

other grounds, plays an important role (Medley & Goodman 1994). Shallow tunnels usually have settlements restriction thus the system behaviour should consider such restrictions.

Figure 5 displays the predicted displacements for the excavation under the tunnelling class displayed in Table 1.

4.2.2 *Observational approach*

For the example a fictitious weak zone (not included in the initial design) was included in the model as the excavation is conducted, monitored data are recorded

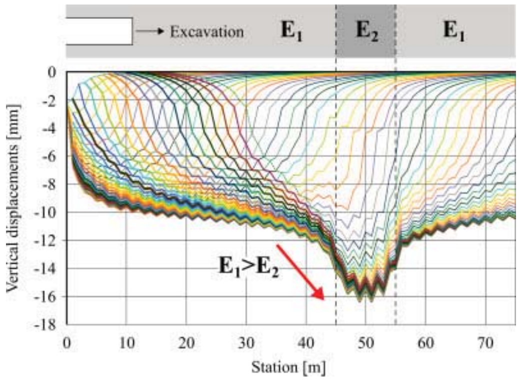

Figure 6. "Monitored" crown displacements.

and interpreted. Figure 6 displays the fictitious monitored data for the crown point.

Though the weakness zone is located around station 45, already well ahead this transition a variation of the displacement trend is noticeable.

Based on the warning criteria, defined during the design stage, for the excavation and the magnitude of the deviation, timely modifications of excavation and support are possible in order to comply with the technical and safety requirements of the project.

Shallow tunnels usually require stiff support systems which yield rather small displacements. Such data is complicated to interpret hence new tools have been developed for this purpose (e.g. the evaluation of the shotcrete utilization) (Radoncic et al. 2009b).

5 CONCLUSIONS

An appropriate geotechnical design should focus on understanding the ground behaviour, analytical and numerical tools used for the design should be selected based on the expected ground behaviours to avoid shortcoming of ground homogenization.

The implementation of the observational method constitutes a useful tool to consider uncertainties contained in the geotechnical design. Its successful implementation depends on good preparation during design, an accurate implementation of the monitoring plan and a correct interpretation of the monitored data.

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