Usage of Monitoring Data to Optimize and Validate the Geotechnical Parameters of Rock Properties in the Underground Space

Ghader Saadati
Unit of Geotechnical Engineering, Universität Innsbruck, Innsbruck, Austria

Michael Mett
Dibit Messtechnik GmbH, Innsbruck, Austria

Heiner Kontrus
Dibit Messtechnik GmbH, Innsbruck, Austria

Barbara Schneider-Muntau
Unit of Geotechnical Engineering, Universität Innsbruck, Innsbruck, Austria

ABSTRACT: Determining parameters, including geomechanical characteristics of rocks or rock mass, initial stress state, underground water conditions, permeability, etc., with high accuracy is difficult and expensive due to the complexity of the geological conditions. On the other hand, analyzing the stability of tunnels and determining the behavioral characteristics of the rock mass with numerical methods has limitations in terms of the validity of the input and output data. One of the practical methods to solve these problems is the use of monitoring system in underground space, which aims to measure displacements and can give an estimate of the stability of structures and rock mass. One possible way to validate or determine parameters on site is the use of precision instruments and perform back analysis on the resulting deformation data. In this research, different back analysis methods are investigated to validate rock masses parameters in tunnels.

Keywords: Monitoring system, Back analyse, Numerical methods, Underground space, Rock mass parameters.

1. INTRODUCTION

In the last decade, various numerical methods such as finite element method (FEM), boundary element method (BEM) and discrete element method (DEM) have been widely used in the field of rock mechanics to design structures such as e.g. tunnels, large underground spaces, dam foundations, etc. The mechanical behavior of such structures is extremely difficult to predict with sufficient accuracy due to a lack of knowledge of the rock mass properties. In other words, the validity of the predictions depends on the accuracy of the input data and chosen constitutive model and how closely they reflect actual rock mass behavior. Therefore, despite the use of accurate geological surveys and complex computer analysis, it is not surprising that the actual behavior of the structures differs from the predicted behavior.

To assess this problem, field measurements are performed on a regular basis during and after construction, which, in addition to get an idea of the stability of the structure, serves to re-evaluate geological prognoses and geomechanical input parameters. Usually it is aimed at minimizing the difference between the measured and the calculated deformation of the structure.

According to the updated information, the original design and construction of the structure might also be modified, if necessary. This is known as observation method. In this context, the question arises how the results of the field measurements can be interpreted quantitatively in an efficient way in order to evaluate the original design and further construct the tunnel. To answer this question, we can use back analysis, which can be seen as bridge between reality and prediction Sakurai (1993). Many efforts have been made to develop different methods of back analysis, as shown in Maiar et al. (1977), Gioda & Yurina (1981), Sakurai & Takeuchi (1983), Yang et al. (1983, 2000), Wang et al. (1984), Yang (1990), Hudson (1992), Zhao & Lee (1996), Sakurai (1997), Singh et al. (1997), Cai et al. (1998), Zhao et al. (1999), Gioda & Locatelli (1999), Gioda & Swoboda (1999) and Swoboda et al. (1999). Recently, a back analysis approach based on case studies has been used to identify the failure mode in tunnels and underground spaces, see Lee & Sterling (1992), Gioda & Locatelli (1999) and Pelizza et al. (2000). The intelligent back analysis that assesses the stability of structures based on the experiences of similar cases is one of the used methods in Shang (2002) and Cai (2002).

The southern Karwendel region has a complex geology and tectonic history, which has been extensively investigated by Ampferer (1949), Gstrein & Heißel (1989) and Heißel (1978). Heißel (1978) published an improved geological-tectonic model that includes the position of the Mühlauer sources. The Karwendel Mountains are part of the Northern Calcareous Alps and consist of the Lechtal Nappe, the Karwendel Thrust Zone, and largely the Inntal Nappe. The rocks of the Inntal Nappe exhibit a large-scale fold structure that strikes mostly east-west and is northward in direction. Although the rock sequence is generally upright, large-scale or pronounced small-scale folding can result in partially overturned or overturned layering. The Inntal Nappe in the Karwendel Mountains includes sedimentary rocks from the Triassic period, ranging from the Alpine Buntsandstein to the Hauptdolomit. The intense small-scale folding affects not only the incompetent rocks of the Alpine Buntsandstein, the Reichenhall Formation, and the Alpine Muschelkalk, but also partially those of the Wettersteinkalk and the Hauptdolomit (see Figure 1).

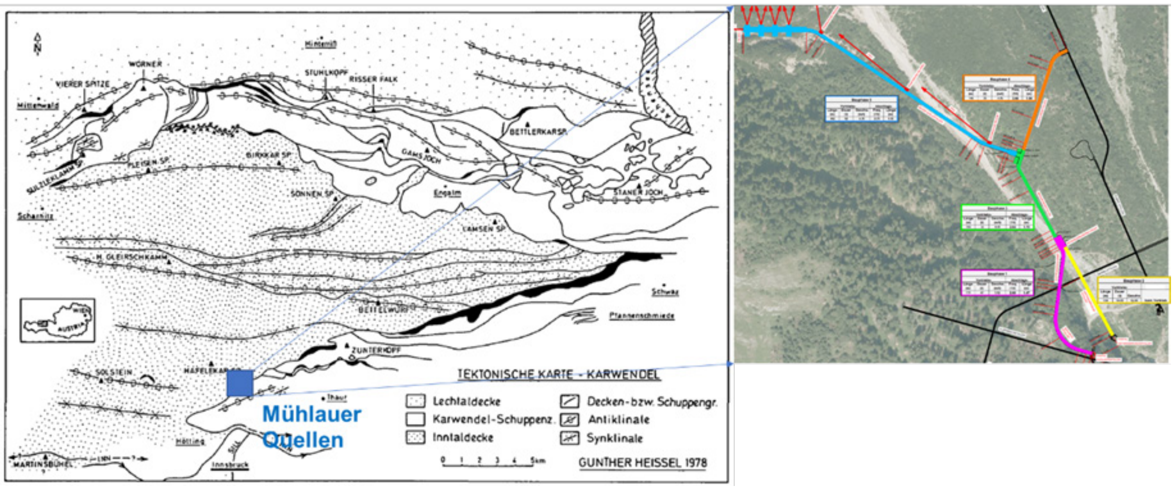

Figure 1. Geological-tectonic map of Karwendel (Heißel 1978) with identification of the location new Mühlauer Quellen tunnel and and sketch of the tunnels (Östu-Stettin 2023).

2. Parameter optimisation

2.1. Numerical modelling

The primary objective of this study is to compare the model outputs with actual measurements taken from the tunnel's instrumentation to determine the accuracy of the model. The tunnel is modelled with RS2 as 2D - plane strain approach. For modelling the excavation process, the operational conditions of the tunnel have to be mapped. The tunnel grating system is activated in a combined manner, including mesh, shotcrete, and lattice. To ensure the model's accuracy, the outer boundary around the structure is determined as five times the radius of the tunnel. The left and right borders of the model are closed in the horizontal direction but free in the vertical direction, and the bottom border of the model is closed in both horizontal and vertical directions.

To mesh the model, a triangular mesh with six nodes is used. The loading conditions of the model depend on the density of the rock and the thickness of the overburden in the desired case study. The behavior is considered by an elast-oplastic constitutive model (Mohr-Coulomb). See Table 1 for original rock mass properties used in the calculation. The Sheorey relation is used to determine the horizontal to vertical stress ratio K, which is dependent on the Youngs's modulus E and the overburden height H, see equation 1 (Evert Hoek's, 2006).

$$K = 0.25 + 7\,E\,(0.001 + \frac{1}{H}) \tag{1}$$

Table 1. Original rock mass properties used for numerical modelling.

Rock mass Properties					
Uniaxial Compressive strength N/m^2	Unit weight kN/m^3	Poisson ratio -	Friction Angel °	Cohesion N/mm^2	Elasticity Modul N/mm^2
30	26	0,3	35	0.7	5000

At selected coordinates in the tunnel environment the horizontal and vertical displacement are evaluated, see Fig. 2. The article investigates the anomalies that occurred in the range of tunnel meter 135 to 164.

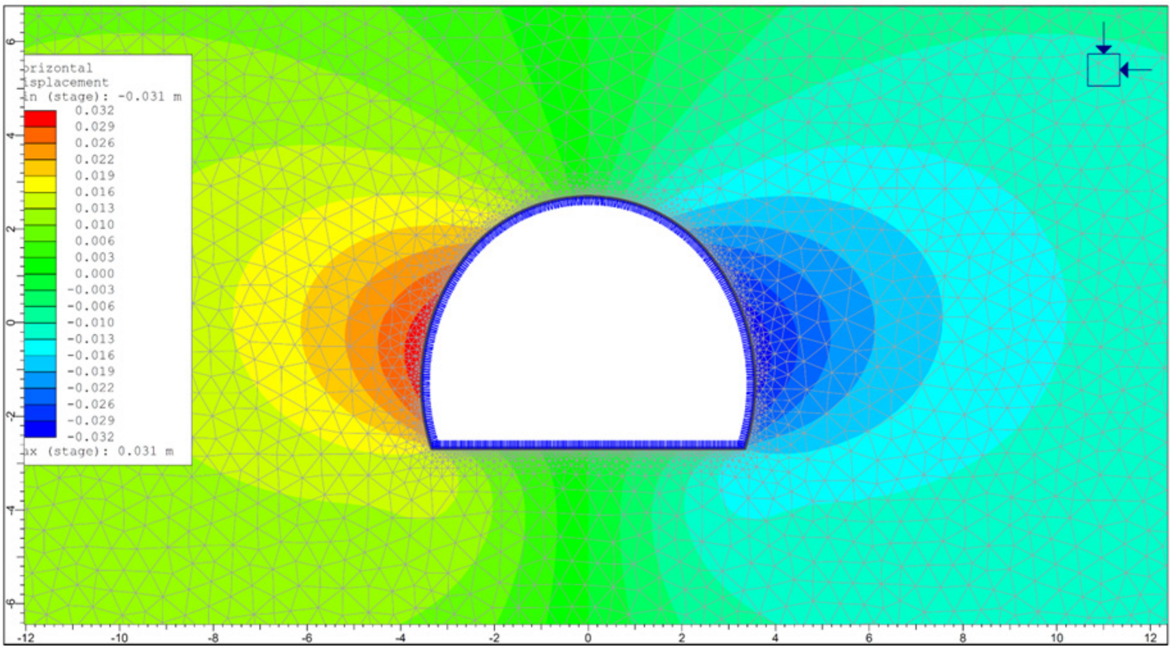

Figure 2. The output of the numerical modeling for one of the two distinct types of tunnel cross-sections in the study is presented below. The RQ4 cross-section with an approximate area of 33 m² with max 3.2 cm displacements.

In this range two different types of cross-sections were used in the numerical model (RQ1 and RQ4), even though the lithology remained unchanged based on the geological prognoses. The amount of displacement was calculated based on the predefined rock mass properties for this lithology. The results of the numerical modeling for each tunnel cross-section are displayed in Fig. 2 and 3, indicating only small differences in the displacements for each type of tunnel section.

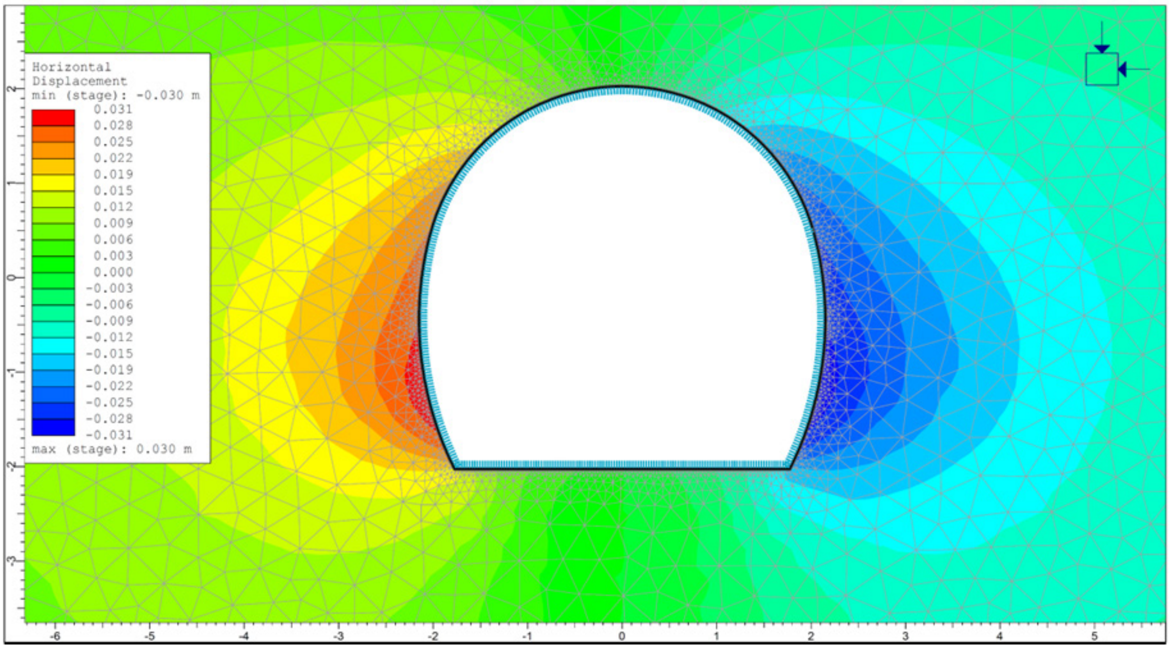

Figure 3. The output of the numerical modeling for distinct type RQ1 of tunnel cross-sections in the study is presented. The RQ1 cross-section of approximately 15 m² with max 3,1 cm displacements.

2.2 Optimisation of rock mass parameters with error function

The error function (equation 2) for back analysis was utilized to determine the discrepancy between the measured displacements in the fields and the displacement obtained from the modelling approach. This method allows for optimization of the geomechanical parameters. Based on the type of rock mass at each measurement section and the chosen constitutive model an optimal parameter combination can be obtained.

$$\text{Error} = \frac{\sum_{K=1}^{N} (u_k - u_k^*)^2}{\sum_{K=1}^{N} u_k^*} \tag{2}$$

In this equation u_k^* is the value of the measured displacement; u_k the calculated displacement (both at point k) and N indicates the number of measured points (Dehghan, 2013).

In geotechnical and underground engineering, validation and adaption of rock mass properties through back- and forward analysis is crucial. Back-analysis is used to validate and adapt internal rock mass properties by comparing deformation results of numerical simulation with measured field data, while forward analysis predicts the deformation behavior of a rock mass under given parameters. Both methods can be used together to validate and adapt assumptions and parameters used in analysis, resulting in better predictions and ultimately, in better suitable rock mass properties.

Table 2. Recalculated rock mass properties in for tunnel meter 135 -160 (for original values see Table 1).

Actual Rock mass Properties						
Uniaxial compressive strength N/m^2	Unit weight kN/m^3	Poisson ratio -	Friction Angel °	Cohesion N/mm^2	Modulus of Elasticity N/mm^2	TM M
30	26	0.3	32	0.6	4554	135
27	26	0.3	34	0.7	4850	140
25	26	0.3	30	0.6	4259	144
27	26	0.3	32	0.6	4580	148
29	26	0.3	34	0.7	4875	153
25	26	0.3	30	0.6	4302	159

A precise displacement measurement for each section was taken, and the error according to eq. 1 was calculated. Subsequently the parameters uniaxial compressive strength, friction angle, cohesion and modulus of elasticity were optimized and presented in Table 2. More appropriate parameters could be obtained in this way. Based on these findings, a review of the type of tunnel support structure was conducted.

3. SUMMARY

The main objective of this research is to validate and adapt geomechanical parameters used in the initial tunnel design, by utilizing back analysis during the construction phase. The study employs a combination of back analysis and forward analysis by numerical modeling techniques, based on measurements of deformation of the structure during construction. The displacement measurements are compared with the modelling results of the initial design.

Using an optimisation method, more suitable rock mass properties can be back calculated for the according tunnel sections. The numerical modelling approach further enables the optimization of the support system and the excavation method, by providing a better understanding of the rock mass behavior and how it will respond to the excavation and support system.

The implementation of these methods provides a suitable possibility of validation and adaption of traditionally obtained parameters through e.g. laboratory tests. The method is cost-effective, time-efficient, and enables to determination of rock mass properties, which is in general not possible in laboratory experiments performed on rock samples. This allows an optimization of the design close to real time from deformation measurement in the tunnel.

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