Back-analysis of rock mass parameters at the Semmering Base Tunnel based on the convergence confinement method

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ABSTRACT: The monitoring of geodetic targets installed at the tunnel lining provides reliable information on the system behaviour. At the Semmering Base Tunnel (SBT), engineers use the software package TUNNEL:Monitor to visualise monitored displacements and to make short-term predictions ahead of the face. A toolbox to apply the convergence confinement method (CCM) to the geodetic measurements has been incorporated into TUNNEL:Monitor for the purpose of back-analysing rock mass parameters post tunnel construction. This paper details the results of two case histories undertaken to assess the suitability of the back-analysis procedure implemented in TUNNEL:Monitor. Findings from the case studies confirm TUNNEL:Monitor is suitable for the back-analysis of rock mass parameters, provided the limitations associated with the procedure are well understood and the procedure is not extended beyond its applicability.

Keywords: TUNNEL:Monitor, Semmering Base Tunnel, back-analysis, displacement monitoring, convergence confinement method, anisotropy.

1 INTRODUCTION

Even with the introduction of more advanced monitoring techniques, the monitoring of geodetic targets remains the most common approach in underground construction across the globe. At the Semmering Base Tunnel (SBT), engineers use the software program TUNNEL:Monitor (2021) to visualise the displacement of geodetic targets and to process the recoded data for short-term predictions. A toolbox to apply the convergence confinement method (CCM) to geodetic measurements has been incorporated into TUNNEL:Monitor. The CCM is based on plane strain- and homogeneous rock mass conditions, and on an axisymmetric excavation- and support geometry. Despite these simplifications, the CCM allows for the back-analysis of rock mass parameters post tunnel construction (i.e. after the construction; excavation- and support parameters and final displacement values are known). The research presented in this paper studies the suitability of the CCM-approach (including the simplifications) implemented in TUNNEL:Monitor for the back-analysis of rock mass parameters (E, φ, and c); and its suitability for back-analysing anisotropic rock masses. Guidance on the application of the back-analysis procedure is also provided in the paper.

2 BACK-ANALYSIS PROCEDURE

The procedure for the back-analysis of rock mass parameters, as described in the paper by Schubert et al. (2010), utilises geodetic measurement records paired with the CCM detailed in the paper by Hoek et al. (2008). The purpose of the back-analysis procedure is for the verification of design parameters and assumptions made at the design stage, aiding in the excavation and support of proceeding tunnel sections, and in the design of future tunnels. If the back-analysis procedure does not return plausible rock mass parameter combinations, the designer may need to revisit the design parameters and assumptions.

The main assumptions of the CCM are that the tunnel is circular, the in-situ stress field is hydrostatic (i.e. equal stress in all directions), the rock mass is isotropic and homogeneous (i.e. failure is not controlled by major structural discontinuities), support response is elastic-perfectly plastic and modelled as an equivalent uniform internal pressure around the entire circumference of the circular tunnel (Hoek et al. 2008). The essential components of the CCM and the back-analysis procedure are detailed in Figure 1. The equivalent support pressure provided by the shotcrete lining (Ps; black vertical arrow in Figure 1) can be estimated using the following two components: a) the estimated shotcrete strength, at the time the displacement rate of geodetic targets cease, based on the temporal development of shotcrete strength equations defined by Hellmich (1999) and Macht (2002); and b) the estimated utilisation of the shotcrete lining based on the 'hybrid method' which is implemented in TUNNEL:Monitor and "…evaluates the strains in the shotcrete lining from the observed displacements and combines it with a thermomechanical constitutive model for shotcrete" (Proprenter & Lenz 2018). "The contribution of the rock bolting to the support resistance may be taken into account through the approximation that the bearing capacity of an anchor related to the anchor pattern corresponds to the support resistance. There are various references to this in the literature, including Hoek (1999)" (Schubert et al. 2010).

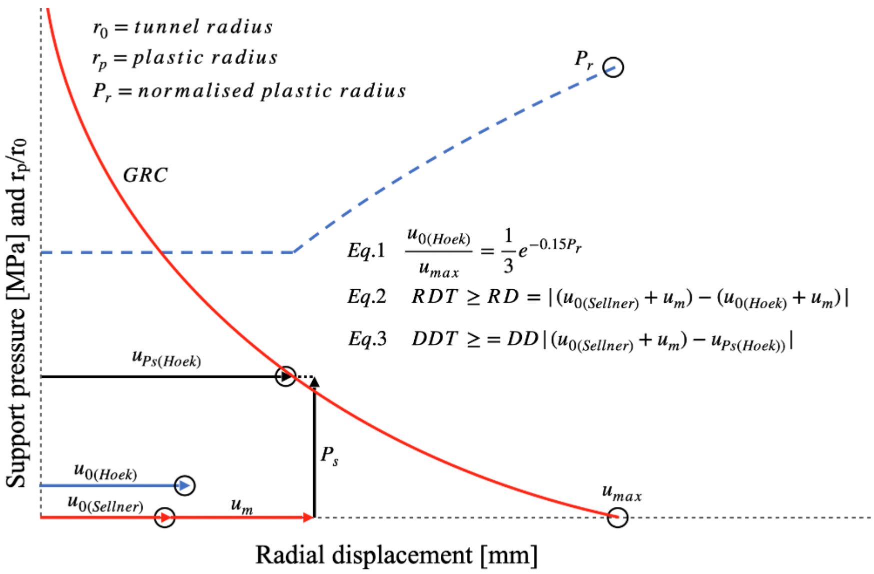

Figure 1. Essential components of the convergence confinement method and the back-analysis procedure.

The Ground Reaction Curve (GRC; red line in Figure 1) based on the analytical solution by Hoek et al. (2008) is derived using an initial set of rock mass parameters and returns the estimated maximum displacement at the boundary of the excavation in the unsupported condition (u_{max}). The normalised plastic radius ($P_r = r_p/r_0$; blue dashed line in Figure 1) is used to derive the ratio $u_{0(Hoek)}/u_{max}$ according to equation 1 detailed in Figure 1. For a given value of u_{max}, the pre-displacement value ($u_{0(Hoek)}$) can be obtained. The measured displacement of geodetic targets (u_m) is used to estimate the pre-displacement value ($u_{0(Sellner)}$) according to the prediction model by Sellner (2000). The prediction model "…enables very reliable short-term analysis of the displacements, taking influences such as support stiffness, various construction phases and their respective face positions and time into account" (Schubert & Radončić 2015). Only radial displacements are assessed; longitudinal displacements are not considered due to the CCM assumption of plane strain conditions. Plausible combinations of rock mass parameters (E, c, and ϕ) are obtained by applying tests to the returned combinations of rock mass parameters. The tests include the Ratio Difference (RD) and the Displacement Difference (DD), with the equations 2 and 3 for these tests detailed in Figure 1; $u_{(Ps(Hoek)}$ defines the evaluated displacement on the GRC at a support pressure equal to P_s. Tolerances are applied to both tests in order to limit the number of returned combinations of rock mass parameters, specifically the Ratio Difference Tolerance (RDT) and Displacement Difference Tolerance (DDT).

3 CASE STUDIES

To assess the suitability of the back-analysis procedure implemented in TUNNEL:Monitor, two case histories from the SBT project in Austria were analysed. Specifically, Case 1: Tunnel Gloggnitz, track 1, tunnel monitoring cross section (referred to herein as monitoring section) MS-1439, and Case 2: Access Tunnel Göstritz, monitoring section MS-214. MS-1439 is located within the core of the Eichberg fault system (Wagner et al. 2020), whereas MS-214 is located within the Grassberg-Schlagl fault zone (ÖBB 2017b). The basis for selecting these monitoring sections is that "within bigger fault zones isotropic conditions (lateral pressure coefficient $k_0 \approx 1$) regarding the primary stress state are predicted" (ÖBB 2014), making them more suitable for the CCM based back-analysis procedure.

3.1 Geology

The main difference between the two monitoring sections is that MS-1439 (Figure 2a) comprises near isotropic and homogeneous rock mass conditions, whereas MS-214 (Figure 2b) comprises anisotropic and near homogeneous rock mass conditions. The lithology of MS-1439 is dominated by tectonically intense sheared schists and phyllites. As a result of the intensive overprint along the fault system, the rock mass is sericitized and sheared and exists mostly as fault material (ÖBB 2017a). The fault system comprises disintegrated and weakened phyllite and schist to fine grained cataclasite rock. Shear bodies of different rocks (including dolomite and quartzite) with varying sizes up to m-size are present within the cataclasite. Bordering the fault core zone (Figure 2a – unit B) are strongly faulted sections with lower cataclasite content and spared zones (Figure 2a – units A and C) (ÖBB 2017a). The rock mass at MS-214 is dominated by moderately anisotropic, folded sericite phyllites (Figure 2b – unit B) and moderately to strongly anisotropic sericite schists (Figure 2b – unit C) (ÖBB 2016). Foliation planes (sericite phyllite and sericite schists) dip moderately to steeply towards the DOD and to the left (Northeast), resulting in out-of-plane anisotropy.

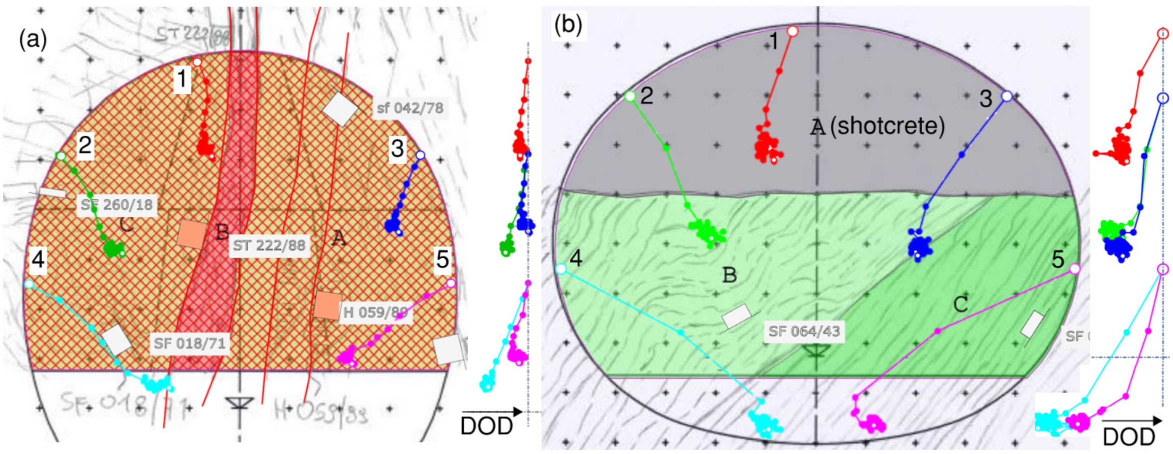

Figure 2. Geological mapping with vector plot (a) chainage 1439.2 m; (b) chainage 214.3 m. (Figures taken from ÖBB (2017a) and ÖBB (2016)).

3.2 *Tunnelling method and geodetic monitoring*

Both MS-1439 and MS-214 were excavated conventionally (according to the NATM), with the tunnel cross section split into a top heading (1 m and 1.3 m round length respectively) and an invert excavation (2 m and 4.4 m round length respectively); ring closure followed the top heading excavation at 16 m and 11 m respectively. Both monitoring sections had similar tunnel supports installed. Radial support for tunnel excavations consisted of a shotcrete lining, steel lattice girders, and grouted rock bolts. The temporary face support consisted of shotcrete and grouted rock bolts; spiles were installed to provide support in advance of the excavation. For the back-analysis, only the equivalent support pressure provided by the shotcrete lining was considered, with the support pressure provided by the radial rock bolts and lattice girders neglected due to the delayed installation of anchor plates and the negligible equivalent support pressure provided by lattice girders (compared to the shotcrete lining). For both MS-1439 and MS-214, the displacement rate of geodetic targets ceased shortly after installation of the tunnel invert lining, in which the top heading excavation was 16 m and 9 m ahead of the respective monitoring sections.

3.3 *Back-analysis settings*

The back-analysis carried out for both monitoring sections is limited to the measured displacement records of the five geodetic targets (locations shown Figure 2) installed following excavation of the top heading. The back-analysis is based on the simplification of a full-face excavation and an equivalent tunnel radius (based on the equal area method). For the back-analysis of MS-1439, only the average final measured radial displacement (u_m) and average pre-displacement (u_0) values were assessed. Due to the anisotropic rock mass conditions at MS-214, each geodetic target (five in total in the top heading) was back-analysed individually (target-wise approach). The search range of rock mass parameters was based on the upper and lower bound design parameter ranges of the rock mass types present, which was considered to adequately cover the possible range of rock mass parameters.

3.4 *Results*

MS-1439: As per the approach described by Schubert et al. (2010), returned combinations for MS-1439 (Figure 3) were narrowed down to plausible combinations using the relationship between pre-displacement and the measured displacement (in this case, u_0:u_m = 0.6:1.0) and the plausible range for the friction angle (in this case, φ = 23°- 27°) and cohesion (in this case, an upper bound of c = 0.8 MPa). As shown in Figure 3, the plausible range of rock mass parameters are within a similar range as the parameters specified in the design. The displacement behaviour at MS-1439 appears to be best represented by the strength parameters of the fault rock that boarders the core zone. However, it is most likely that the in situ strength and stiffness parameters of the rock mass at this monitoring section are a combination of both the core zone and fault rock that boarders the core zone, and that the assumption of mixed rock mass parameters for the back-analysis procedure is appropriate. The back-analysis procedure implemented into TUNNEL:Monitor is therefore considered appropriate for the determination of rock mass parameters at MS-1439.

MS-214: To obtain combinations of rock mass parameters for MS-214 (results in Table 1), the lower bound search range for the elastic modulus of the rock mass was extended below the design range according to design documents; the DDT and RDT values for MP-4 and MP-5 were increased (DDT = 10 - 15 mm, and RDT = 0.3 - 0.32) above that required for the other geodetic targets (DDT = 2 - 5 mm, RDT = 0.2 - 0.25). MP-4 and MP-5 (tunnel side walls) displaced against the DOD more than the other geodetic targets, with the left tunnel wall displacing more than the right. The radial and longitudinal displacement behaviour observed at MS-214 is likely due to the foliation planes present. Such out of plane displacement behaviour cannot be adequately captured by the CCM based back-analysis procedure, which is limited to in-plane radial displacement and isotropic rock mass. To overcome these limitations, each monitoring target was analysed separately. Furthermore, the back-analysis procedure cannot adequately return anisotropic rock mass parameters (parameters normal and parallel to the plane of anisotropy), instead 'smeared' parameters representative of the overall rock mass are returned. However, by comparing the orientation and dip angle of foliation to that of the DOD, the user may in 'simple cases' assess if the returned combinations of rock mass parameters are more representative of normal or parallel parameters. For Case 2, the orientation of foliation planes to the DOD can explain the displacement behaviour of monitoring points. Less radial displacement and more longitudinal displacement occurs at MP-1 (crown) because of slip along foliation planes that dip toward the DOD. Higher radial displacements occur at MP-4 and MP-5 (side walls) because displacements develop parallel to the foliation planes. Compared with MP-4 and MP-5, the returned elastic modulus for MP-1 is higher as a result of lower radial displacement. The displacement behaviour of MP-2 and MP-3 are between that of the crown and side walls.

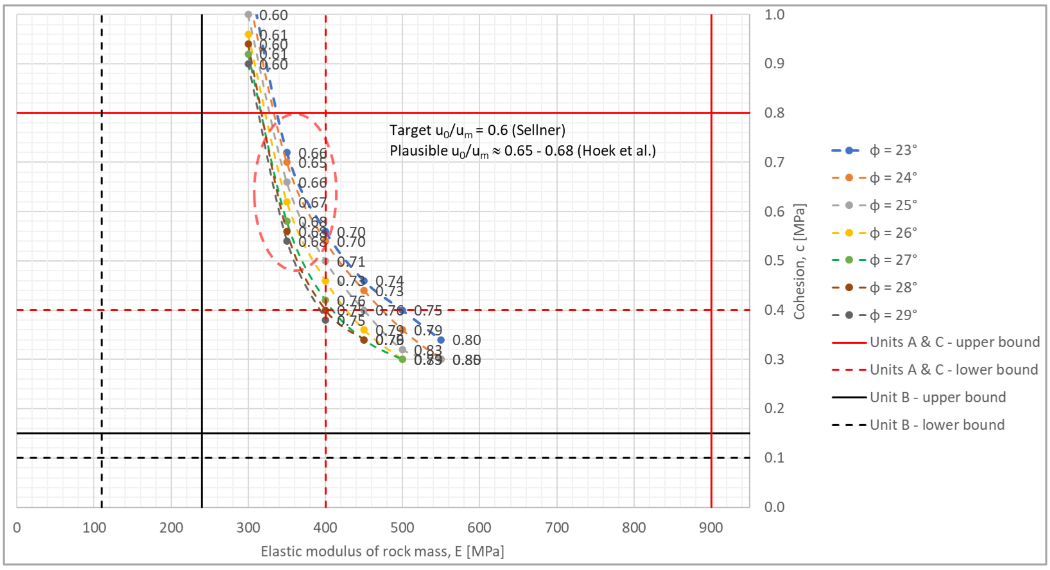

Figure 3. Case 1 - Back-analysed combinations of rock mass parameters. The value adjacent to each point is the ratio of $u_{0(Hoek)}$:u_m. (Figure taken from Martin (2022)).

Table 1. Case 2 – Design range and returned rock mass parameters (from back-analysis).

Parameter	Design Range	MP-1	MP-2	MP-3	MP-4	MP-5
E [MPa]	400 - 900	150	100	100	50	40
ϕ [°]	23 - 30	23 - 28	23 - 29	23 - 29	23 - 29	23 - 29
c [MPa]	0.4 - 0.8	0.4 - 0.5	0.5 - 0.8	0.5 - 0.8	0.7 - 0.8	0.7 - 0.8

4 GUIDANCE ON THE BACK-ANALYSIS PROCEDURE

As a minimum, to perform a suitable back-analysis good-quality monitoring data (reasonable accuracy and reading intervals) and suitable constitutive models for support (sophisticated methods such as the Hybrid method for shotcrete) are required. The fit quality of the pre-displacement value according to Sellner (2000) improves with additional geodetic measurement epochs. In general, the more ground conditions deviate from the CCM assumptions the less applicable the back-analysis procedure becomes. When possible, fixing at least one of the three rock mass parameters (E, ϕ, or c) prior to undertaking the back-analysis procedure is recommended. Use of the target wise approach allows for the assessment of anisotropic rock masses and identifying the tunnel location impacted most. Geological mapping records should be reviewed in conjunction with the back-analysis procedure. There are no set values for the RDT or DDT, however limits set by the user should be reasonable and consistent across multiple back-analyses. Early ring closure is best modelled as a full-face excavation, whereas late ring closure is best modelled on the initial excavation stage separate to subsequent excavation stages. Frequent back-analysis is recommended to understand which settings have the most impact on the returned results. For further guidance see Martin (2022).

5 CONCLUSIONS

As outlined in Section 3.4, the back-analysis procedure was successful for Case 1 with the returned parameters aligning with the design parameters. Whereas the returned elastic modulus values for Case 2 were lower than the design values. It may be that the Case 2 rock mass design parameters require reevaluation (back-analysis correctly applied), or that the back-analysis input parameters included errors (back-analysis incorrectly applied). Further evaluations of monitoring sections would likely shed light on the true cause of difference. The back-analysis procedure described in this paper is a simple, yet powerful tool provided the underlying simplifications and limitations are well understood and not extended beyond its applicability. Beyond the current version of TUNNEL: Monitor, the procedure could be further developed by automating the systematic back-analysis of rock mass parameters along the tunnel alignment, allowing the routine to be performed daily.

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