Tunnelling and Underground Space Technology 71 (2018) 215–222

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Angular dependence of rock cutting forces due to foliation

Martin Entacher[a,*], Erik Schuller[b]

[a] SSP BauConsult GmbH, Olympiastraße 39, 6020 Innsbruck, Austria
[b] Chair of Subsurface Engineering, Montanuniversität Leoben, Erzherzog-Johann-Straße 3, 8700 Leoben, Austria

ARTICLE INFO

Keywords:
TBM
Tunnel boring machine
Anisotropy
Foliation
Rock cutting

ABSTRACT

A series of rock cutting tests was conducted with three different metamorphic rock types. Samples were prepared with alpha angles of 0°, 45° and 90° to investigate the influence of foliation angle on the rolling forces ($F_{R,scaled}$) of a mini disc cutter (scale 1:8). Results show that $F_{R,scaled}$ increased by a factor of about 2 at an alpha angle of 0° compared to 90° for all three rock types. In a subsequent step, a way to implement the results into a TBM performance prediction model to derive a correction factor for angular dependence of TBM performance was shown. The resulting correction factor for overall TBM performance ($F_N0°/F_N90°$) is in the range of 1.33–1.80 which is in good agreement with previously published TBM field data by Büchi (1984) and Thuro (2002).

1. Introduction

1.1. Motivation

Reliable tunnel boring machine (TBM) performance prediction is an essential part of successful mechanized tunnelling operations. It is generally accepted that the net penetration rate is governed mainly by intact rock properties (e.g. σ_c, σ_t), rock mass parameters (e.g. joints, stress state) and machine parameters (e.g. power, tool geometry, spacing). The present study deals with the influence of foliation of metamorphic rocks on cutting forces. Strictly speaking it belongs to the category of intact rock properties. Due to the complex nature of rock anisotropy (described vividly by Barton and Quadros, 2014) there is no clear distinction between joint sets and anisotropic rock texture for many practical applications. Consequently, foliation was either disregarded or smeared into the category of rock mass parameters in existing performance prediction models.

Previous studies have indicated that rock foliation influences the net penetration by a factor of up to 2 (Büchi, 1984, see Section 1.2 for more details) depending on the angle relative to the cutting direction. Thus, a thorough investigation of the influence of rock anisotropy on mechanized excavation is strongly needed to improve existing models. This paper will contribute to the understanding of cutting anisotropic rock by presenting and interpreting results from scaled rock cutting tests on three different metamorphic rock types and show possibilities on how to use the results within existing TBM performance prediction models.

1.2. Related work

Rock anisotropy in the form of foliation, schistosity, bedding planes, layered rocks, cleavage, single joints or multiple systematic joint sets is ubiquitous in rock engineering (Barton and Quadros, 2014). In many cases it will lead to transversely isotropic mechanical behaviour which was extensively studied by many researchers. Shea and Kronenberg (1993) focused on unconfined and confined compressive strength (σ_c, CCS) of rocks with different mica contents, Nasseri et al. (2003) on Himalyan Schists, Cho et al. (2012) on Korean Gneiss, Shale and Schists, Gholami and Rasouli (2014) on Iranian Slates and Hou et al. (2015) on Shales. Comprehensive papers on σ_t testing (Brazilian tests) of anisotropic rocks were written by Cho et al. (2012) or Vervoort et al. (2014). Shear Testing of Shale was done by Heng et al. (2015) and Kim et al. (2012) focused on Young's modulus, P-Wave velocity and thermal conductivity of anisotropic Korean rocks. Earlier studies can be found in the references of these papers. The most recent comprehensive papers on anisotropic mechanical behaviour were published by Zhou et al. (2016), Chen et al. (2016) and Shi et al. (2016).

In uniaxial compression, the σ_c – orientation angle graph typically shows a strong U-shape (Asadi and Bagheripour, 2015) with the lowest strength values at 45° – φ/2 and the highest values at 90° (plane of anisotropy perpendicular to loading) or less often 0° (plane of anisotropy parallel to loading). As confinement increases (triaxial loading) the strength values increase and the curve starts to flatten out and the U-shape becomes less distinct. In contrast to that, the angular dependence of indirect tensile strength (σ_t) shows a different characteristic: The minimum strength values are found at 0°, the maximum values at

---

* Corresponding author.
E-mail addresses: entacher@sspbauconsult.at (M. Entacher), erik.schuller@unileoben.ac.at (E. Schuller).

http://dx.doi.org/10.1016/j.tust.2017.08.009
Received 20 December 2016; Received in revised form 10 July 2017; Accepted 5 August 2017

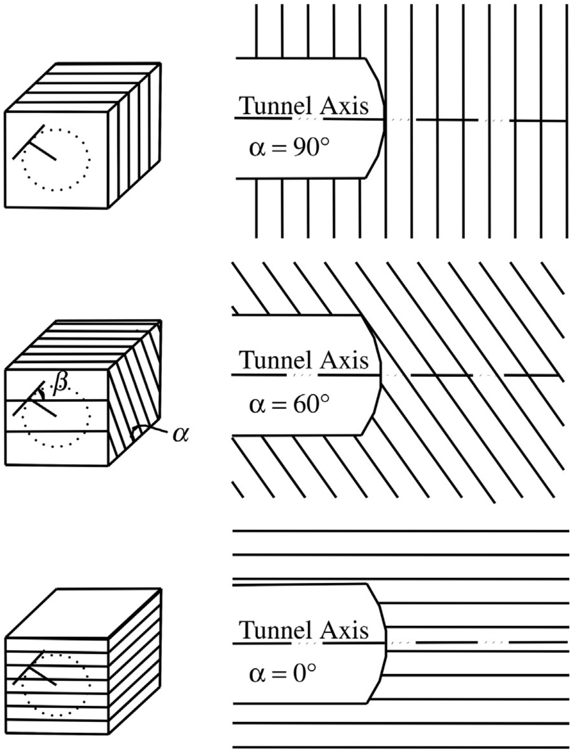

Fig. 1. Definition of alpha angle (Gong et al., 2005).

90°. For most rock types there is a steady increase between these two values without the U-Shape that is observed in σ_c testing.

Bridging the gap to mechanized tunnelling, many papers that deal with angular dependence of net penetration focus on joints. Analysis of field performance with respect to joints was done by Wanner and Aeberli (1979) or Yagiz and Kim (2010), numerical simulations were carried out by Gong et al. (2005), Bejari et al. (2011), Bejari and Khademi Hamidi (2013) or Zhai et al. (2016). These studies indicate that the relationship between joint orientation and achievable penetration rate is a reverse U-Shape. Hence, the influence of joint angle shows a slightly different characteristic than the influence of foliation angle. While the NTNU performance prediction model (Bruland, 1998) covers joints and fissures, the original CSM-Model (Rostami and Ozdemir, 1993) does not include rock mass effects. However, various suggestions for incorporating rock mass were made in the past (e.g. Yagiz, 2002).

Only few studies were published on the influence of foliation angle. Fig. 1 shows the definition of the foliation angles alpha and beta relative to the cutting direction. For the investigation of performance prediction only alpha needs to be investigated. Beta can have strong local effects (see for example Entacher et al., 2013) but evens itself out with every full rotation of the cutter along the face.

Selected data from previous studies are summarized in Fig. 2. Fig. 2a and b are actual TBM field data (modified from Büchi, 1984; Thuro, 2002), c and d show mean normal forces recorded during full scale linear cutting machine (LCM) tests (modified from Sanio, 1985; Ho-Young et al., 2011). All data were normalized to one to show the relative increase with changing alpha angles. Additional roadheader and wedge penetration data can be found in the referenced papers. The PhD thesis of Büchi (1984) deals extensively with the influence of anisotropy on TBM performance. It contains TBM performance data from a tunnel in mica gneiss (Fig. 2a). One data set with a performance increase due to foliation angle of up to more than *+100%* (data extrapolated) is limited to a small subsection where rock anisotropy could be isolated from other disturbing influences. The evaluation of a much larger section (i.e. the whole tunnel) showed the same trend but much more conservative values (*+33%*). Fig. 2b shows TBM field data in phyllite (*+85%*) and phyllite-carbonate-schist interstratification (*+37%*) published by Thuro (2002). Again, the TBM performance increases as the alpha angle increases. The shapes of the curves and also the magnitudes show a similar trend compared to Buechi's results. The results of indentation tests from Sanio (1985) confirm this typical relationship. Sanio also carried out linear cutting tests (LCM – Linear Cutting Machine) on two different rock types which are shown in Fig. 2c. Finally, a recent study from Korea (Ho-Young et al., 2011) compares the results from 0° to 90° linear cutting tests on Asan Gneis (Fig. 2d). The mean normal forces were normalized to 1 in Fig. 2c and d for better illustration. The influence of rock anisotropy was also investigated by means of numerical simulation by Schormair (2010).

From the results shown in Fig. 2 it can be seen that the influence of the foliation angle on performance is consistent in the publications of Büchi (1984), Thuro (2002), Sanio (1985) and Ho-Young et al. (2011). (Note that the graph's shape for a normal force increase is inverted compared to a factor for TBM performance, i.e. penetration.) The shape of the relationship between TBM performance and alpha angle is very similar to the relationship between tensile strength obtained from Brazilian tests (σ_t) and loading direction (see Fig. 4). It is however not similar to relationship between σ_c results and loading angle (U-shape). Sanio (1985) concluded that the influence of anisotropy can be calculated easily from the anisotropy factor obtained from tensile tests (or Point load tests which correlate strongly with both σ_t and σ_c). The anisotropy factor is the ratio between the highest and lowest strength value with respect to the angle between plane of anisotropy and loading direction. Despite this statement even Sanio's own data do not show a consistent correlation between anisotropy factor and wedge indentation or linear cutting results. Further investigations to determine the magnitude of the influence are needed.

2. Material properties and testing procedure

2.1. Material properties

Three different metamorphic rock types were investigated. Their strength parameters, Young's modulus, specific weight and mineral composition are listed in Table 1. Uniaxial compressive strength tests were carried out load-controlled until elasticity parameters were obtained. Young's modulus was determined as the secant modulus of an unloading/loading loop. The control parameter was then switched to circumferential strain to investigate post-failure behaviour. The plane of anisotropy was perpendicular to the loading direction for all σ_c tests. Stress-strain curves from uniaxial compressive strength testing and corresponding photographs of the rock texture are shown in Fig. 3.

Brazilian tensile strength (σ_t) was determined according to the ISRM Suggested Methods (Ulusay and Hudson, 2007). The tests were carried out load-controlled with a loading rate of 1.2 kN/s. The angle between loading direction and foliation was 0°, 45° and 90° for Stainzer Hartgneis (SHG) and Luserna Gneis (LG) and 0° and 90° for Amphibolite (AM). The number of tests was chosen according to the standard deviation. LG testing was finished after 3 tests per angle (small standard deviation) while 5–6 tests per angle were needed for SHG and AM to achieve reliable results.

Fig. 4 shows the results of Brazilian tensile testing in absolute (MPa) and relative values (Anisotropy Factor AF). The relative values were obtained by dividing all results by the mean value of the 0° tests. LG showed by far the strongest anisotropy factor and the smallest scatter with an AF of 3.77. SHG's (AF = 1.98) and AM's (AF = 1.80) anisotropy factor is less pronounced and the test results have a few outliers. The relationship between indirect tensile strength and foliation angle is very similar to the relationships observed in Fig. 2. In view of Sanio's (1985) findings and the supposedly significant influence of tensile strength on rock breakage it could be expected that the results of the scaled rock cutting tests will correlate with the results shown in Fig. 4.