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Full Length Article

Hard rock tunnel boring machine penetration test as an indicator of chipping process efficiency

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A R T I C L E I N F O

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A B S T R A C T

The transition from grinding to chipping can be observed in tunnel boring machine (TBM) penetration test data by plotting the penetration rate (distance/revolution) against the net cutter thrust (force per cutter) over the full range of penetration rates in the test. Correlating penetration test data to the geological and geomechanical characteristics of rock masses through which a penetration test is conducted provides the ability to reveal the efficiency of the chipping process in response to changing geological conditions. Penetration test data can also be used to identify stress-induced tunnel face instability. This research shows that the strength of the rock is an important parameter for controlling how much net cutter thrust is required to transition from grinding to chipping. It also shows that the geological characteristics of a rock will determine how efficient chipping occurs once it has begun. In particular, geological characteristics that lead to efficient fracture propagation, such as fabric and mica contents, will lead to efficient chipping. These findings will enable a better correlation between TBM performance and geological conditions for use in TBM design, as a basis for contractual payments where penetration rate dominates the excavation cycle and in further academic investigations into the TBM excavation process.

1. Introduction

It is generally accepted that during hard rock tunnel boring machine (TBM) excavation, a cutter first creates a crushed zone at the cutter-rock interface and the stresses from the thrust of the cutter are transmitted through this crushed zone into the adjacent undamaged rock (Snowdon et al., 1982; Bruland, 1998; Cigla et al., 2001; Zhang, 2001; Rostami et al., 2002). The induced stresses and dilation within the crushed zone cause tensile fracturing of rock away from the crushed zone. Eventually, fractures generated by subsequent cutter passes extend either to the rock surface or to the fractures propagating from adjoining kerfs and coalesce to form chips. This occurs at different cutter thrust magnitudes for different rock types. If the cutter thrust necessary for tensile fracture propagation is not achieved, due to excessively high cutter thrust requirements or an underpowered TBM, then only grinding at the crushed zone occurs. Grinding produces only fines, rather than chips, leading to much lower penetration rate. Chipping is a more efficient excavation process because generating chips through tensile fracturing is much more efficient than the formation of fines in the crushed zone (Teale, 1964; Snowdon et al., 1982; Bruland, 1998; Gertsch et al., 2007; Yin et al., 2014). The formation of chips by the chipping process is therefore critical for achieving high penetration rates.

Endeavours to develop penetration rate prediction formulas using net cutter thrust for intact rock (Robbins, 1970; Bruland, 1998) and jointed rock masses (Barton, 2000; Bieniawski et al., 2006; Sapigni et al., 2002) demonstrate the value of analytical methods to predict penetration rate for design and performance assessment. Maidl et al. (2008) showed that weaker rocks required lower thrust to achieve the same penetration rate as stronger rocks using a penetration rate versus thrust schematic loosely based on Robbins (1970). Recently, several prediction models have also been proposed to determine relationships between TBM performance and rock mass characteristics (Sapigni et al., 2002; Alber, 2008; Gong and Zhao, 2009; Hassanpour et al., 2011; Farrokh et al., 2012).

This research explores what TBM penetration testing can show the excavation process. Based on the early works by Villeneuve (2008) and Frenzel et al. (2012), penetration tests are defined

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and corresponding values are demonstrated for TBM performance analysis. Geological characteristics are linked to the chipping process identified with the penetration tests. TBM operational data and results from penetration tests are analysed to provide feedback to TBM operators about whether excavation is occurring efficiently through chipping or inefficiently through grinding. Then TBM penetration test results are used to identify areas of stress-induced face instability. Finally, TBM penetration test data are demonstrated for further understanding of relationships between rock strength, geological characteristics and chipping process.

2. Methods and materials

2.1. Penetration test methodology

We performed a total of 16 penetration tests in three different rock units in the Swiss Alps: schist, granite and gneiss, using three Herrenknecht hard rock gripper TBMs with a range of 8.83–9.58 m in diameter. All TBMs utilised 432 mm diameter cutters with 90 mm spacing on centre. During normal TBM start-up, only a few data points at low penetration rates were recorded by the data acquisition system (DAS) due to the sampling interval (typically 0.1 s). In order to capture sufficient data through the full range of penetration rates, penetration tests were adopted (Villeneuve, 2008; later described in detail in Frenzel et al., 2012), and conducted by gradually increasing the TBM thrust from full stop to the maximum thrust over a period of 8–10 min. The cutterhead rotational speed (RPM) was kept constant during these tests, typically ranging from 5.5 rpm to 6.2 rpm, and was selected based on the face condition (i.e. it would be higher in stable face conditions than that in blocky face conditions). Depending on the operator, RPM and rock type, the length of tunnel tested is approximately 30–200 mm.

The penetration rate (mm/rev) is used in this investigation, rather than speed (mm/min), because this removes the effect of RPM and allows comparison of test results from different strokes. The thrust value obtained from the DAS is gross thrust, which is the amount of force exerted by the thrust pistons. This thrust incorporates friction on the TBM head, which is independent of cutting processes occurring at the tunnel face. The net cutter thrust is used, which is the gross thrust minus the frictional losses, divided by the number of cutters, to allow comparison of test results from different locations and different TBMs. The friction contribution to gross thrust is estimated by averaging the gross thrust required to reverse and advance the TBM cutterhead (i.e. moving the cutterhead when it is not touching the rock at the face, usually during cutter changes). The gross thrust also includes the impacts of TBM stiffness and the losses in the hydraulic systems, but these should remain constant for any TBM.

2.2. Geological materials

At test locations, geological and geomechanical data were collected from the exposed rock walls, the chips on the conveyor system and through exploratory core drilling ahead of the tunnel face. Lithology and rock mass characteristics were recorded by mapping the tunnel walls, logging the core, when available, and collecting chips and wall samples at regular intervals. Each rock unit was encountered over a tunnel length of hundreds of metres and has variability at the metre to tens of metres scale in terms of mineralogy, grain size and fabric. These investigations were conducted in unweathered, massive rock masses (Fig. 1a–c) in order to focus on the relationship between intact rock strength and rock cutting process. In these rock masses, TBM performance is dominated by intact rock fracturing processes, rather than rock mass failure processes associated with pre-existing fractures and joints, such as those reported in Sapigni et al. (2002) and Hassanpour et al. (2011, 2015). Due to the tunnel depth (1800–2500 m), the stresses in the face commonly led to spalling and face instability (Fig. 1d), which was not necessarily associated with spalling in the walls (note the cutter kerfs in the gauge area of the face shown in the upper right corner of Fig. 1d).

The schist and granite in this study are generally foliated, with varying intensities of schistosity (Fig. 2a, c and d). Foliation, when present, is consistently dipping steeply and nearly parallel to the tunnel face, with spacing at the scale of tens to hundreds of millimetres. The gneiss in this study has banding (Fig. 2b), which is subhorizontal, with spacing also at the scale of tens to hundreds of millimetres. All of the lithologies are typically composed of quartz, potassium-feldspar, plagioclase and micas, with minor components of alteration minerals, such as chlorite, sericite and pyrite (Villeneuve, 2008). The mineral composition of the schist is typically 25–30% quartz, 50% feldspar and 25–35% mica. More micacious sections of the schist contain 30% quartz, 30% feldspar and 40% mica. The average quartz content in the granite is 30%, with feldspar content around 50% and mica content around 20%. Some less foliated sections contain around 50% quartz, nearly 50% feldspar and less than 5% mica. More micacious sections of the granite contain less than 15% quartz, nearly 50% feldspar and over 40% mica. The mineral composition of the gneiss is typically 35% quartz, 55% feldspar and less than 10% mica.

Point load index strength tests were performed on cores sampled ahead of the tunnel face in the granite. If such cores were not available, uniaxial compressive strength (UCS) was obtained from cores sampled and tested by the contractor from tunnel walls in the schist and granite (Table 1). No strength values are available for the tests in the gneiss. The UCS results did not include elastic modulus or tensile strength. Uniaxial compression tests were not always conducted on samples from the same locations as the penetration tests. Thin section analyses of rocks from uniaxial compression test locations and penetration test locations were utilised to select the most appropriate UCS value (if there were several UCS values near a penetration test site). For Granite 4, the nearest UCS values do not correspond to the lithology encountered during the test so the point load index strength value from a sample at the test location was converted to UCS according to the ratio of point load index strength to UCS for that lithology derived in Villeneuve (2008).

3. Penetration test results in Alpine schist, granite and gneiss

The penetration rate and net cutter thrust data from a penetration test are plotted against each other to obtain a penetration curve for each test, as shown in Figs. 3–5.

The common logarithms of both penetration rate and net cutter thrust can be plotted (Figs. 6–8) to derive the penetration coefficient (PC) and critical thrust (M_1, in kN) to obtain the penetration rate of 1 mm/rev as defined by Bruland (1998). The linear regression of the logarithm curves is defined by Bruland (1998) as

$$\log_{10} i_0 = A_R \log_{10} M_1 + B_R \tag{1}$$

where i_0 is the penetration rate, and A_R and B_R are the regression constants (as indicated in Figs. 6–8). Bruland (1998) showed that PC is equal to A_R, while M_1 can be found by solving Eq. (1) for $i_0 = 1$ mm/rev. The values of PC (or A_R), B_R, and M_1 for the penetration tests obtained in this study and those from two marble samples tested in Yin et al. (2014) and one granite sample tested in Gong et al. (2007) are given in Table 2.