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On the definition and classification of mixed face conditions (MFC) in hard rock TBM tunnelling

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Abstract

The further development of Tunnel Boring Machines (TBMs) has led to an increasing applicability of this excavation technique in an progressively wider range of rock mass conditions (e.g. increasing rock strength and abrasivity, stress conditions…), as well as, driving lengths and machine diameters. However, the evaluation of potential TBM application, estimates on performances, tool wear, construction time and overall construction costs still remain a demanding task for clients, consultants and contractors in the course of many TBM projects.

Mixed Face Conditions (MFC) play a significant role in judging on the applicability of a TBM. There is a lack for a clear definition of MFC, even though that today MFC may be mentioned and quantified in tender documents. MFC is defined by areas of significantly different boreability at the tunnel face. Direct consequences of a MFC are damaged cutter discs and cutter bearings, hubs and saddles, the overall lifetime of cutters, all of it demanding more frequent cutter controls and changes. In addition, MFC causes increased vibrations and dynamic loading of the cutterhead and the main bearing. Indirect consequences to TBM operation due to minimizing damages are the reduction of the thrust and / or the cutterhead rotation speed, both affecting TBM performance. So, a MFC is a handicap for TBM tunnelling which influence penetration rate, cutter consumption, provokes potential TBM damages, and consequently daily advance rates and excavation cost in a negative way.

The present paper comprises and discusses the current state of knowledge regarding the definition and identification of MFC in hard rock TBM tunnelling. It introduces concise definitions and a new methodological approach for MFC classification based on empirical analysis of outstanding TBM projects which can be used as a viable contractual solution of MFC evaluation.

Keywords

TBM Tunnelling, Hard Rock, Mixed Face Conditions (MFC)

ISRM

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1 Introduction: MFC and hard rock TBM tunnelling

The Tunnel Boring Machine (TBM) method has led to an increasing applicability in a progressively wider range of rock mass conditions (e.g. increasing rock strength and abrasivity, stress conditions...), as well as driving lengths and machine diameters. However, the evaluation of potential TBM application, estimates on performances, tool wear, construction time and overall construction costs still remain a demanding task for clients, consultants and contractors in the course of many TBM projects.

Performance and cutter wear estimates in hard rock TBM tunnelling are usually based on empirical models which have been developed for typical tunnel boring in systematic fractured rock masses. However, special effects, like "blocky" ground condition or "Mixed Face Conditions" do indeed present special processes in the interaction between cutter head and rock mass, which have an significant impact on performance, tool wear and, consequently, on construction time and costs.

MFC is a handicap for TBM tunnelling which influence penetration rate, cutter consumption, provokes potential TBM damages, and consequently daily advance rates and excavation cost in a negative way (Fig. 1).

Fig. 1: Underground rehabilitation works in front of a severely worn cutterhead.

For many years it is common practise that the tender documents indicate and quantify the rock strength and fracturing degree of the rock mass specified for different sections along a tunnel project. Rock strength and fracture classes represent the main geotechnical input parameters for best known predictor models. Tender documents however hardly provide indications for MFC or only in an indirect way and not quantified combined with a clear definition. Consequently, MFC often may result in claims for "unforeseeable or differing geological site conditions".

This paper comprises and discusses the current state of knowledge regarding the definition and identification of MFC in hard rock TBM tunnelling. It presents a definition for MFC combined with a basic quantification and classification (three classes. low – medium – high MFC) with the goal to be assessed by the geologist at tender stage/documents and subsequently to be characterized during actual tunnelling by engineering geological evaluation (e.g. engineering geological mapping at tunnel face or tunnel wall: back-mapping, chip analysis…).

2 Mixed Face Conditions (MFC): Current State of the Art

2.1 Definitions and identification

The general understanding of a Mixed Face Conditions (MFC) is a situation, where two or more rock mass bodies with significantly different boreability are encountered at the same tunnel face. It is common understanding that all cutters on the cutterhead have to achieve the same penetration rate per one revolution whether cutting through hard or soft rock, massive or closely fractured rock mass or no cutting work at all due to local overbreak at tunnel face. Under such conditions, overloading of cutters and high peak loads might occur, which do not stop a typical hard rock TBM of today's state of the art design, but might cause significant negative effects to TBM performance (i.e. m/day), wear (i.e. cutter consumption, cutters/m³) and excavation cost.

However, until the present date there is no generally accepted definition of Mixed Face Conditions in hard rock TBM tunnelling. A review of existing research and standards gives the following picture:

MFC have originally been described for TBM advances in soils. The presence of cohesive and non-cohesive soil at the face or the occurrence of soil and rock at the face was titled MFC by Fowel and Johnson (1981). Later, several researchers have analysed MFC in rock tunnelling. Some of them are Büchi (1992), Bruland (1998), ITA (2000), Blindheim et al. (2012), Streingrimsson et al. (2004), Toth et al. (2013) and Alber et al. (2018).

The Austrian standard for underground works for TBM tunnelling (ÖNORM B2203-2, 2013) describes MFC as the simultaneous occurrence of continuous strata with "significantly differing" boreability, but without providing classification or quantification.

Basic approaches for definition and quantification of MFC have focussed on contrast of intact rock strength at the tunnel face (usually determined by the rock´s Unconfined Compressive Strength, UCS). UCS ratios (ratio between weakest and strongest material) of approximately 1/10 have in the past been used in order to define and identify MFC according to Streingrimsson, (2002) and Toth et al. (2013) among others.

However, the interactions taking place during the excavation of heterogeneous rock are often complex and more factors than just rock strength contrasts may play a role for the excavation processes. Recently, Alber et al. (2018) have applied a broader focus on the problem, including contrasts in fracture spacing and face instabilities. Alber et al. (2018) argue, that under circumstances, where larger parts of the face have been removed due to structurally controlled failure or high in-situ stresses (typically resulting in rock spalling or rock bursting), theoretically indefinite boreability contrasts evolve between the "holes" and the still remaining parts of the face, leading to typical Mixed Face effects.

As a resume of the existing literature, the authors conclude that UCS ratios below 1/10 ratio causes impact on TBM tunnelling in hard rock and those situations should be considered for the definition and identification of MFC. In addition, UCS alone may have shortcomings as a parameter used to characterise rock boreability.

2.2 Challenges and consequences of MFC in hard rock TBM tunnelling

Today typical hard rock TBMs are applying 17" or 19" cutters with a specified maximum cutter load of 260kN and 315 kN respectively. This cutter load is defined as a maximum applicable load and not as an average load level to be applied. Actual projects indicate that in typical hard and massive rock and average cutter load of 80 - 85% can be expected. This will allow for acceptable variations of the cutter loads as described above and result in good lifetime for cutters as predictable in advance by predictor models and verified in practise.

The basic consequence of a Mixed Face Condition is, that cutters cutting through "harder" sections do consume more cutter load to achieve the same penetration of those cutters cutting through "softer" rock sections. Also, cutters with no contact to the rock due to local overbreak at the tunnel face cannot absorb any thrust force and consequently their portion is distributed to the other cutters.

All these situations result in uneven loading of a single cutter which range from no load (overbreak) to reduced load (softer and / or closely jointed rock) to potential overloading for penetrating in harder, massive rock. In addition, any abrupt change from soft to hard or from not too high cutter load leads to significant peak loads. The latter are considered responsible for increased vibrations to the cutterhead and its main-bearing. Extreme peak-loads are caused as well in case of blocky ground: big rock blocks fall out from tunnel face due to structurally and/or stress induced situations. The cutterhead then operates like a crusher instead of cutting the rock by rolling cutters.

As a summary, the "direct" consequences of MFC include:

- Impact loading on a cutter disc when approaching a rock area with lower boreability from an area with better rock boreability;
- Enhanced dynamic loading and vibrations at the cutterhead, at the main bearing and at the TBM main body;
- Increase of cutter wear due to impact loading, the typical abrasive wear of discs is not dominant anymore due to an increased portion of failed cutters.

General experience for TBMs with a diameter > 4.5m indicates a 10 – 15% of cutter failures in case of very abrasive rocks (e.g. Quartzite, gneiss, granite…: CAI $\geq$ 4.25 and/or CLI < 8). In case of low rock abrasivity (e.g. limestone, shale, marble…: CAI $\leq$ 2.5 and/or CLI > 35) cutter failures may result in 15 – 20% due to extended rolling distance per cutter ring. In case of typical MFC the portion of failed cutter may increase to 35 – 50%.

In addition, the TBM operation, when possible, and machine/cutters maintenance need to be adapted to the MFC, the following "direct and indirect" consequences can result in lower TBM penetration rates (m/h) and an increase of downtime – non-productive time per working shift due to:

- Reduction of the cutterhead's rotational speed;
- Reduction of applied thrust;
- Increase in scheduled inspection of cutterhead and discs;
- Increase in unscheduled disc changes. during production shifts instead of maintenance shift. These may even have to be executed during a stroke and are strongly influencing the TBM performance
- Extended maintenance shift due to additional works – more cutters and scrapers to change, more intensive repair work
- More frequent overhauling of cutterhead: downtime for several days
- Increased spare part costs for cutter rebuild work – reduced overall life-time of cutters/ cutter bearings
- Increased maintenance costs for TBM and muck transportation system (problems with conveyors)

It is important to recognise that all these aspects delaying the project and increasing production costs are not new but are clearly accentuated due to MFC. In addition, their influence to tunnelling performance can hardly be calculated at tender period if not clearly defined in tender documents.

So, as above discussed, MFC is a handicap and geological risk for hard rock TBM tunnelling which severe consequences in daily advance rates and excavation cost. Therefore, MFC need to be identified and characterized at early stages of the projects (tender stage/documents) and subsequently during actual tunnelling by face mapping.

3 New methodology for identification and classification of MFC in hard rock TBM tunnelling

3.1 Identification of MFC

The identification of MFC during hard rock TBM tunnelling should be done based on engineering geological evaluation (e.g. engineering geological mapping at tunnel face or tunnel wall, chip analysis…).

The definition of Mixed Face Conditions (MFC) in hard rock TBM tunnelling is the following: *"MFC in hard rock tunnelling occurs in case of the existence of two or more rock mass bodies with significantly different boreability parameters encountered at the tunnel face and occur at the interaction of cutterhead and rock mass while cutting the rock. A MFC is a handicap for TBM tunnelling which affects the operational parameters, penetration rate and / or affects the cutter consumption and/or affects TBM cutterhead or main body".*

Boreability is defined as the resistance (in terms of ease or difficulty) encountered by a TBM as it penetrates a rock mass composed of intact rock containing planes of weakness. Boreability is a combination of Drillability (intact rock) and rock mass fracturing (rock mass). The authors would like to include local over-breaks (e.g. rock face instability, blocky ground…) at tunnel face to the term MFC: representing an extreme situation. Fig. 2 shows examples of identification of potential MFC.

Fig. 2 Examples of identification of potential MFC left photo: core drilling indicating contact between sandstone (UCS ~ 100 MPa; low degree of fracturing) and lutite (UCS ~ 15 MPa; highly fractured), right photo: field mapping indicating potential MFC due to blockiness.

The evaluation of MFC in hard rock TBM tunnelling is based on:

- Rock Strength;
- Degree of fracturing;
- Blockiness;

3.2 Classification methodology for the of MFC

The methodology for classification or categorization of the potential of MFC in hard rock TBM tunnelling is carried out based on the above listed rock mass characteristics, rock strength, degree of fracturing and occurrence of blockiness using a rating system (MFC rating).

The MFC rating is the resultant of the strength factor (k_{UCS}) plus the fracturing factor (k_f) or blocky ground factor (k_b). The ratings for MFC would only be applicable in case the smaller tunnel section with different boreability corresponds at least to width of three times the face-cutter spacing (as a layer or dyke) or represent an area of >15% of the total tunnel cross-section. Finally, the resulting rating is adjusted according to the TBM diameter.

$$MFC\ rating = \left[k_{ucs} + k_f\ (or\ k_b)\right] \cdot k_D$$

- Strength ratio factor (k_{ucs})
- Fracturing factor (k_f) or blocky ground factor (k_b)
- TBM diameter factor (k_D)

The larger the MFC rating, the more probable will be the occurrence of MFC and relevant the consequences. The classification is introduced (Table 1) based on three levels: low, medium and high.

Table 1 Classification of the potential and consequence of MFC (low, medium and high) based on the proposed rating methodology.

MFC rating classification	MFC rating range
Low	1 – 35
Medium	35 – 65
High	65 - 100

*Maximum MFC rating is limited to 100.

3.2.1 Rock Strength ratio factor

The rock strength is evaluated on the basis of the Uniaxial Compressive Strength (UCS) according to ISRM (1979). Fig. 3 shows the relationship between the UCS at the "hard" geomechanical area and the ratio UCS between hard/soft geomechanical areas. The values are the minimum to be considered for the identification of MFC based on rock strength. The higher the UCS at the "hard" geomechanical area, the lower is the ratio "hard/soft" which is identified as MFC.

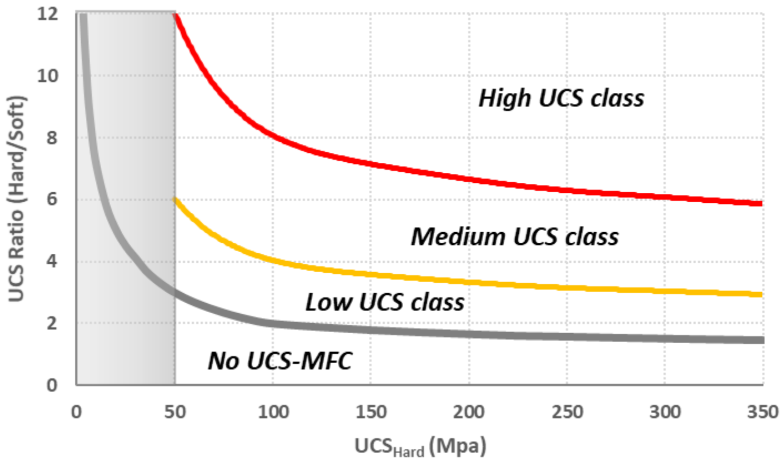

Fig. 3 Relationship between the UCS at the "hard" geomechanical area and the ratio UCS between hard/soft geomechanical areas

Table 2 shows the ratings to apply for every UCS class above described.

Table 2 Rating for the UCS ratio classes

UCS ratio Classes	Rating
No UCS ratio - MFC	0
Low UCS ratio class	10
Medium UCS ratio class	20
High UCS ratio class	40

3.2.2 Fracturing factor (k_f)

The general level of degree of fracturing and the distinction between the geomechanical areas at the tunnel face is evaluated based on the average spacing (cm). High degree of fracturing results in greater rock mass boreability. Table 3 shows the proposed fractures classes based on the average spacing (cm) in systematic fractured rock masses defined for MFC classification.

Table 3 Fractures classes based on the average spacing (cm) defined for MFC classification in case of systematic fracturing

Fracture classes	Average spacing (cm)
X	> 80 cm
Y	20 – 80 cm
Z	< 20 cm

Table 4 shows the rating based on the combination of proposed fracture classes.

Table 4 Rating based on the combination of the proposed fracture classes

Combinations of fracture classes	Rating
XX, YY, ZZ	0
XY, YZ	20
XZ	40
Overbreaks*	40

The rock strength (UCS), of the area with facture class X will be relevant. Table 5 shows the correction factor for strength of the rock (UCS, MPa) of the rock area with fracture class X.

Table 5 Correction factor for strength of the rock (UCS, MPa) of the rock area with fracture class X

Rock strength Classes - X	Correction factor
< 100 MPa	0.7
100 – 200 MPa	1.0
> 200 MPa	1.5

The fracturing factor k_f is the resulting of the rating from the average spacing (Table 4) corrected by the coefficient based on the rock strength (MPa) of the rock area with fracture class X (Table 5).

3.2.3 Blocky ground factor

Blockiness would be applicable for voids at the face representing an area of >15% of the total tunnel cross-section and voids larger than an equivalent of two cutter spacings. The blocky conditions are defined in three classes: low class (overbreak), medium class (Large blocks: 0.5 – 1 m3) and high class (Large blocks: > 1 m^3). The large blocks would have a minimum rock strength (UCS) of 100 MPa. Table 6 shows the blockiness classes and the corresponding rating (k_b).

Table 6 Rating for blockiness

Blockiness classes	Rating (k_b)
Low class - Overbreak*	40
Medium class - Large blocks: 0.5 – 1 m^3	60
High class - Large blocks: > 1 m^3	80

3.2.4 TBM diameter factor

Larger TBM diameters (e.g. 8 - 12 m) have lower density of cutters than small TBM diameters (e.g. 3 - 5 m). Still, larger TBMs have usually twice the number of cutters and thus more cutters will be influenced by the presence of a layer or dyke. Machine and cutterhead stiffness are difficult to achieve for large diameter TBMs. Maximum rolling cutter disc velocity is similar for all TBM diameters. In summary, more severe damages are considered in larger TBM diameters due to larger area exposed (e.g. cutterhead wearing and damages, main bearing damages…). A factor for the TBM diameter has been considered to assess the potential of MFC (Fig. 4).

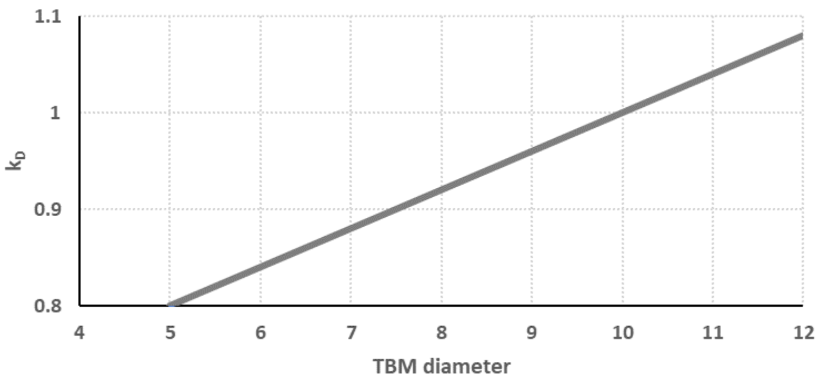

Fig. 4 TBM diameter factor for MFC rating

3.2.5 Illustrative example

Table 7 illustrates two hypothetical examples for the evaluation of MFC in hard rock TBM tunnelling. Example 1 is a combination of rock masses with UCS ratio 2.5 (UCS hard 250 MPa) and a combination of fracture classes XY. The TBM diameter is 10 m. The resulting MFC rating is 40 categorised as "medium".

Example 2 is a combination of rock masses with UCS ratio 2.5 (UCS hard 150 MPa) and blockiness high class. The TBM diameter is 8 m. The resulting MFC rating is 83 categorised as “high”.

Table 7 Illustrative examples of the evaluation of MFC

Example 1			***Example 2***		
Parameter	**Values**	**Ratings**	**Parameter**	**Values**	**Ratings**
UCS (MPa)	Hard 250 / Soft 100 MPa	k_{UCS} = 10	UCS (MPa)	Hard 150 / Soft 90 MPa	k_{UCS} = 10
Fracture spacing (cm)	Hard 150 cm / Soft 60 cm	k_f = 20 / k_{UCS} = 1.5	Blocky ground: Large blocks	Blocks 2 m^3	k_f = 80
TBM diameter (m)	10	k_D = 1	TBM diameter (m)	8	k_D = 0.92
MFC Rating		40 (Medium)	MFC Rating		83 (High)

4 Conclusions

Mixed Face Conditions (MFC) in TBM tunnelling projects in hard and abrasive rock have a significant impact on performance, tool wear and, consequently, on construction time and excavation costs. That means MFC affect the tunnelling in a negative way and therefore it is important that tender documents include an assessment on the potential occurring of MFC along the tunnel.

The new methodology identifies and categorizes MFC in hard rock TBM tunnelling based on general geological and geotechnical investigations, considering the main aspects creating MFC, which are: significant difference in rock strength, significant difference in rock mass fracturing and occurrence of blockiness at tunnel face using a rating system (MFC rating). Finally, the resulting rating is adjusted according to the TBM diameter. The larger the MFC rating, the more probable will be the occurrence of MFC and relevant the consequences.

The assessment of potential MFC can be provided divided in three Classes low – medium – high and consequently integrated to the contract. Consequently, the tenders should include additional time and cost estimate per meter of tunnel with MFC. During construction, the actual encountered conditions shall be mapped by engineering geological face-mapping or back-mapping – probably on a daily rate – to describe and assess the potential sections with tunnel excavation in MFC – classified by the same above mentions criteria to the three MFC classes.

References

Alber, M, Plinninger, R.J, Düllmann, J. (2018). Mixed Face Conditions (MFC) in hard rock TBM drives - causes, effects and solutions - in: Litvinenko (ed., 2018): Proceedings EUROCK18, Geomechanics and Geodynamics of Rock Masses, S. 1093-1099, London (Taylor & Francis), ISBN 978-1-138-61645-5

Blindheim, O.T., Grøv, E., Nilsen, B. (2002).The effect of mixed face conditions (MFC) on hard rock TBM performance. World Tunnel Congress, WTC 2002, Sydney.

Bruland, A. (2000). Hard Rock Tunnel Boring: Vol 1-7. PhD thesis. Norwegian University of Science and Technology (NTNU), Trondheim, Norway, 2000.

Büchi, E.T. (1992): New TBM Generation with 20” Cutters. Tunnelling Experience at Klippen Hydropower-Sweden.- in: TBM Symposium – Lucia 1992, Atlas Copco Stockholm, BeFo Stiftelsen Bergteknisk Forskning, Stockholm.

Fowell, R.J., Johnson, S.T. (1982). Rock Classification and Assessment for Rapid Excavation, in: Farmer, I. (Hrsg, 1982): Proc. Symp. Strata Mechanics 1982, Elsevier, Rotterdam. pp. 241 – 244.

ISRM International Society for Rock Mechanics (1979) Suggested method for determining the uniaxial compressive strength and deformability of rock materials. International Journal of Rock Mechanics & Mining Science, Vol. 15 (1979), pp 137-140.

ITA (2001). Glossary terms (tunnel.ita-aites.org/en/component/seoglossary/1-main-glossary/M).

Steingrimsson JH, Grøv, E. and Nilsen, B (2002) The significance of mixed-face conditions for TBM performance. World Tunnelling, Vol. 9 (2002), pp 435–441.

Toth A, Gong Q, Zhao J (2013) Case studies of TBM tunnelling performance in rock-soil interface mixed ground. Tunnelling and Underground Space Technology Vol. 38 (2013), pp. 140-150.

Önorm B 2203-2 (2005): Underground works – Works contract – Part 2: Continuous driving.