

THE SIGNIFICANCE OF MIXED-FACE CONDITIONS FOR TBM PERFORMANCE

The TBM tunnelling technique initially focused on the soft rock environment. As the technique developed towards stronger machines, more powerful motors and larger cutters, hard rock TBM tunnelling became a routine task. Today, there are few ground conditions where the TBM technique is not feasible. A certain and in some cases serious limitation is, however, represented by varying ground conditions, such as dykes, faults, weakness zones or even soils/soft rock, combined with hard rock. This is commonly referred to as mixed-face conditions. Variable geological conditions may call for customised machine design, and in the development of the design, geological knowledge is crucial. An identification of scenarios that may cause a threat to the successful implementation of the TBM-method, is more important than for conventional drill and blast tunnelling, as the latter has a greater flexibility.

Reliable forecasting of project cost and time schedules are crucial for all sub-surface projects, and not least for TBM-tunnelling. A method commonly used for prediction of TBM performance is the so-called NTNU-model. The first version of this model was published in 1976. The NTNU-model has been continuously updated as new information has become available with the most recent published update by Bruland in 1998.

The NTNU-model does not take fully into account the effect of mixed-face conditions on TBM performance. Such conditions have shown to be highly influential at several recent projects. In his Siving-thesis at NTNU, Steingrímsson (2000), used geological data from Iceland as an example in an approach aimed at developing an universal correction factor for mixed-face conditions. This paper intends to present the essentials of this approach and exemplify the use of the suggested "mixed-face correction factor".

MIXED FACE TUNNELLING EXPERIENCES

The term "mixed-face"

Mixed-face condition is a situation characterised by two or more geological formations present simultaneously on the tunnel face. Most commonly, this is represented by contacts between rock units with different mechanical properties, and by veins or dykes within the formation. Experience has shown that veins of weaker material do not normally cause trouble as long as they represent only a small part of the face. Rock formations with similar mechanical properties may not qualify to be called mixed-face as the difference in the net penetration rate of each individual layer is insignificant. Under such circumstances the layer contact may temporarily increase the penetration.

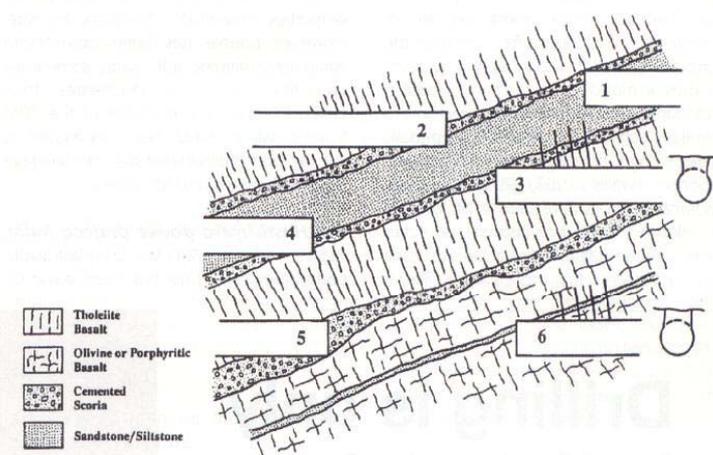


Figure 1. Potential situations for mixed-face boring in basaltic rock mass (Jónsson 1992)

To our knowledge, there is no unambiguous definition of what is required for varying geological conditions to be qualified as "mixed-face conditions". For instance, the conditions at Meráker (see the next Section of this paper) were described by the contractor as mixed-face considering the differences in uniaxial compressive strength (UCS) of typically 250MPa for the strongest (metagabbro) and 40-50MPa for the weakest (shale/phyllite), however, many rock engineers would probably not agree to this.

A definition of mixed-face conditions as the difference in UCS between the weakest and strongest layer of a minimum of 1:10, has apparently gained some acceptance. Still, there is considerable disagreement regarding what is to be considered as mixed-face conditions for hard rock TBM tunnelling, and regarding the consequences of mixed-face on TBM performance. This is clearly demonstrated by the long and difficult discussions that have

been experienced on several recent TBM projects.

The degree of mixed-face depends on the mechanical properties of the geological formations and the geometry of such formations. In a horizontal tunnel a vertical dyke crossing the tunnel perpendicularly will normally not be particularly problematic. As the geological formations are aligned more parallel to the tunnel axis the situation becomes increasingly unfavourable. This is the case for instance in the Icelandic basalt formations, where the highly regular and layered rock mass usually dips at 2°-10°. By comparing the average layer thickness distribution in Icelandic rock mass with a tunnel of the height of 5-8m, it is evident that a large part of such a tunnel might be excavated in mixed-face conditions. In Icelandic tunnelling mixed-face conditions have been encountered e.g. in the Ólafsfjarðarmúli road tunnel (3.1km) with 90% of its length as mixed-face, in the access tunnel for the Blanda hydro

power station (2.5km) with some 65% of the length (Harðarson 1991) and in 80% of the length of the Hvalfjörður road tunnel (5.8km).

Previous experiences with mixed-face

Through various references, information is available on TBM-tunnelling in mixed-face conditions. In the following a few projects will be briefly described focusing on the problems associated with mixed-face conditions.

Lesotho Highlands water project.

During the excavation of the transfer tunnel, mixed-face conditions were encountered in several sections of the tunnel. In the Lesotho basalt formation from Mesozoic times, dykes and sills of dolerite are considerably stronger than the surrounding basalt. When boring sections of such a mixed-face conditions, vibration and 'hammering' or impacts caused severe damages on the cutterhead, especially cutter ring breakage was frequently reported (Wallis 1993/1995). In these sections the gross thrust had to be lowered in order to reduce the vibration and cutter wear. On the Katse drive, a blocky basalt was encountered that proved to be difficult

to handle for the open face type of TBM. Blocks falling from the face were destroying cutters and even the cutter saddles, requiring a false face to be fitted to the cutterhead in order to hold the blocks in place and give the cutters time to grind/crush them.

Eyði hydropower project, Faroe Islands.

The Faroe Islands consists of a Tertiary basalt formation with many similarities to the Icelandic bedrock. The conditions, however, are more homogeneous and include a more random occurrence of sedimentary layers and are without central volcanoes within the lava stratum (Garrett 1989, Jónsson 1992). The lava stratum, as in Iceland, is compiled of many individual layers, but since the layers have similar properties mixed-face conditions are rare. However, trouble has been experienced whilst encountering tuff layers, sometimes consisting of several decimetres thick clayey material. The diameter of the TBM tunnels which have been excavated is 3.35m, and thus smaller than the average distance between the tuff layers.

Dul Hasti hydro power project, India.

Excavation for the 390 MW Dul Hasti hydro power project in India has been going on



Figure 2. Photo illustrating the different characters of massive, homogeneous metagabbro and weak, highly anisotropic phyllite (in the centre of the picture where the hammer is located)

since 1989. The up-stream part of the headrace tunnel is located in jointed quartzite interbedded with phyllites and the down-stream part is located in micaceous gneiss and schist. The boring commenced using a TBM of 8.3m diameter in 1991, but after 1,240m of tunnelling the TBM came to a halt. From 1995-1997 the client kept on with the boring making a progress of 400m. In 1997 a new contract was awarded to a Norwegian-Indian joint

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venture. After 1,230m of boring with great difficulties a cave-in at the face buried the machine and closed the case as to further TBM attempts. A main problem at this project was the high intensity of very abrasive and strong quartz formations within the softer phyllite. In the quartzite sections the penetration rate dropped significantly, resulting in an average penetration rate of 0.7m/h with an average cutter life of 45m³/cutter. In the hardest sections cutter life down to 20m³/cutter was not unusual (Johansen 2000, Divatia *et al.* 1993).

Manapouri hydroelectric power project, New Zealand. At the Manapouri hydropower project in New Zealand, a second tailrace tunnel was completed in early 2001 by a 10.05m diameter Robbins TBM equipped with 68 disc cutters of 432mm (17 inch) diameter. The 10km long tunnel is located within Palaeozoic metamorphic and igneous rocks of the Fjordland complex. The metamorphic rocks consist mainly of gneiss, calcisilicate, and quartzite, and the intrusive rocks are composed of gabbro and diorite. Uniaxial strength of the rock is up to 226MPa (Papke *et al.* 1999). At Manapouri, a discussion has arisen on whether or not the conditions are to be considered as mixed-face, and to what extent they have affected the tunnel performance. According to the contractor, considerable delays have been caused by conditions claimed to be mixed-face. The contractor describes the rock conditions as "cutting through a marble cake of different rock qualities" (Wallis 2000). Heavy vibrations of the TBM while boring are claimed by the contractor to be the result of the large 10m diameter flatfaced cutterhead cutting across different bands of rock, and the high wear of cutter

rings and severe cracking of the cutterhead are claimed to be the results of cutters bouncing across differing rock interfaces.

Meråker hydropower project, Norway. A 10.7km long, 3.5m diameter transfer tunnel at Meråker was bored in 1991 to 1992 by a Robbins High Performance (HP) TBM equipped with 483mm (19 inch) diameter disc cutters. The geology along the tunnel was dominated by Cambro-Silurian metasediments such as slate, phyllite, and meta-greywacke. Some tunnelling sections consisted of harder rock such as greenstone and meta-gabbro. Figure 2 illustrates the different character of phyllite and meta-gabbro at Meråker. When phyllite and meta-gabbro were encountered simultaneously at the face, the contractor referred to this as mixed-face conditions (Johannessen *et al.* 1993). Problems associated with mixed-face conditions, such as excessive cutter wear, were reported occasionally. The Meråker tunnel, however, achieved very good results, particularly in sections of slate/phyllite (average weekly advance rate was 253m, best week achieving 427m).

The effects of mixed-face

The examples described above clearly demonstrate that the occurrence of mixed-face conditions has an adverse effect on TBM boring. In the following the most common effects of mixed-face will be further detailed:

Load distribution on the cutters and net penetration rate

By studying the applied thrust distribution on the cutters it is evident that the cutters working on the stronger part of the face are taking up more thrust than the cutters on the weaker part. Theoretically, higher thrust

applied to the strong part of the face should result in higher penetration rate. However, experience from mixed-face conditions yields a different conclusion. When the cutters are bouncing on and off strong and weak layers, massive vibrations of the cutterhead may be experienced. In order to prevent damage to the TBM due to the heavy vibrations, the thrust level has to be lowered. The stronger layer limits the thrust application, and consequently the penetration rate is reduced. It is also evident that the thrust level may have to be reduced due to torque limitations of the weaker rock dominating over the stronger rock.

Cutter wear

As the cutters move over the face they are taking up highly variable loads. Cutter wear and failure is the result of such loading. In highly abrasive rocks like quartzite or gneiss; the cutters are generally worn down by abrasion. In mixed-face conditions the hammering action produces broken or cracked cutter rings, and the cutters show tendency of chipping as small flakes are broken off the cutter edge. Due to highly dynamic loading and high momentum of the cutters, the bearings tend to fail. In blocky ground the cutter saddles of open type TBM's may be damaged. Larger cutters may in some cases improve the situation, since larger cutter diameter gives space for larger bearings and longer "rolling distance". This may reduce the down time required for cutter change.

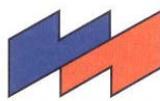
The cutterhead design

In mixed-face conditions, the cutterhead may also suffer from the constantly variable loading. Cracks tend to form, and frequently it is reported that the cutterhead



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structure needs to be re-welded and strengthened during excavation. To withstand the constant flexing and bending when excavating in mixed-face conditions, the cutterhead must be sufficiently strong and stiff. It is equally important that the cutterhead is properly designed. Cutterheads with domed shape are for that reason considered stable, and more capable to apply high thrust to the face and the cutters, rather than flat faced cutterheads (Wallis 2000, Alber 1998).

Contractual claims

A risk assessment for mixed-face conditions is an important issue to be addressed in the planning of a TBM tunnelling project, and particularly for large tunnel diameters, since the risk of encountering mixed-face generally increases with increasing tunnel diameter. Failing to report the degree of mixed-face may cause serious contractual consequences. However, a major obstacle is the capability of predicting the occurrence of mixed face conditions, and to quantify the effects of mixed-face conditions. An appropriate documentation of the engineering geological conditions of the formations and a sound understanding of the significance of mixed-face conditions can improve the efficiency of tunnelling in such circumstances. The risk of mixed-face conditions must be addressed so the machine design can be customised for the project. Identifying the risk of encountering mixed-face conditions imposes the need of establishing contractual regulations to deal with such occurrences. Various ways exist to handle such aspects in the contract documents. In this connection, the issue and possibility of risk sharing should always be addressed. A thorough classification of the tunnel whilst tunnelling is required for the determination whether geological conditions encountered are meeting the mixed-face requirement.

MIXED FACE CORRECTION FACTOR

To include the effects of mixed-face in the forecasting for a tunnelling project, a correction factor could be a useful tool to adjust the performance prognosis. A theoretical approach to be discussed here, suggests a methodology developed for such an adjustment.

The basic rule for the proposed correction factor is to use the calculated or measured penetration rates from the homogenous faces as a proportional strength indicator for the mixed-face components. It can be concluded that the strong layer on the face is thrust limiting in the boring process. It is suggested that the reduction in penetration rate, caused by

the reduced gross thrust, is in the inverse proportion of the penetration rate in the stronger layer (i_A) and the average penetration (i_{AB}) of the two layers on the face. A correction factor (k_{AB}) can then be applied to the average net penetration rate in order to correct the calculated penetration rate for mixed-face (A denotes the proportion of the hard layer and B the proportion of the soft layer):

(1) correction factor: $k_{AB} = \left[\frac{i_A}{i_{AB}} \right] = >$

(2) $k_{AB} = \left[\frac{i_A}{(A \times i_{AB} + B \times i_B)} \right]$

The mixed-face correction factor k_{AB} represents the penetration reduction as a result of reduced thrust applied through the mixed-face section. The correction factor k_{AB} is then multiplied by the calculated net penetration rate (i_0) for the section to find the penetration rate in each class of the mixed sections, for example for i_{MF-II} :

(2) Net penetration in the mixed-face section: $[i_{MF-II} = k_{AB} \times i_0]$

The average penetration rate is found by using the proportion of the mixed-face section lengths and the penetration rates for each section. After finding the penetration rate for the mixed-face sections, they are added by weight in an overall correction factor k_{MF} which is used as to find the average penetration rate for the entire tunnel:

(3) Average net penetration rate after correction: $i_{0-total} = i_0 \times k_{MF}$

A simple demonstration of the correction factor follows:

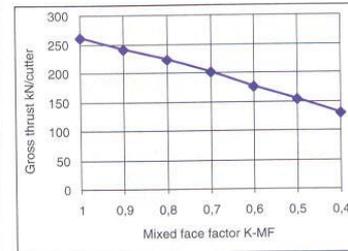


Figure 3. Reduction of applied gross thrust as a result of increased mixed-face proportion

A total tunnel length of 100m, out of which 50m is 100% in hard rock (A) with $i_A = 2m/h$ and the remaining 50m is 100% in soft rock (B) with an $i_B = 4m/h$. The time needed to advance these 100m will then be:

(4) Excavation time = $\left(\frac{50m}{2m/h} \right) + \left(\frac{50m}{4m/h} \right)$
 $= 37,5h \Rightarrow i_0 = \frac{100m}{37,5h} = 2,67m/h$

Assuming that the next 100m section is divided horizontally; with a 50% of the tunnelling face being hard rock (A) and another 50% being soft rock (B), the correction factor will be:

(5) Correction factor: k_{AB}
 $= \left[\frac{i_A}{(0,5 \times i_A + 0,5 \times i_B)} \right]$
 $= \left[\frac{2}{(0,5 \times 2 + 0,5 \times 4)} \right]$
 $= 0,67$

The penetration rate for the 50/50 mixed face situation is then:

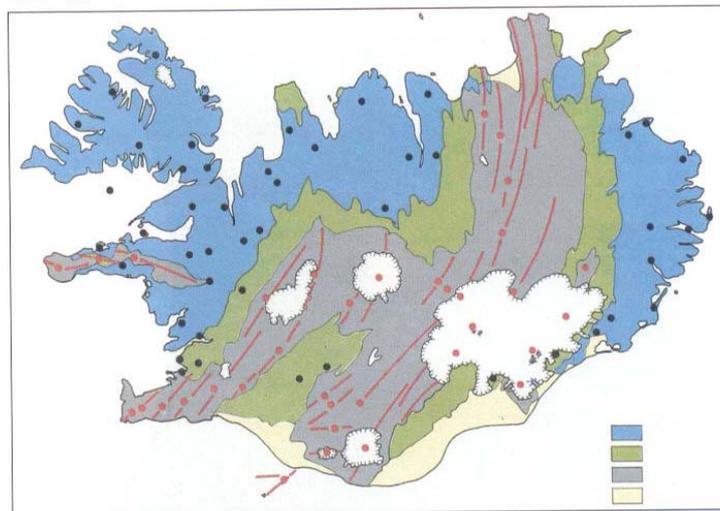


Figure 4. General geology of Iceland (Jóhannesson 1989)

$$(6) I_{MF} = k_{AB} \times I_0 = 0,67 \times 2,67\text{m/h} = 1,79\text{m/h}$$

As can be seen, the penetration rate corrected for mixed-face ($I_{MF} = 1.79$) is lower than the un-corrected penetration rate of the strong proportion of the face, ($I_A = 2.0\text{m/h}$).

EXEMPLIFYING THE MIXED FACE CORRECTION FACTOR

For the purpose of demonstrating the mixed-face correction factor developed above, an example based on geological data from basaltic bedrock in Iceland will be used.

Geological setting in the example

The example includes a late Tertiary and Quaternary bedrock. The Tertiary rock mass consists of extensive, but relatively thin, layers of basalt lavas, lying on top of each other, with a gentle dip of the strata. The basalt layers are separated by thin sedimentary interbeds. The oldest bedrock is found on the West and East coast on either side of the Mid-Atlantic Ridge which crosses the Island from south-west to north-east. These are not more than 15 million years old. (Sæmundsson 1979). The bedrock consists mainly of basalt, with small portions of acidic and intermediate igneous rocks and sedimentary interbeds. The Quaternary bedrock differs from the Tertiary as the occurrence of hyaloclastic palagonite formations, called "Moberg" formations become more frequent within the rock mass.

Each lava unit can generally be divided into three layers with a wide variation in mechanical properties. These are the top scoria, the crystalline middle part and the



Figure 5. Top scoria, and bottom scoria almost welded together, only thin sediments are fingered into the top scoria (Steingrímsson 2000)

bottom scoria. The top scoria is a porous slag, which forms on the top of the lava as it flows and gradually cools off. It is composed of basalt fragments, partly glassy and partly crystalline. The dense middle part, mechanically defined as "basalt", is the core of the lava unit. The bottom scoria is similar to the top scoria, but usually much thinner. The Moberg formation, a hyaloclastic basalt (pillow lava) and tuff, formed underwater or as a sub-glacial eruption is considered a particular formation.

A 3-dimensional fracturing model

The basis for performance prediction discussed herein is the NTNU-model (Bruland 1998). An important input parameter in this model is the fracturing factor K_s . The data base of the NTNU model is to a great extent based on rock types like gneiss, phyllite, slate and schist, i.e. rocks

with a distinct layering or parallel structure. The fracturing input in the NTNU-model is the angle (α) between the tunnel axis and the layering structures, and the distance between the weakness planes. For a basalt stratum this method is not considered quite applicable. The crystalline part of the lava flow has characteristic columnar jointing patterns. The scoria is associated with random jointing and highly irregular fracture patterns. The sedimentary layers have a horizontal cleavage whilst the Moberg formations are highly irregular. In our example, a 3-dimensional fracturing takes into consideration the fracturing patterns of the lava stratum being different from the formations on which the model is based. In order to adjust the performance model to the lava stratum a method for calculating the K_s factor was developed. A Model based on a primary joint distance and form factor was established (Steingrímsson 2000). There the basalt is given columnar jointing, the scoria, random jointing (modelled by a cube), sediments and the tuff with disc formed jointing, and finally the pillow lava with elongated jointing. Primary joint distance is the thickness of the column, the disc and the cube. The angle between the joint sets and the tunnel was then determined and then the $K_{s-total}$ parameter could be calculated for each joint model.

Classification of mixed-face

To predict the portion of a tunnel to be excavated in mixed-face conditions the geological formations must be classified according to the boring properties. Subsequently, a layer thickness criteria needs to be established. In our example, the sedimentary interbeds and the scoria have similar mechanical and boring

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Table 1: Mixed-face classification for a 7.2m diameter TBM

Mixed-face Classes	0	I	II	III	IV	V
Basalt thickness (m)	6.7-7.2	5.7-6.7	3.6-5.7	1.0-3.6	0-1.0	0
"Soft layer" thickness (m)	0-0.5	0.5-1.5	1.5-3.6	3.6-6.2	6.2-7.2	7.2

properties, whilst the basalt differs completely. Thus, it seems reasonable to classify the scoria and the sediments together as the "soft" component of the face, while the basalt is classified as the "strong" component of the face. The Moberg formation, and also the tuff and the tuff-breccia, are classified as the "soft" components while the pillow lava and cube jointed basalt are classified as the "strong" components. The layer thickness criterion was based on the "working area" of the mixed-face. The working area changes as the layer, or its contact moves across the face. A layer of definitive thickness has the largest area when it is centred on the face and it has the smallest area at the very bottom or at the top of the face.

Table 1 shows the mixed-face classification of the rock mass applied in this example. Four classes of mixed-face conditions have been established, and two classes with homogeneous rock mass conditions. Class 0 is defined by an up to 0.5m thick layer of soft rock components, as the effect of a layer of such limited thickness is considered negligible. Class V represents the homogeneous weak rock mass without any basalt on the face. The two transition classes Mixed-face classes I and IV each have an additional 1.0m of mixed rock, while the two truly mixed-face categories, Mixed-face classes II and III, represent minority/majority situation of the two components. In this example 3,800m of core logs were available for classification, and the following distribution was achieved:



Figure 6. A typical mixed-face situation, layer contact between conglomerate and basalt (Steingrímsson 2000)

- **Homogeneous face conditions (Mixed-face classes 0 + V)**
50.0%
- **Transitional face conditions (Mixed-face classes I + IV)**
20.9%
- **Mixed-face conditions (Mixed-face classes II + III)**
29.1%

The mixed-face analysis in this example indicates that it needs to be taken into consideration in the penetration rate prognosis.

TBM prognosis including mixed-face correction

For this example a TBM with a diameter of 7.2m and with 51 cutters, each 483mm (19 inches) in diameter, was chosen. Installed capacity is 2,700kW to supply gross thrust of 260kN/cutter and 7 revolutions per minute. The 483mm cutters are often designed for a 310-320kN loading. In the NTNU model it is assumed, however, that 260-280kN/cutter is applied to the 483mm cutter. A cutter loading in the lower range was chosen because of the high fracturing of the rock mass, as

recommended by Bruland (1998). Due to the expected high degree of mixed-face where high momentary loading of the cutters will occur, it is recommended not to stress the cutters to the limit of their capacity.

The net penetration rate I_0 is a main output of the NTNU-model. Inaccuracies in the calculation of I_0 will affect almost all other output by the model. In this example the Steen-Lichtenberg method was applied in the calculation of net penetration rate to include the variations in geological input parameters. For the estimate of the fracturing factor $K_{s-total}$ three sets of values were used for all primary fracturing factors of the different rock types; the upper and lower limits representing the most pessimistic and the most optimistic values, and the engineering value (or "best guess"). The weighted average of the net penetration rate I_0 was calculated to a 3.5m/h, with a standard deviation of 0.5m/h. Thus, with 67% confidence limit, the net penetration rate is 3.5 ± 0.5 m/h, and with 95% confidence limit it is 3.5 ± 1.0 m/h.

With the mixed-face correction factor suggested in this article the net penetration is adjusted to an average corrected figure of **3.21 m/h**.

The cutter life in mixed-face conditions is undoubtedly reduced due to vibrations and hammering effects as discussed before. However, the study presented here is

Table 2: Geological input parameters used in this example and calculated net penetration rates I_0 for the different rock units

Rock type:		Basalt I	Basalt II	Scoria III	Sedim. IV	Tuff V	Pillow Lava VI
DRI	Typical value	45	50	55	70	80	45
CLI	Typical value	35	45	55	70	60	45
Primary joint Spacing (m)	Lower limit 1%	2.0	1.6	1.0	0.6	0.8	0.8
	Engineer Value	0.7	0.6	0.5	0.2	0.35	0.35
	Upper limit 99%	0.4	0.3	0.1	0.05	0.05	0.05
Form factor		Col.	Col.	Cube	Disc	Cube	Col.
Porosity (%)		4	4	10	6	6	10
Net penetr. Rate I_0 (m/h)	Average value*	2.7	3.1	4.3	4.3	4.8	4.2
	Standard deviation*	0.4	0.4	0.6	0.6	0.6	0.7

*Steen-Lichtenberg method used for calculation of standard deviation and average value

Table 3: Example of net penetration rate and correction factors for three selected formations

Geological formations	Moberg formation A	Basalt formation B	Basalt formation C
Net penetration rate (m/h)	4.46	3.27	2.90
Mixed-face correction factor k_{MF}	0.98	0.70	0.93
Net penetration rate (m/h) corrected	4.35	2.31	2.71

focused primarily on penetration, and the cutter life will therefore not be discussed in detail.

CONCLUSIONS

Mixed-face conditions affect machine design, tunnelling layout, actual net penetration rate, machine utilisation and cutter life. Thus, time and cost aspects are both pending on the presence of such geological conditions. To take into account the presence of this phenomenon it is important that the pre-investigations focus on this aspect properly. Further, that adequate conditions are implemented in the construction contract to encompass the possibility of encountering mixed-face conditions. Experience shows that claims on "Differing site Conditions" are often related to unexpected mixed-face conditions. Being launched into a tunnel there is little room for adjusting the TBM design if the machine does not prove to be suitable for the job.

Experience shows that mixed-face conditions cause vibration and hammering effects in the machine. In some cases an improved cutterhead is needed to allow efficient tunnelling in such circumstances. Lowering the gross thrust on the cutterhead to reduce damaging vibrations in the machine might be an advantage, reducing also the high dynamic loading on the cutters running on and off the strong part of the face. Lower gross thrust results in a lower overall penetration rates.

This article presents a proposal for an universal mixed-face correction factor. The correction factor is basically taking into account the relative occurrence of rock types of different mechanical properties, and the net penetration of each such rock type.

The relevancy of the proposed correction factor for Mixed Face Conditions has been exemplified using geological information compiled from 3,800m of core logs from Iceland as a calculation example. For this example, a calculated net penetration rate was reduced by 10% when adjusted for mixed-face conditions.

It must, however, be underlined that a comparison with actually performed TBM tunnelling remains to be carried out to correlate the correction factor. The basic concept of this model is to establish an empirical method that can be adjusted later on by adding empirical factors to the basic model.

Acknowledgement

The authors appreciate the contribution from Landsvirkjun (the National Power Company).

References

- Alber, M. 1998. Design of high speed TBM drives. 8th International IAEG Congress. A.A. Balkema.
- Blindheim, O. T., Grøv, E., Nilsen, B. 2002. Mixed face conditions in TBM tunnelling. ITA World Tunnel Congress. Sydney
- Bruland, A. 1998. Project report 1B-98, Hard rock tunnel boring. Advance rate and cutter wear. NTNU – Department of Construction Engineering.
- Bruland, A. 1998. Project report 1C-98 Hard Rock Tunnel Boring. Costs. NTNU – Department of Construction Engineering.
- Divatia, E., Venkataesha, C.R., Binquet, J. and Colombet, G. 1993. Design of a 10,6km long headrace tunnel for Dul Hasti hydroelectric project (India). Options for tunnelling 1993. Elsevier Science Publishers.
- Garrett, R. 1989. Faroe Islands TBM. *World Tunnelling*. February 1989.

Harðarson, B. 1991. Icelandic rock tunnelling quality. ITA World Tunnel Congress. ITS Icelandic Tunnelling Society.

Johannessen, S., Askilrud, G. 1993. Meraaker Hydro – Tunnelling the Norwegian Way. Rapid Excavation and Tunnelling Conference.

Johansen, E. D. 2000. Dul Hasti hydroelectric project in Kashmir. Fjellsprengningsskonferansen. Tapir. (in Norwegian).

Papke, M., Heer, B. 1999. Building the second Manapouri tailrace tunnel. *T&T*. May 1999.

Jónsson. 1992. Tunnelling in basalt in Iceland and the Faeroe Islands with special reference to the bored tunnels at the Fljótsdalur and Eiði hydro projects. Tuncon '92 Design and construction of tunnels.

Steingrímsson 2000: Jon Haukur Steingrímsson. Karahnjúkar hydropower project, rock engineering analysis. Civil Engineering (M.Sc) thesis, NTNU – Department of geology and mineral resources engineering. 69 pages.

Sæmundsson, K. 1979. Outline of the geology of Iceland. Jökull no. 29.

Wallis, S. 1993. Lesotho highlands water project, volume 2. Laserline.

Wallis, S. 1995. Lesotho highlands water project, volume 3. Laserline.

Wallis, S. 2000. Manapouri struggles to make headway, *T&T* April 2000.

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tunnels get people together.
for more quality in life. **but...**

...first of all!

VOEST-ALPINE BERGTECHNIK

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