Even Lein Iddeng

Full Face Tunnel Boring in Hard Rock Conditions - Detection and Influence of Mixed Face Conditions

Master's thesis in Construction Engineering
Supervisor: Pål Drevland Jakobsen
June 2019

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Abstract

A common source of trouble and dispute in hard rock TBM-tunneling is unforeseen and unfavorable geology known as Mixed Face Conditions (MFC). MFC has the potential of causing severe problems and may trigger hazards, resulting in reduced TBM performance. Being a common term in TBM-tunneling, there is however no clear and unambiguous scientific definition on MFC, making it a sensitive and highly discussed topic in the TBM-tunneling industry, primarily when actualized in relation to additional costs and claims. As a way to better assess geology as MFC and the influence it has on the overall TBM performance, the work in this Thesis is about the possibility of determining the presence of MFC on the working face of hard rock TBM's from signatures in TBM performance recordings.

Up-to-date literature on the influence and detection of MFC is assessed and presented to reveal the possibility of determining MFC presence from recorded TBM performance data. TBM data from the recently finished Follo Line tunnel were provided for analyzes, and a TBM raw-data filtering code is developed and presented. The developed filtering code ensures adequate filtering of error recordings and non-representative data, enabling analyses of a representative set of TBM performance data, recorded solely during actual boring operation. Results and analyses of the literature and filtered TBM performance data is presented and explain

From literature, it was found possible to determine a correlation between geology constituting the same effects and problems on the TBM performance as MFC, but possibly not MFC exclusively. Through the analysis of filtered TBM performance data, it was further found plausible to determine a correlation between TBM performance signatures and the presence of MFC, but not solely from TBM performance data. To determine the presence of MFC from performance data, it is thus suggested that the signature of MFC presence is substantiated by data on cutter tool life, geological face mappings and other factors relating to MFC.

Sammendrag

En vanlig kilde til problemer og tvister ved bruk av TBM for driving av tunneler i hardt fjell, er uforutsett og ugunstig geologi kjent som Mixed Face Conditions (MFC). MFC kan forårsake alvorlige problemer under driving og potensielt resultere i redusert maskinytelse og forsinkelser. Begrepet Mixed Face Conditions er et mye brukt uttrykk ved TBM-driving, men det finnes ingen klar og utvetydig vitenskapelig definisjon på MFC. Mangelen på en definisjon gjør MFC til et sensitivt og omdiskutert tema i tunnelindustrien, først og fremst ved aktualisering i relasjon til økte kostnader og krav. For bedre å kunne definere geologi som MFC samt vurdere innflytelsen MFC har på maksinytelse og prosjektframdrift, studerer denne masteroppgaven muligheten for å detektere MFC på stuff, gjennom analyse av signaturer i maskindata.

Oppgaven presenterer den viktigste vitenskapelige litteraturen relatert til deteksjon og innflytelse av MFC-geologi, for å undersøke mulighetene for å detektere MFC fra maskindata. Ufiltrert maskindata fra den nylig ferdigborede Follobanen ble gjort tilgjengelig for analyse, og en filtreringskode er utviklet og presentert. Den utviklede filtreringskoden sikrer tilstrekkelig filtrering av feillogget- og ikke-representativ data, som videre muliggjør analyser av et representativt sett med maskindata utelukkende logget under boringen. Resultater og analyse av litteraturen og den filtrerte maskindataen finnes presentert og forklart i oppgaven.

Gjennom litteraturen ble det funnet mulig å fastslå en korrelasjon mellom geologi som gir tilsvarende effekter og problemer som MFC, men antagelig ikke MFC isolert. Fra analysen av filtrerte maskindata ble det videre funnet plausibelt å kunne detektere en sammenheng mellom signaturer i maskindata og mulig forekomst av MFC på stuff, men ikke utelukkende fra maskindata i seg selv. For å fastslå forekomster av MFC gjennom maskindata, foreslås det at datasignaturer ansett som mulig MFC, underbygges av data på kutterlevetid og kutterbytter, ingeniørgeologiske kartlegginger, samt data fra andre faktorer relatert til MFC.

Preface

Submitted to the Department of Civil and Environmental Engineering at the Norwegian University of Science and Technology (NTNU), this Master Thesis is the culmination of achieving a Master of Science in Construction Engineering. The Thesis was carried out in the spring of 2019 with Associate Professor Pål Drevland Jakobsen at NTNU as main supervisor, and Engineering Geologist Guro Isachsen from Bane NOR as co-supervisor. I would like to express my gratitude to Associate Professor Pål Drevland Jakobsen for his great support and guidance, and to Guro Isachsen for making this Master Thesis possible by providing data and information.

Following a 5-year integrated master's program at NTNU, this has been a long journey providing me with huge amounts of knowledge in highly specialized fields, but also in a wider sense. I would also like to highlight the unique student community in Trondheim, with all the social activities it has to offer. Many people have advised, supported and motivated me during the work on this Master Thesis and the journey as a whole. I would like to give a special thanks to colleagues and friends at the office Verkstedloftet, my teammates at NTNUI Ice hockey and all the friends I have made during my years in Trondheim and on exchange.

Last but not least, I would like to thank my family for supporting me and making it possible to fully focus my time on studies. They have always encouraged and motivated me in reaching my goals and been there in times when motivation has been lower. They are people whom I admire.

Even Lein Iddeng
Trondheim, June 10th 2019

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Chapter 1

Introduction

Utilization of the underground to facilitate functional and redundant civil infrastructure is essential and necessary, especially where space above the ground is limited. The introduction and development of Tunnel Boring Machines (TBM's) have made it possible to tunnel all kinds of complex ground conditions, from loose soils to hard rock conditions. Compared to traditional tunneling in hard rock by the method of Drilling & Blasting (D&B), TBM-tunneling reduces the excavation damage zone and has less influence on the surroundings. Strong vibrations and stress to the soil or rock mass is minimized, and the circular profile limits the need for ground support and overburden. TBM design is tailored according to the geological conditions the machine is set to excavate, and the desired finished tunnel product. TBM-tunneling thus represents a more industrialized way of tunneling as the process of boring and installation of lining and invert segments are done simultaneously in one continuous operation, leaving a tunnel ready for technical installations.

Being tailored for given geological conditions, a common source of trouble and dispute in TBM-tunneling is unforeseen and unfavorable geological conditions on the working face known as Mixed-face ground or Mixed Face Conditions (MFC). The term MFC is common in both soft ground and hard rock TBM-tunneling but interpreted and used in a verity of ways. Although being widely used, there is no clear scientific definition of MFC and its boundaries. It is thus a sensitive and highly discussed topic in TBM-tunneling, primarily when used in relation to additional costs and claims.

MFC has the potential of causing severe problems and may trigger hazards if proper measures are not initiated in time, resulting in reduced TBM performance. When TBM performance is reduced, the risk of project delay and increased cost can become significant to contractors operating TBM's, the project owners, and to the society as a whole. The lack of a clear and scientific definition of MFC makes it challenging to develop fair and substantiated compensation mechanisms for contractors, and to prepare contracts and tenders that take care of all stakeholders, minimizing the room for misinterpretations and disputes.

TBM design and operation requires extensive and expensive geological mapping along the predicated tunnel corridor to get an overview of the geology and its properties. To get an idea of the extent and significance of geology that can represent MFC, further geological surveying is needed both before and during operation, often putting a halt to the boring process. When tunneling with closed shielded TBM's, the excavated tunnel ground surface is neither visually visible for inspection or back mapping, making it very difficult to substantiate the presence of zones with MFC significance.

The effects of MFC on TBM performance depends on the TBM-design and -operation, and the properties and extent of the MFC-zone. In the search for a better understanding of MFC, the literature suggests to not look solely at geological properties but to research the nonlinearity of TBM performance for a better understanding of MFC. Looking into economic growth, urbanization and technological improvements, more future tunneling projects will be suitable for TBM's, thus giving value to contributions on the topic and challenges of MFC.

1.1 Thesis Objective & Statement

The objective of this Thesis is to determine if there is a correlation between TBM performance data and the presence of rock mass properties of possible MFC in shielded hard rock TBM-tunneling. Further, the purpose is to possibly contribute to the development of a better way to assess rock mass properties as MFC, and how rock mass of MFC significance affects the TBM performance. Unfiltered TBM performance data and cutter data from a recently excavated railroad tunnel in the Oslo area, known as the Follo Line project, is provided from the Norwegian National Railroad Administration (Bane NOR). Based on this data, the objective of this Thesis is pursued through the following problem statement:

Is there a possibility of determining a correlation between TBM Performance data and the presence of "Mixed Face Conditions" at the working face of shielded hard rock TBM's, using data from the Follo Line project?

1.2 Scope & Limitations

To adequately pursue the objective set in this Thesis, access to sufficient TBM data is required. The amount of data provided and its quality, together with the objective, shapes the scope and sets the limits for this Thesis. With access to unfiltered TBM performance data and cutter data from one of the northbound double shield TBM's on the Follo Line project, the scope of the work in this Thesis and the working limits is as follows:

Scope

- Gather an up to date knowledge on MFC in hard rock and its presence in TBM-tunneling.
- Development of a filter in MATLAB to clean the unfiltered TBM performance data so that analysis is possible (continued work from previous Specialization Project fall 2018).
- Analyze the TBM performance data for a correlation between TBM performance data and the presence of MFC, substantiating using cutter data and literature.

Limitations

- The literature review is conducted solely with a focus on MFC in hard rock and hard rock TBM-tunneling.
- The data access is limited to data from one out of four excavated tunnels on the Follo Line.
- No laboratory research conducted.

1.3 Structure of Thesis

The Thesis is comprised of seven chapters together with appendices.

Chapter 1 contains an introduction to the topic of Mixed Face Conditions, the Thesis objective & statement, and the scope & limitation of the Thesis.

Chapter 2 presents a summary of hard rock TBM tunneling in Norway. The TBM solutions used at the two most recent Norwegian TBM projects are explained, describing how the topic of MFC has been actualized in Norwegian hard rock TBM-tunneling.

Chapter 3 presents the up to date theory on Mixed Face Conditions in hard rock TBM-tunneling, describing the suggested definitions of MFC, the problems and effects of hard rock MFC on TBM performance, and the possibilities of predicting and substantiating the presence of MFC from TBM data. Ground characterizations and TBM specification on the Follo Line project is included.

Chapter 4 describes the research methodology of the Thesis, which consisted of a literature review, development and validation of the raw TBM performance data filtering code, analysis of filtered TBM performance data, and a field trip to the Follo Line project rig.

Chapter 5 presents the results and analysis on the possibilities of detecting a correlation between the recorded TBM performance data and the presence of MFC from literature and from the analyzed TBM performance data.

Chapter 6 contains the discussion of the results, filtering code and analysis

Chapter 7 presents the conclusion of the Thesis and suggestions on further work

Chapter 2

Background

2.1 Background & Motivation

December 10th, 2015, the 7.23 diameter main beam TBM of The Robbins Company Inc. had its breakthrough on the new Lower Rossaaga hydropower project. After excavating a total of 7.5 km of hard Norwegian rock, the breakthrough of TBM nicknamed “Iron-Erna” marked the completion of the first TBM driven tunnel in Norway for over 20 years and a new era of Norwegian TBM-tunneling (Robbins, 2015). TBM-tunneling has a long history in Norway, with the first projects being initiated in the mid-1960s. Over a period of about 30 years, a total of 258 km tunnel was excavated by the use of TBM’s. The majority of these kilometers were water tunnels related to hydropower projects. With fewer such project, the need for long water tunnels decreased and TBM-tunneling in Norway came to a halt in the early 1990s. TBM-solutions were tested in some road projects but showed insufficient due to increased cost from extensive stopping to expand the circular profile. Norwegian contractors continued operating TBM’s outside Norway for around a decade, but the knowledge and experience gradually vanished with the norm being drill and blast for most new tunnel projects (Jakobsen *et al.*, 2015).

After Lower Rossaaga, the Norwegian Parliament appropriated funds to Bane NOR for the construction of two railroad tunnels, the new Ulriken Tunnel, and the Follo Line Project. For the new 7km Ulriken Tunnel, Bane NOR issued a tender open for the project to be carried out by D&B- or TBM-solutions. The chosen joint venture was awarded the excavation contract based on an open gripper TBM solution, and the TBM had its breakthrough August 29th, 2016. Following in September 2016, four double shield TBM's were assigned the job of excavating some 18.5 km of a 22 km tunnel on the Follo Line. This new high-speed railroad between Oslo and the municipality of Ski was planned and designed for excavation by TBM. Before the construction started on the Follo Line in 2016, all previous TBM projects in Norway were conducted using open machines (Jakobsen *et al.*, 2015). In open TBM-tunneling, the excavated rock mass surface is visible and accessible for back mapping, giving the possibility of substantiating the presence and extent of unforeseen geological conditions such as MFC. Disputed and claims of compensation raised on the basis of unforeseen geology could hence be verified more easily and resolved in a more straightforward way.

When using double shielded TBM's, as in the Follo Line project, tunnel workers are protected by shields covering the tunnel face behind the cutter head. The front shield overlaps a back shield where frost and water protective concrete element lining is mounted continuously within the range of the back shield. The concrete lining covers the circumference of the excavated tunnel for the whole length of the tunnel, leaving the geological conditions unobservable while in operation as well as in the finished tunnel product. The only possibility of inspecting the rock mass is through the cutter head of the TBM when stopped or else restricted to specific zones where rock exposures are accessible (Macias *et al.*, 2014). Disputes and compensation claims based on unforeseen and unfavorable geological conditions are hence very difficult to substantiate and to verify. The challenges that MFC represents in hard rock TBM-tunneling, especially in lined double shield TBM-tunneling, have thus been actualized in Norwegian tunneling through the Follo Line project.

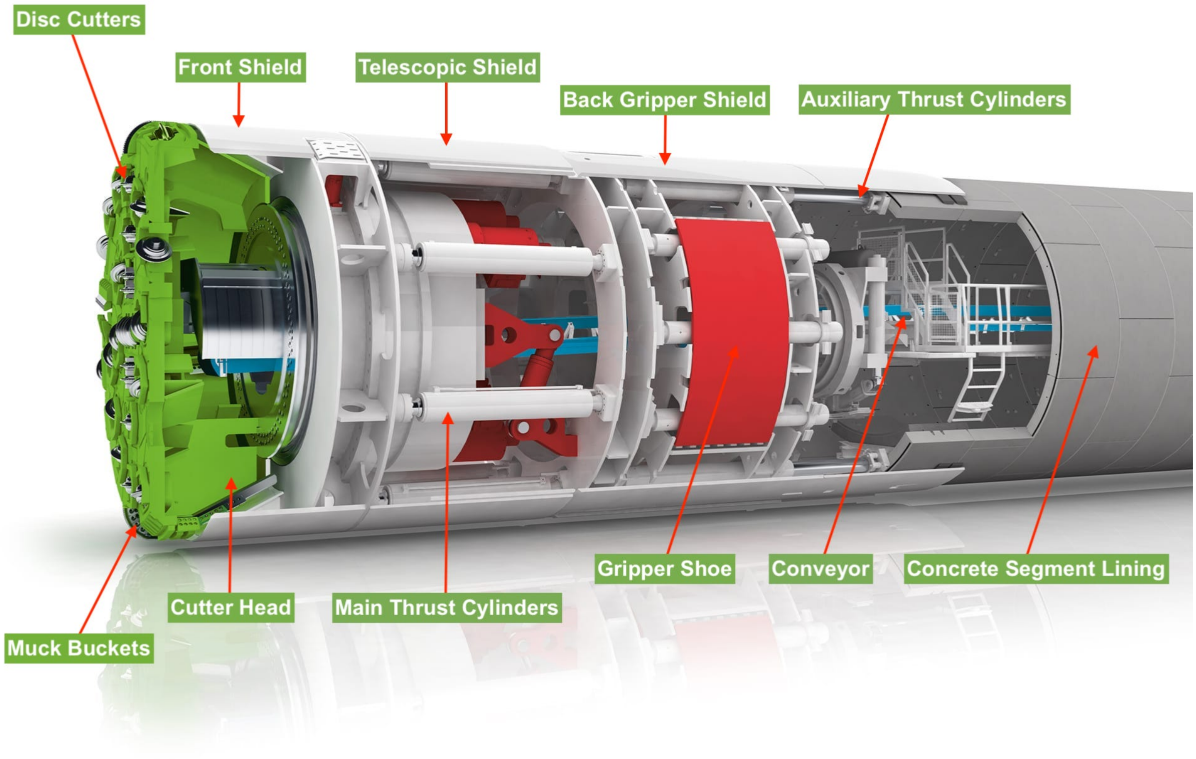


Figure 2.1: Double shield TBM by Herrenknecht (Modified www.Herrenknecht.com)

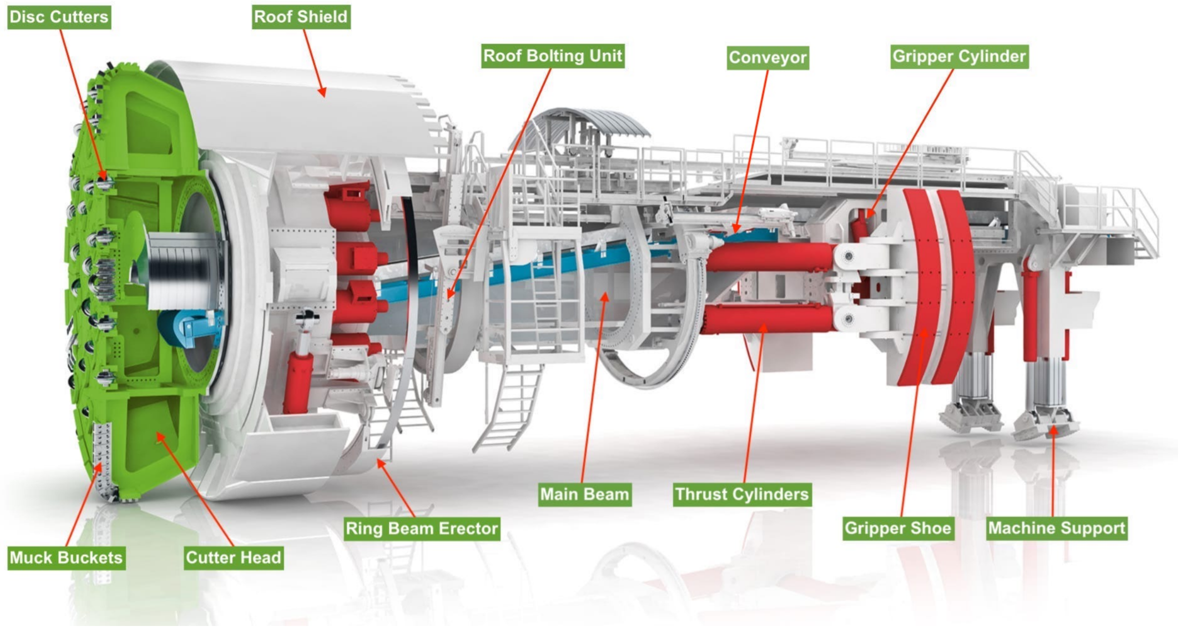


Figure 2.2: Open gripper TBM by Herrenknecht (Modified www.Herrenknecht.com)

TBM projects tend to be large and complicated, often having an extensive list of stakeholders. For the Follo Line project, Bane NOR decided to meet the TBM market with an Engineering Procurement Construction (EPC) contract. EPC contracts are characterized by little direct control from the project owner, leaving Bane NOR with the task of ensuring progress, safety, environmental requirements, noise regulations, and working conditions (Kjelland, 2015). The contractor is free to solve the project within its boundaries, having full control over the detailed engineering design and to procure equipment and materials, but committed to construct and deliver functionality according to contract (*EPC - Engineering Procurement Construction*). For the Follo Line project, this means that the contractor did the mapping and documentation of MFC for the project owner during excavation based on their interpretation of MFC, which again gives the basis for discussion and possible compensation.

With no clear and scientific definition of MFC, it is difficult to develop fair and substantiated compensation mechanisms for contractors and to develop contracts and tenders that take care of and secures all stakeholders. Misinterpretations, disputes, and interest conflicts are likely when the discussion basis, contract, and project reports contain ambiguities or unclear descriptions. If legal action is taken in pursuit of a solution or agreement, the outcome can be very costly to one or more parties, the communities the project is set to serve and the society as a whole. It is desirable to minimize the chance of cost overruns and project delays, especially in large state-owned projects. With the Norwegian parliament being unified around great investments in infrastructure for the years to come, there are many future projects suitable for TBM's, keeping the topic of MFC in hard rock TBM-tunneling relevant in Norway. MFC as a sensitive and highly discussed topic together with the actualization of the topic in Norwegian tunneling in recent years is the motivation for this Thesis.

Chapter 3

Theory

3.1 Mixed Face Conditions definition

Also known as Mixed-face ground, Mixed Face Condition is a common term used in both soft ground and hard rock TBM-tunneling for the occurrence of mixed geological conditions on the working face of TBM's, influencing the TBM performance. Even though being a common term in TBM-tunneling, there is however no clear, unambiguous definition on MFC or Mixed-face ground, especially for tunneling in hard rock conditions. This can be seen from looking into the glossaries of recognized associations within the tunneling industry, namely the glossary of ISRM (International Society of Rock Mechanics) and the ITA (International Tunneling Association).

ISRM:	No definitions on *MFC* or *Mixed-face ground* (ISRM, 2019)
ITA:	Has the following for the term *Mixed-face tunnel*; "A tunnel requiring excavation of both earth and rock materials in the same heading at the same time. Some owners may extend the definition of rock to include boulders larger that 3 ft in diameter because of similar difficulties of removal."(ITA, 2019)

(Blindheim, Grov and Nilsen, 2002) Highlighted the effects of MFC on hard rock TBM performance and the importance of taking MFC into account during planning, design, preparation of tender documents, bidding, construction, and follow up. Also, they recognized that little research and data were published on the topic of MFC at the time, leaving issues with MFC to experience-based judgment. Going through different case studies from TBM driven projects in the 1990s, the most significant contributions on the understanding for MFC found at the time was (Büchi, 1992) and (Steingrimsson, Grøv and Nilsen, 2002).

Through experience with TBM-tunneling at the Klippen Hydropower project in Sweden, (Büchi, 1992) defined MFC as:

"*The term mixed face conditions is used when the tunnel face consists of at least two rock types with completely different boreability – in simple terms a mix of soft and hard rock*"

Büchi further exemplified the proposed definition as a rock mass interface with intrusions or lenses that consist of rock with Uniaxial Compressive Strength (UCS) around 2.5 times the strength of the surrounding rock. From reviewing some previous TBM project that encountered MFC, the difference in UCS was further investigated by (Steingrimsson, Grøv and Nilsen, 2002), which recognized that the hard rock TBM-tunneling industry had accepted a definition of MFC as; *"a difference in UCS between the weakest and strongest layer of a minimum of 1:10".* (Steingrimsson, Grøv and Nilsen, 2002), also tried to quantify the effect of MFC by establishing a correction factor for the Norwegian University of Science and Technology (NTNU) TBM performance prediction model.

TBM performance prediction models are important tools that can be used at various stages of TBM-tunneling projects. Describing the applicability of the NTNU TBM performance prediction model at the new Ulriken tunnel in Norway, (Macias, Andersson and Eide, 2017) demonstrates how such a prediction model can be used through various stages in TBM-tunneling projects as a tool for:

- Estimating net penetration rate and cutter wear
- Estimating time consumption rate and excavation costs, including risk
- Assessing risk linked to variation in rock mass boreability and machine parameters
- Establishing and managing contract price regulation
- Verifying machine performance
- Verifying variation in geological conditions

There are several TBM performance prediction models, both empirical and theoretical. The two most recognized prediction models in use today are the empirical NTNU-model and the theoretical Colorado School of Mines (CSM-model). Due to the applicability of TBM performance prediction models, there is thus a desire to develop models that can handle MFC. Since 2002, research on MFC and contributions to the understanding definition of MFC can be divided into; 1) attempts on adjusting or implementing MFC into these models or development of new models. 2) Analyzes on the effects and the consequences of MFC on TBM performance through case studies of TBM projects and or laboratory tests. However, looking into literature and documents of the last 10 years, the geological definition of MFC as two or more geological conditions on the working face with a UCS ratio of 1:10 between the weaker and stronger rock mass, still seems to hold recognition in the industry.

(Geng *et al.*, 2016, Ma *et al.*, 2015, Tóth *et al.*, 2013, Vergara and Saroglou, 2017, Zhang *et al.*, 2010) show that modern literature reefer to (Steingrimsson, Grøv and Nilsen, 2002). (Zhang *et al.*, 2010) Did a theoretical analysis of the dynamic characteristics of excavation torque and rotational speed in MFC TBM-tunneling. Recognizing the definition of 1:10 in UCS, MFC was illustrated as a continuous percentage area (30%, 50% or 70%) of a soft rock on a hard rock working face. The soft rock was assigned a UCS of 40 MPa and the hard rock 200 MPa, close to the 1:10 ratio.

(Tóth *et al.*, 2013) stated that a definition based solely on the UCS ratio of the encountered geological materials is oversimplified but recognized that the 1:10 ratio still was used by industry at the time. Based on a case study of the Deep Tunnel Sewage System in Singapore, (Tóth *et al.*, 2013) tested the correction factor model proposed by (Steingrimsson, Grøv and Nilsen, 2002). The model of Steingrimsson, which was developed based on layer banded geological MFC compositions, were tested on the geological MFC composition of rock-soil interface found in Singapore. The results indicated that the model of Steingrimsson was not suitable for the MFC composition in Singapore. Developing a statistical penetration rate model based on data from the Singapore DTSS project, Tóth contributed to the understanding of MFC by establishing an MFC composition classification system and further redefining MFC to the following:

"Mixed face ground is the ground, where there are two or more geological materials simultaneously present on the tunnel face with significant differences in material properties that influence significantly, a) penetration rate of the TBM or b) operational parameters of the TBM or c) support system installed behind the TBM."

Three different classes of MFC was established:

- *Rock-Soil Interface (RSI)*
- *Boulder Soil Matrix (BSM)*
- *Layer-Banded Rock (LBR).*

Rock-Soil Interface MFC is typically the transition from soil to weathered rock above solid bedrock or hard rock in combination with weakness zones consisting of soft ground/soils. RSI is characterized by the distinct difference in material properties between the soil and the rock. This is considered the most common type of MFC according to (Tóth *et al.*, 2013), which also recognizes unfilled karsts as an extreme case of RSI.

Figure 3.1: Rock-Soil Interface (RSI) from (Tóth et al., 2013)

Boulder Soil Matrix is a type of MFC where boulders, cobbles or correstones are embedded in a soft soil matrix. This is typically alluviums and residual soils with embedded spherical rocks of high strength (Ma *et al.*, 2015, Tóth *et al.*, 2013).

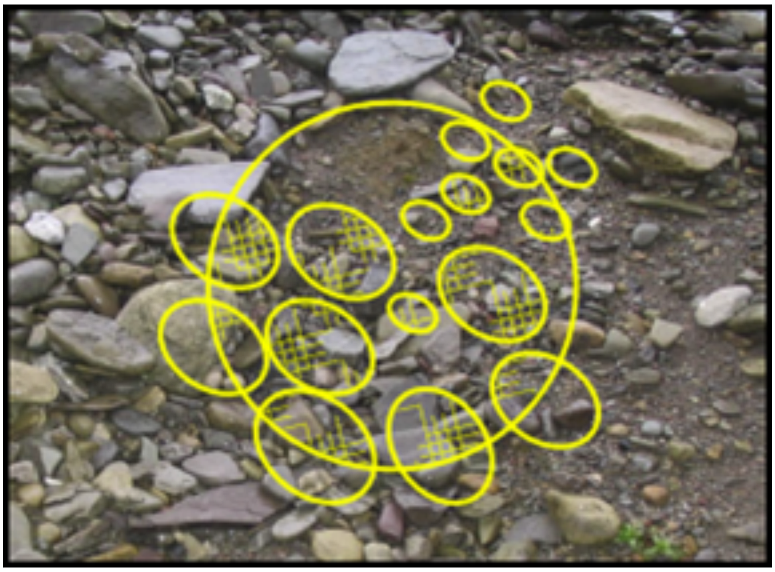


Figure 3.2: Boulder Soil Matrix (BSM) from (Tóth et al., 2013)

Layer-Banded Rock is MFC where layers of rock mass with significantly different material properties are present in an otherwise homogeneous rock, typically represented by rock bedding sills/dykes, faults or hard intrusions and shear zones. The MFC effects in LBR conditions are a combination of area ratio, material properties, and the orientation of the bands (Ma *et al.*, 2015, Tóth *et al.*, 2013).

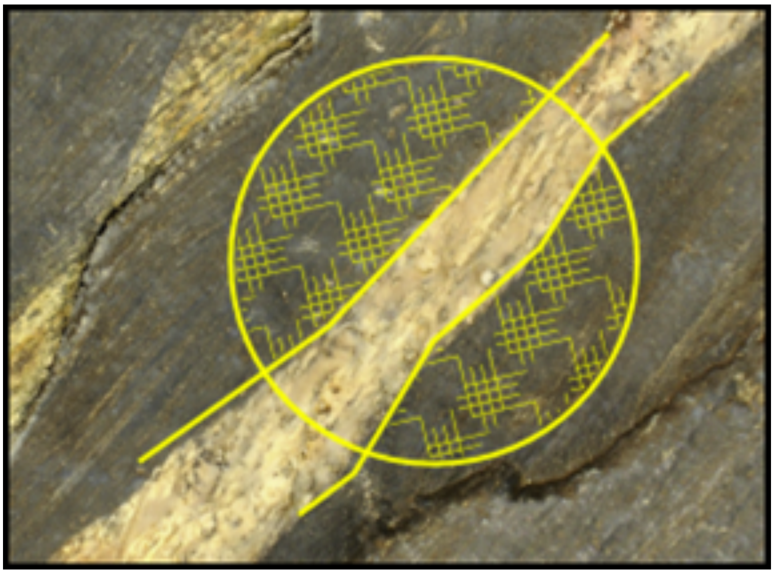


Figure 3.3: Layer-Banded Rock (LBR) from (Tóth et al., 2013)

Since (Tóth *et al.*, 2013), no further attempts on redefining MFC is found. Looking at the problems of encountering MFC in TBM-tunneling, and possible solutions to avoid or limit these problems, (Ma *et al.*, 2015) presents a review of definitions and classifications of MFC. The definitions proposed by Büchi and Steingrimsson is recognized, and the classification system of Tóth is presented, but (Tóth *et al.*, 2013) not referenced. However, (Ma *et al.*, 2015) criticizes the definition of (Steingrimsson, Grøv and Nilsen, 2002) for failing to incorporate TBM operation and performance parameters. A table of factors relating to MFC in TBM-tunneling is further presented, consisting of 1) Ground conditions parameters, 2) TBM machine parameters, and 3) Operation parameters.

(Geng *et al.*, 2016) studied the mechanical performance of a TBM cutter head in MFC by simulating LBR conditions with concrete of different strength in a full-scale TBM laboratory experiment. (Vergara and Saroglou, 2017) proposed a TBM performance prediction index for MFC, correlating the thrust force and net penetration rate to a percentage of rock on the working face, the intact rock UCS and the rock quality designation by rock mass rating. Looking into these recently published articles on MFC, both (Geng *et al.*, 2016) and (Vergara and Saroglou, 2017) recognizes the definitions of (Steingrimsson, Grøv and Nilsen, 2002) and (Tóth *et al.*, 2013) in their work, but no new proposals on MFC-definitions are presented in this up to date literature. The definitions of Steingrimsson and Tóth thus appears to be the prevailing definitions of MFC in both academia and industry.

3.2 Hard rock boring process

According to the International Society of Rock Mechanics, hard rock conditions are understood as a rock with Uniaxial Compressive Strength above 50 MPa (ISRM, 1978). Understanding the boring process of hard rock TBM-tunneling is fundamental to the understanding of problems and effects related to Mixed Face Conditions in hard rock. In hard rock TBM-tunneling, the rock mass is mechanically excavated by rolling disc cutters mounted to a rotating cutter head which is pressed with large force against the rock mass. The applied thrust force is transferred to the rock mass through the rock-cutter contact area. The indentation of the disc cutters into the rock mass induces high compressive stresses in the contact area, crushing the rock to powder at the cutter edges and forming radial cracks in the rock mass under the cutters.

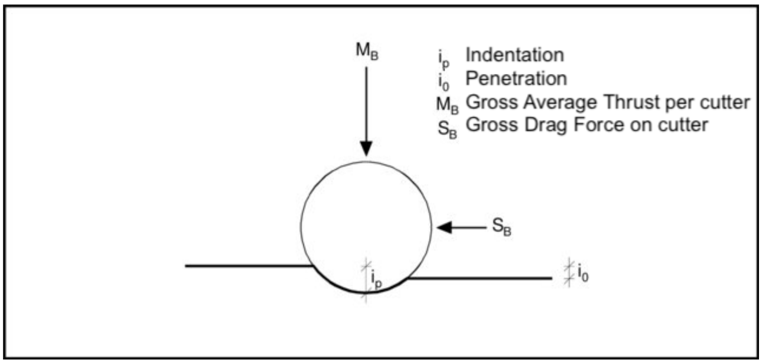


Figure 3.4: Penetration and indentation of a disc cutter. Modified (Bruland, 1998b)

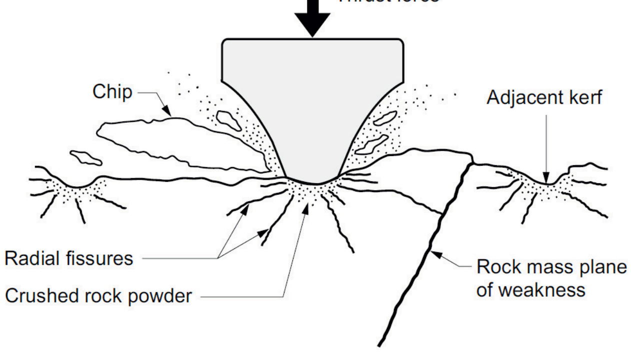


Figure 3.5: The principle of chipping under a disc cutter (Bruland, 1998b)

When retracting the cutter head from a continuous and stable working face, the penetration of the disc cutters can be seen as circular kerfs in the rock mass. The TBM advances as the rock mass is chipped out from the working face as a result of the cracking formations along the principal stress trajectories between the cutters and cracks of adjacent kerfs. The resistance encountered by the TBM as it penetrates and advances through the rock mass is understood as the boreability (Bruland, 1998b).

Figure 3.6: Kerfs a on stable working face at the Follo Line (Bane NOR)

The TBM Penetration Rate denotes the advance rate of the cutter head, which is measured in mm/rotation as an average of several rotations. Further, the Net Penetration Rate is defined as meters/hour while the cutter head rotates with thrust against the rock mass working face (Bruland, 1999). TBM performance is furthermore understood as the result of this interaction between the geological rock mass properties and the TBM-design and -operational parameters (Ma *et al.*, 2015). TBM performance is evaluated from recorded TBM performance data and substantiated from cutter change data and different geological back mapping.

Normalized to the critical thrust force (M_1), understood as the force needed to penetrate the rock mass 1 mm, the relation between penetration rate (i_0) and the gross average thrust force per cutter (M_B) is illustrated by (Bruland, 1998b) in the following figure (b = penetration coefficient):

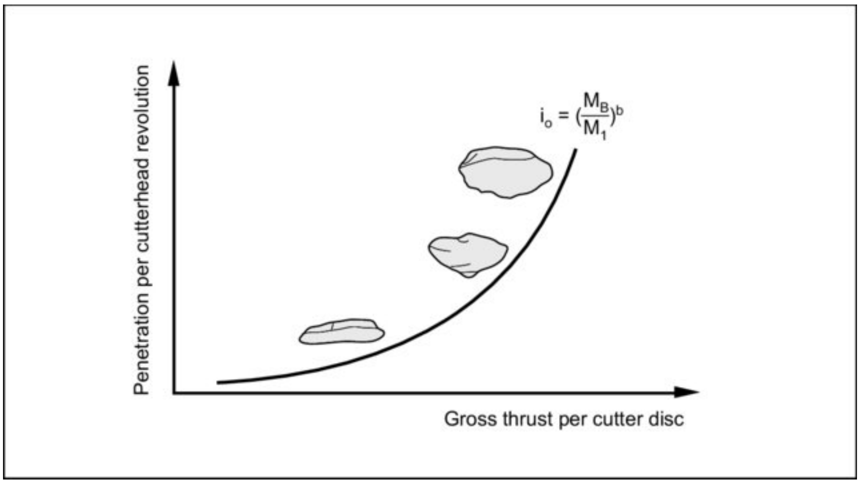


Figure 3.7: Penetration curve (Bruland, 1998b)

From the figure, one can see that high gross thrust induces higher indentation and greater chipping, resulting in greater penetration rate. The gross thrust is, however, limited by the maximum possible thrust and the fact that the rock mass properties might prevent full utilization of the available gross thrust force (Bruland, 1998b).

Considering rock mass properties, the rock mass fracturing and the intact rock properties is believed to be the most important geological parameters affecting the net penetration rate in TBM projects. (Macias *et al.*, 2014) looked into the influence of rock mass fracturing on the net penetration rate in hard rock TBM-tunneling, back mapping 1200 meters of excavated tunnel and analyzing the corresponding TBM performance data from a project on the Faroe Islands. The analysis showed a good correlation between rock mass fracturing, thrust, and the net penetration rate. From this study, one can see that the degree of fracturing influences net penetration rate significantly. In low fractured rock, the intact rock properties dominate the chipping as the boreability is governed by the rock drillability, resulting in low net penetration rate even at high thrust. Further, with increased fracturing, less thrust force is required to achieve higher net penetration rates or to maintain a desired rate.

Fractures can be understood as a general term for all types of discontinuities and planes of weakness in the rock mass (Macias, 2016), and generally enhances the chipping process as the rock mass is already partly broken. When boring in fractured rock, enhanced penetration rate can also be experienced from fallouts along weakness planes. This is due to the rigidity of the cutter head, which leads to unloading of the cutters located within the void area. As the cutters in the void area lose contact with the rock mass, the excess thrust from the unloading is transferred to the rest of the cutters which experiences increased effective thrust resulting higher penetration rate (Bruland, 1998b). High thrust force and fracturing generally increase the net penetration rate. However, the extent of fracturing and geological conditions like MFC, blocky ground, and weakness zones might cause operational machine problems requiring thrust force reduction or other operational measures that lower the penetration rate. The most common problems limiting the penetration rate and reducing the TBM performance is excessive wear and damage to cutters and abnormal vibrations.

In heavily fractured rock, extreme chipping might limit the penetration rate if the muck removal and or conveyer capacity is exceeded. Soft ground behavior from extreme fracturing or soils on the working face of hard rock TBM's might prevent cutters from rolling and or result in high indentation. Cutters prevented from rolling are likely to experience flat wear followed by lost functionality due to the gradual loss of effective contact stress under these cutters. The high indentation may result in friction between the cutter hubs and the working face, which increases the rotational resistance, possibly torque limiting the boring process and lowering the penetration rate. Momentary impact loads to the disc cutters due to a sudden increase in rock stiffness might cause significant damage to the cutters and induces abnormal vibrations, which can damage the TBM. Such momentary impact loads can be experienced when disc cutters traverse void areas, blocky fractured rock and areas on the working face with a sudden significant change in rock strength. When hazardous abnormal vibrations are detected, thrust force reduction is usually the countermeasure with a resulting reduction in penetration rate.

According to (Macias *et al.*, 2014), the first 270 meters of the 1200 meter long tunnel on the Faroe Islands were mixed face, described as basalt intrusions in a confining sill. Due to varying proportions of the two rock types and changing boreability over the 270-meter section, data from this section was omitted from the analysis on the influence of rock mass fracturing. No clear relationships were found in the MFC, and the difficulty of categorizing such conditions due to the wide range of lithologies and lack of a clear definition was recognized as the reason for omitting the MFC section from the analysis. According to (Blindheim, Grov and Nilsen, 2002) the probability of encountering several sections of MFC in hard rock tunnels is high. It is also emphasized that the effects of MFC could be hard to distinguish from those experienced in any hard rock with presence of fractures, for example, void areas from fallouts on the working face. Different types of MFC conditions, constantly changing geological properties in MFC zones, and the fact that MFC problems and effects can resemble effects seen in other geological conditions, somewhat complicates the quantification of problems and effects in MFC. When looking into the problems and effects of MFC and when analyzing TBM performance data, it is thus important to be aware of the possibility of misinterpretations when back mapping is limited.

An example of MFC influence on TBM performance can be seen from performance data recorded in the MFC encountered on the Faroe Islands. From the first 270 m, low thrust force is applied in an area where one according to theory should see high thrust due to the low fracturing mapped in this section. MFC properties have prevented full utilization of the available thrust force, and the result is a clear drop in net penetration rate in the following figure:

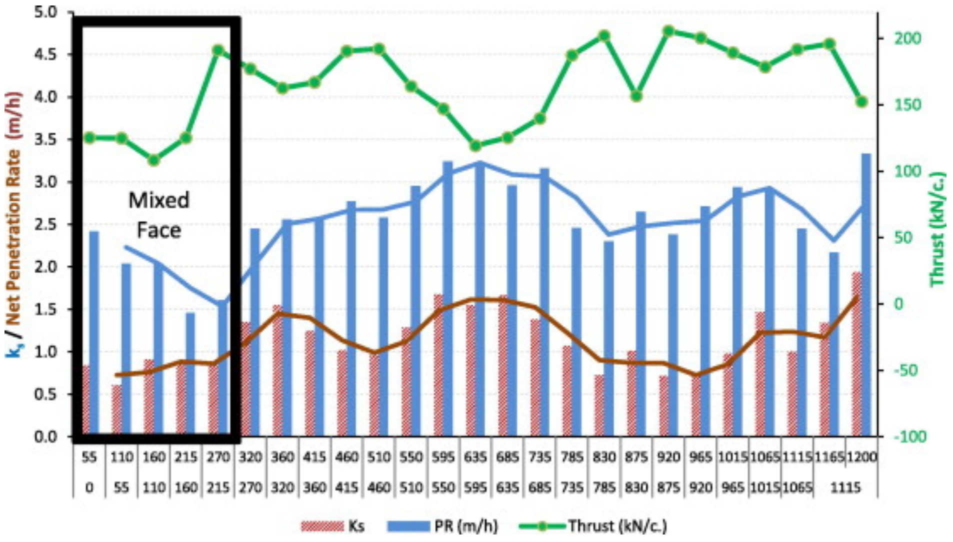


Figure 3.8: Net Penetration Rate, fracturing factor K_s and Thrust, along 50m weighted average sections observed in the Faroe Islands Project (Macias et al., 2014)

3.3 Hard rock MFC problems and effects on TBM performance

As the TBM performance is a result of the interaction between the rock mass and the TBM, dependent on rock properties and the TBM design and operation, one cannot expect the problems and effects of encountering MFC to be the same for any given TBM and type of MFC (Blindheim, Grov and Nilsen, 2002, Ma *et al.*, 2015). In general, MFC problems can be summarized as abnormal cutter wear, vibrations to- and variable loading of the cutter head, main bearings and rig, steering difficulties, unstable working face, ground settlements and problems with high water pressure and the clearance of excavated material. In hard rock TBM-tunneling, the most likely MFC compositions encountered are of the types LBR and RSI, which constitutes the following problems and effects:

3.3.1 Abnormal cutter wear

According to (Ma *et al.*, 2015), three aspects constitute problems with high abnormal cutter wear in MFC; a) Flat- and multi-flat wear, b) Breakage of the cutter ring or cutter bearing, and c) falling blocks from an unstable tunnel face destroying cutters and or the saddles.

a) The problem of flat- and multi-flat cutter wear from boring in MFC is further divided into three reasons by (Ma *et al.*, 2015): 1) In RSI, the soft ground portion may not induce the necessary rolling force to overcome the rotational resistance in the cutter bearings, leading to concentrated abrasive contact and eventually flat wear. If the flat worn surface does not develop too wide, the rotational resistance may increase sufficiently to induce rolling when the cutter reenters the hard rock portion, repeating the process and inducing multi-flat wear (Zhao, Gong and Eisensten, 2007). 2) The cutter housing is filled with excavated material that prevents the cutters from rolling, inducing flat wear. 3) Shock loads to the cutters in the sudden transition from soil to hard rock in RSI or soft rock to hard rock in LBR conditions can result in a short stoppage of rotation which again can induce the development of flat wear.

b) Transversal shock loads experienced by the cutters in the sudden transition from soil to hard rock in RSI or soft rock to hard rock in LBR can also induce breakage of the cutter ring or bearing. The cutter ring can experience chipping off flakes from the cutter edge and or damage to the bearing, which in turn can prevent rolling of the cutters and flat wear if cutters are exposed to abrasive contact at the working face. Extreme shock loads can also lead to cracking of the cutter ring.

c) Fallouts of blocks from the working face can damage cutters and or the cutter saddles

Abnormal cutter wear effects TBM performance as the utilization time of the TBM decreases with increased time being addressed to cutter change and the possible need for unscheduled cutter changes (Blindheim, Grov and Nilsen, 2002).

3.3.2 Vibrations & Uneven load distribution

According to (Blindheim, Grov and Nilsen, 2002), the transversal shock loads experienced by cutters in RSI and LBR conditions contribute to a variable and highly dynamic loading of the cutter head, inducing vibrations that can cause cracking of the cutter head and damage to the TBM. The rigidity of the cutter head forces all the cutters to progress with the same penetration per rotation, meaning that the applied thrust force is unevenly distributed between the weaker and stronger rock on the working face. In RSI and LBR conditions this uneven loading can induce large forces that have to be taken up by the cutter head, main bearing and the frame of the TBM. The uneven loading of the cutter head can also lead to difficulties steering the TBM.

Through various references on TBM-tunneling in MFC presented by (Steingrimsson, Grøv and Nilsen, 2002), the main indication of MFC presence are the abnormal vibrations experienced by the operators. To reduce vibrations, overloading, excessive wear to cutters and possible course deviation, thrust and or RPM is usually reduced (Blindheim, Grov and Nilsen, 2002, Bruland, 1998b, Ma *et al.*, 2015, Macias *et al.*, 2014, Macias, 2016, Steingrimsson, Grøv and Nilsen, 2002, Tóth *et al.*, 2013). Reducing thrust force, RPM, or both of these operational parameters, the TBM performance is affected negatively by the following reduction in advance rate and following project delay (Tóth *et al.*, 2013). Cracking of the cutter head or damage to the TBM will potentially require challenging and time-consuming repairs, with the following delay in project advance (Blindheim, Grov and Nilsen, 2002).

3.4 Predicting the presence of MFC from TBM performance data

From the descriptions of the problems and effects encountered in Hard Rock MFC, the possible correlations between the resulting TBM performance data and the presence of MFC should be observed as an evident reduction in penetration rate from reduction in thrust force and RPM. However, no clear attempts are found in the literature on quantifying the level which one should reduce these operational parameters to handle MFC problems and effects adequately. (Blindheim, Grov and Nilsen, 2002) did suggest that a reduction of thrust force to 85-90% should account for MFC of the type LBR unless the difference in strength ratios were to be very high. If reductions in RPM proves necessary, a further suggestion implies a reduction of RPM by the same percentage as thrust force. From (Steingrimsson, Grøv and Nilsen, 2002) it is noted that lower torque can be seen when soft rock/soil is present on the working face, which would constitute MFC of RSI type.

3.5 Substantiation of MFC presence from TBM cutter data

From the problem with abnormal and excessive cutter wear, MFC can induce the need for unscheduled cutter changes. Cutter changes are usually done in specific intervals, however, if MFC prevails it may be necessary to perform unscheduled changes which can be seen from the cutter change log if otherwise changed according to schedule. When conducting cutter changes, the position of the changed cutters on the cutter head is recorded together with the wear pattern that induced each respective change (Bruland, 1998a). Cutter data can also be used to calculate the cutter life between cutter changes if the amount of wear on each cutter is recorded accordingly. If cutter life can be calculated, one should see a reduction in cutter life in the aftermath of zones with MFC presence (Myrlund *et al.*, 2019). It is thus, to a certain extent, possible to substantiate the presence of MFC from cutter data. Interesting signatures found in the TBM performance data which are followed by unscheduled cutter changes recordings an abnormal amount of blocked, cracked or oil leaking cutters, hence substantiates assumptions on MFC presence from the signatures observed in TBM performance data. From observations of cutter consumption in rock mass with layer-banded rock, described as marked single joints, (Bruland, 1998b) indicates that one can expect an increased in cutter consumption of 15%. In general, increased cutter consumption could be seen as a significant deviation from the average consumption.

3.6 Ground Characterizations in the Follo Line TBM sections

The ground characterization is based on the Geotechnical Baseline Report UFB-30-A-30065 (Jernbaneverket, 2014a, 2014b). According to these reports, the TBM sections of the Follo Line tunnel alignment are situated in three various Precambrian gneiss formations. Having similar mechanical properties and being hard to visually separate, these gneiss formations are summarized as one rock type. The gneiss rocks are however described to have pronounced foliations, giving the rock mass a clear anisotropic mechanical behavior. Further, the gneiss formations have intrusions from the Perm period and amphibolite dykes/sills. The amphibolitic dykes/sills are described to have a thickness in the range of decimeters to meters and some above 10 meters. At approximately km 7.8, the tunnel alignment crosses one rhomb-porphyry dyke ranging 20-30 meters in thickness (Jernbaneverket, 2014a).

According to (Jernbaneverket, 2014b), multiple rock mechanical test was conducted on rock samples from the area of the tunnel alignment. These tests show low to very low drillability and high to very high rock strength. From cutter life index tests, the mean cutter life is categorized as low, but results deviate within the range of medium cutter life and up to extremely low cutter life.

Two main joint sets are indicated along the tunnel alignment, mostly planar and characterized as smooth to rough. One joint set is following the foliation of the rock mass in an NW-SE to N-S orientation, dipping westwards (35°-90°) and averagely spaced at 0.5 m to 1.1m. The other joint set is steeply dipping at an E-W oriented strike, averagely spaced at 0.2 m to 2.0 m. Several weakness zones intersect the tunnel alignment, described to occur as heavily jointed rock mass with minimal soil content or as crushed zones with clay transformations. The rock mass is anticipated to follow the behavior of an unsupported full-face excavation with the potential of small local gravity induced falling or sliding of blocks. Occasional falling and sliding of blocks due to shear failure on discontinuities are assumed on the working face. Smooth joints and crushed zones contribute to reduced shear capacity. Most importantly, MFC is assumed to occur over approximately 15% of the tunnel, described through examples as the following (Jernbaneverket, 2014a):

“Mixed face conditions are likely to occur. An example of mixed face may be a very hard amphibolite with UCS of 250 MPa mixed with gneiss with UCS of 100 MPa. Another example may be a combination of solid rock and a weakness zone.”

Bedrock and mapped weakness zones along the northbound section of the tunnel alignment is presented in APPENDIX–A, covering the full length of the tunnel where TBM-data are provided by Bane NOR for analysis.

3.7 Follo Line TBM’s

Table 3.1: Some main design parameters for the TBM’s used on the Follo Line (Kalager and Gammelsæter, 2019)

Item	Specifications
Installed power	Approx. 6900 kW
TBM cutting diameter	9.96 meters
Cutter size	19’’ wedge lock, back-loading
Number of cutters	71 cutters
Load per cutter ring	315 kN
Max. Rec. cutter head load	22 365 kN
Cutter head rotational speed	0 – 6.06 RPM
Max overload torque	16 672 kNm at RPM of 3.67

Table 3.2:Net Rates of penetration including probing and pre-grouting by August 2018 (Kalager and Gammelsæter, 2019)

Rate of penetration mm/min	Maximum	Average	Minimum
Northbound machines	52.93 mm/min	31.05 mm/min	14.94 mm/min

Table 3.3: Advance rates including probing and pre-grouting by end of August 2018 (Kalager and Gammelsæter, 2019)

Advance rates	Average	Highest
Day	14.1 m	31 m
Week	85 m	144 m
Month	364 m	568 m

3.8 TBM data information

Unfiltered TBM performance data and cutter change data were provided for the northbound machine of the nickname Eufemia. The provided data covered the whole length of the excavated 8880 meters, containing the following information:

Table 3.4: Parameters in unfiltered TBM performance data of Eufemia (Bane NOR)

Parameter	Unit	Comment
Timestamp	dd.mm.yyyy HH:MM:SS	24-hour clock
Ring Number	number	Ring lining of 1.8m in width
Main Drive Speed	rotations/min	RPM
Advance Speed	mm/min	
TBM Station	chainage number	Recording on sinking chainage
Advance Thrust Force	kN	
Main Drive Torque	kNm	
Penetration	mm/rotation	Penetration Rate

Table 3.5: Cutter data parameters (Bane NOR)

Parameter	Unit	Comment
Timestamp	dd.mm.yyyy	
TBM station	chainage number	
Bored meters	meters	Between changes
Cutter consumption	number	Per change, per week and monthly
Cutter change	type of wear	Position of changed cutter
Ring wear	number	Degree of wear for each cutter at their respective position

Chapter 4

Research Methodology

Prior to this Thesis, the topic of MFC within hard rock TBM-tunneling was studied through a Specialization Project carried out during the fall of 2018. The purpose of this pre-project was to gain first-hand insight into significant literature and up to date knowledge on the topic. A scoping literature review was conducted to establish a qualitative knowledge platform on MFC and TBM performance data. This platform was furthermore used to define the objective, problem statement, and research methodology for this Thesis. The specialization project also included the initial development of the MATLAB raw-data filter code of this Thesis, a filter that is applied to the raw TBM performance data to make it suitable for quantitative analysis.

4.1 Literature review

The scoping literature review conducted in the prelude of this Thesis mostly consisted of searching online bibliographic databases for papers published in international journals which assures the quality of the literature. Literary searches have supplemented the initial review throughout the work on this Thesis. Discussions with supervisors, looking into the references list of recognized literature and literary sources provided by supervisors is highlighted. Literature has been searched solely on the topic of hard rock TBM-tunneling, and this Thesis refers to both English and Norwegian literature on this topic. The author recognizes the literature review as important to the qualitative evaluations found in this Thesis and gives context to the quantitative research.

4.2 Filtering TBM data

Bane NOR provided the unfiltered TBM performance data with the following description on accuracy and applicability; *"The raw-data is completely unfiltered and needs to be examined thoroughly before being analyzed,"* meaning as recorded by the TBM performance logging system. Set to analyze the TBM performance data solely from the actual boring operation, data recorded during other operational activities would need to be filtered out. In addition, non-representative and unrealistic recordings must be filtered out to achieve a representative set of data. Bane NOR informed that special awareness should be applied to the following when filtering the TBM performance data:

I. Holes in the data due to downtime on the logging system
II. Halts in production followed by non-representative performance recordings from the phase of restarting the boring operation
III. Recordings of non-representative performance during retraction of the cutter head from the working face
IV. Unrealistic performance recording due to errors in the logging system
V. Misinterpreted TBM performance in weakness zones and special geological conditions as error recordings

The logging system of the Follo Line TBM recorded eight excavation parameters for a default time step of 10-30 seconds during the entire two-year excavation, equivalent to a dataset containing 8 columns and a total of 1 648 904 rows of data. Such big datasets are difficult and insufficient to handle manually. Based on the list above, a filter consisting of three filter operations have thus been developed in this Thesis using the mathematical computational software MATLAB. The basis and description for each of these filter operations follow, and a stepwise explanation is furthermore found in the code attached in the APPENDIX–B. MATLAB, as a powerful tool for processing big data matrices, were also used to reduce noise, plot and analyze the TBM performance data after filtering.

4.2.1 Filtering on TBM station number

Holes in the TBM performance data, retraction of the cutter head and unrealistic TBM position recordings can be detected from the recorded TBM station number. The TBM station number denotes the position of the TBM and its performance to a reference point. For the TBM's used at the Follo Line, this reference point is related to the starting point of the future railroad. The Norwegian railroad network uses kilometer chainage as a distance reference model to get exact indications of respective locations along the different railroad lines. The kilometer reference chainage along the future Follo Line railroad has its start and zero-point in Oslo and increases southbound towards the terminus in the city of Ski. All four TBM's used in the project were assembled in a pre-blasted assembly hall midway along the tunnel alignment, meaning that the northbound machines have been excavating on a decreasing TBM station number and the southbound on increasing.

Cutter head retraction of the northbound TBM of Eufemia can thus be seen as a sudden increase in recorded station numbers, as the station numbers are to continually decrease during the actual boring operation. Holes in the performance data can be detected from sudden jumps in the recorded TBM stations where the station number decreases more than a predefined jump length limit. The starting position of Eufemia was at the chainage point of 11780, and the machine had its breakthrough at chainage 2890. Unrealistic TBM station recordings can be detected either as station numbers recorded outside of the chainage range from 11780 to 2890 or as misplaced recordings in an otherwise continuously decreasing record. The presence of unrealistic station recordings can be visualized from plotting the recorded TBM stations in the unfiltered data to the length of the unfiltered dataset. In the following figure, the vertical droppers represent unrealistic recordings.

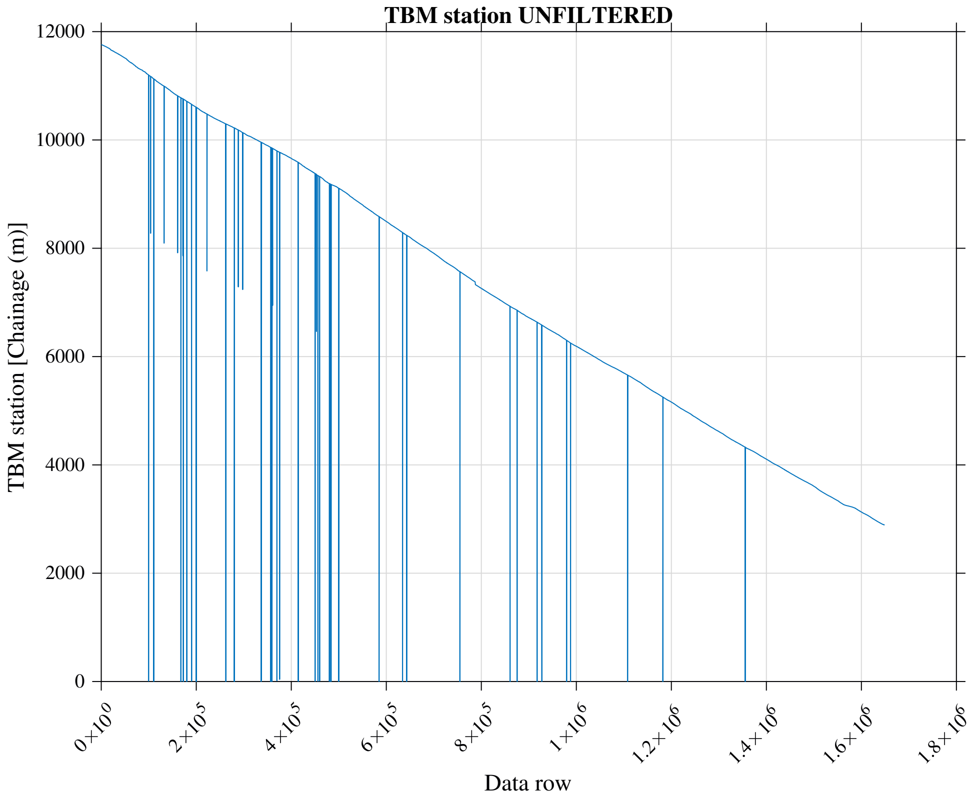


Figure 4.1: TBM Stations to the length of unfiltered Raw-data

Retractions of the cutter head, holes in the data and unrealistic recordings are detected by the filtering code and their position in the unfiltered reference data stored so that results can be investigated and confirmed. The original raw data is also stored and used as an unfiltered reference data so that the effect of filtering can be compared and analyzed to the unfiltered data. Based on the position of the detected recordings in the unfiltered data, TBM performance confirmed to be recorded during reattraction of the cutter head, and unrealistic recordings are filtered out, and a filtered dataset output is established. The output data from filtering by TBM station number presents a dataset with a continuously decreasing TBM station numbering, consisting of data solely from the actual boring operation which addresses points I, III and IV in the list of awareness.

4.2.2 Filtering on timestamp

Recording TBM performance data in 10-30 second intervals, the logging system assigns the recorded performance to a timestamp for each respective time interval. The timestamp consists of the date and time of each recording. Halts in production can be seen from the timestamp as a change in date and or in time higher than the default time step of the logging system. A change in timestamp can indicate a hole in the data and may be misinterpreted as a real halt during production if not controlled and confirmed. The presence of real halts can be substantiated from looking at the corresponding recordings of TBM station number, as the position of the working face at real halts shall remain unchanged when the boring operation restarts. According to Bane NOR, the performance recorded within the first 1-3 minutes before the actual boring operation is fully resumed, may not represent the actual performance and should be filtered out.

The filtering code detects all changes in the recorded timestamp greater than two times the default time step, which is set equal to a criterion of 1 minute in the data already filtered on TBM station number. To separate real halts from holes in the data, timestamp changes detected from the time criterion are controlled to changes in the corresponding recordings of TBM station numbers and the affiliating ring number. The ring number denotes the number of the last concrete lining ring to be mounted behind the cutter head. With a width of 1.8 meters, the concrete lining ring number increases by one for every 1.8 meters of the excavated tunnel. The recorded ring number substantiates the presence of holes longer than 1.8 meters in cases where the TBM station number erroneously have remained unchanged for timestamp and ring number recordings showing clear indications of holes. Such holes are not detected when filtering on TBM station numbers alone.

The positions of real halts in the filtered data are stored, and the consecutive recordings from the initial phase after restarting is analyzed for the presence of non-representative TBM performance data. Rock mass properties before and after real halts are unchanged and similar performance is assumed when full actual boring operation is resumed. The filter code thus checks the median TBM performance records of thrust force and penetration rate for approximately 3 minutes prior to each halt. The median is used instead of the mean, as a measure to exclude the possible influence of previous non-representative recordings that can be given unrealistic weight when averaging. Further, for each halt, the code checks if and when the TBM reaches 80% of the pre-halt median within the first 3 minutes of the restarted actual boring operation. The TBM might not reach the pre-halt medians if operational adjustments have been conducted during a halt. Real halts and non-representative recordings are thus handled by filtering out all recordings between detected real halts and the point of 80% resumed performance, however, limited to 3 minutes if pre-halt medians are not reached within the first 3 minutes of actual boring, addressing point I and II.

4.2.3 Filtering of unrealistic TBM performance recordings

The logging system can record unrealistically large or small recordings of TBM performance parameters. Such values are typically recorded during the process of retracting the cutter head or pushing it back towards the working face. Unrealistic performance can also appear in the recorded TBM performance from error recordings during excavation. The basis for first to filter on TBM station number and secondly timestamp in the filter code is to filter out all non-representative recordings from other operational activities and the initial phases after restarting the actual boring operation. Unrealistic recordings from the actual boring operation require further analysis as they can cover up significant signatures and lead to misinterpretation of the data.

It is essential to distinguish very high and low recordings of TBM performance due to local geology like weakness zones from unrealistic performance recordings. The developed code for filtering of unrealistic values is thus based on the machine specifications and scatter- and normal-distributions of the Advance speed and Penetration, controlled against the geology.

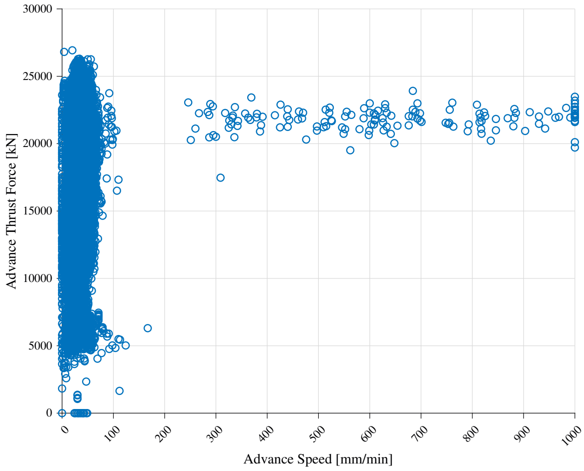


Figure 4.2: Advance speed vs. Thrust force before filtering of unrealistic recordings

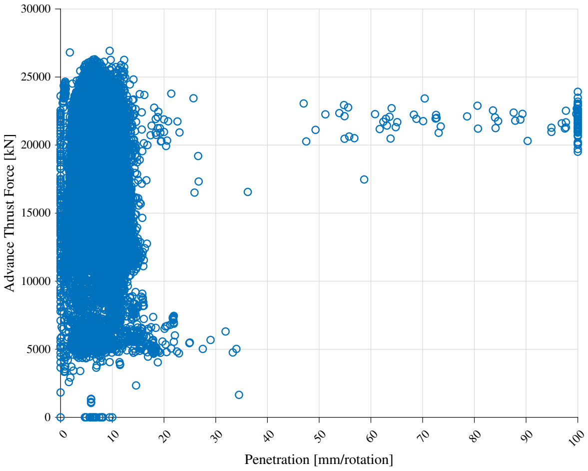


Figure 4.3: Penetration vs. Thrust force before filtering unrealistic recordings

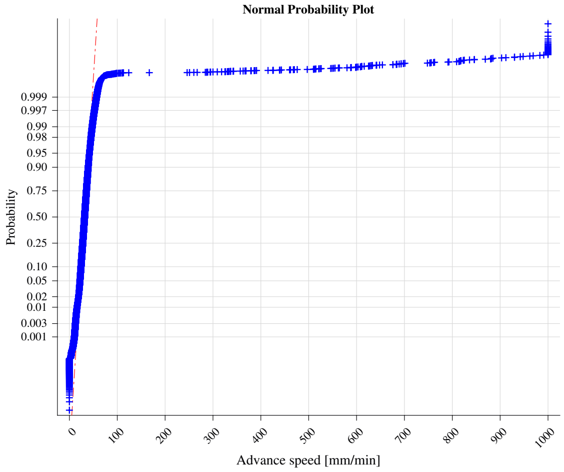


Figure 4.4: Normal distribution of Advance speed recordings before filtering of unrealistic recordings

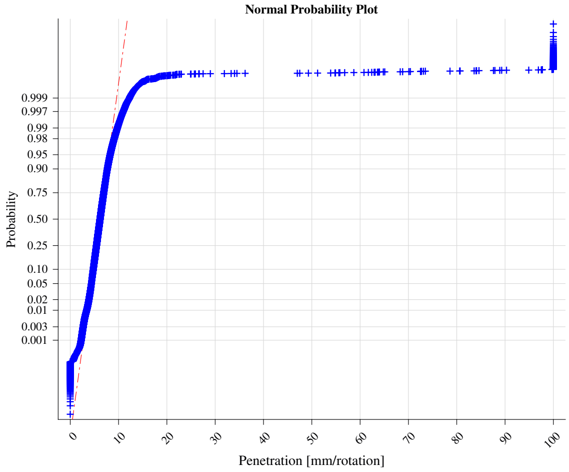


Figure 4.5: Normal distribution of Penetration recordings before filtering of unrealistic recordings

Recordings that show TBM performance greater than physically possible from machine specifications and design are unrealistic. From the scatter plots and normal distributions, one can see that some recordings of very high magnitude are present in the data even after filtering the data to contain recordings solely from actual boring. The recordings of greatest magnitude cannot be achieved during TBM boring, and most of these recordings are also outside the 99.9% percentile. According to (Kalager and Gammelsæter, 2019), the RPM of the machines were within 0-6.06 and the maximum advance speed experienced by the northbound machines 52.93 mm/min, including probing and pre-grouting. From the data filtered on TBM station and timestamp, TBM performance was found to be within the RPM range and the advance speeds within the 99.9% percentile, close to the reported maximum although conservatively not adjusted for other operational activities.

From the analysis on unrealistic recordings, it was found realistic to filter out Advance speed recordings above 75 mm/min and Penetration recordings above 25 mm/rotation. Few recordings are found for Thrust forces below 5000 kN and some recording show progression of the cutter head even for zero applied thrust force which is considered unrealistic. The filter code is thus developed to consider all recording below 3550 kN, corresponding to 50 kN/cutter, to be unrealistic. The chosen filter-criterions for filtering on unrealistic recordings were further substantiated by looking into the data filtered by these criterions and their relation to the geology and position in the fully filtered data.

The data recordings filtered as unrealistic from the above criterions showed little to no coherence to adjacent recordings or correlation to the geology and were mostly single deviations. Based on the author’s knowledge about the geology, only one questionable zone was found in the area within chainage 3770-3650, where unrealistic recordings appeared in groups. Showing reasonable, it was decided to go with the above criterions and the filter code filters out unrealistic recordings to address point IV and V, presenting a dataset filtered according to all points in the list of awareness.

4.3 TBM-data Analysis

A possible correlation between TBM performance data and the presence of MFC was analyzed by visually interpreting plots of filtered TBM performance data and cutter change data. This was done based on the up to date knowledge on MFC theory in hard rock conditions and the available information on geology. Interesting signatures found from the plots were further compared to geological face mappings where these were available.

4.3.1 Plotting TBM performance data

From the common TBM operational adjustments done in MFC described in the literature, it was decided to plot the Advance thrust force, RPM, and Penetration rate to the TBM station number. With access to the cutter change log and wear descriptions, signatures in the plots of the three performance parameters were compared to the cutter wear pattern along the chainage of the tunnel. When filtered, the TBM performance data set still contains a significant amount of data showing the behavior of pulsating and jagged signal data when plotted. When plotted without reducing noise, it is difficult to suitably interpret the data from visual inspection as important patterns may remain undetected due to the noise. This can be seen from plotting the filtered data without reducing noise by smoothening the data.

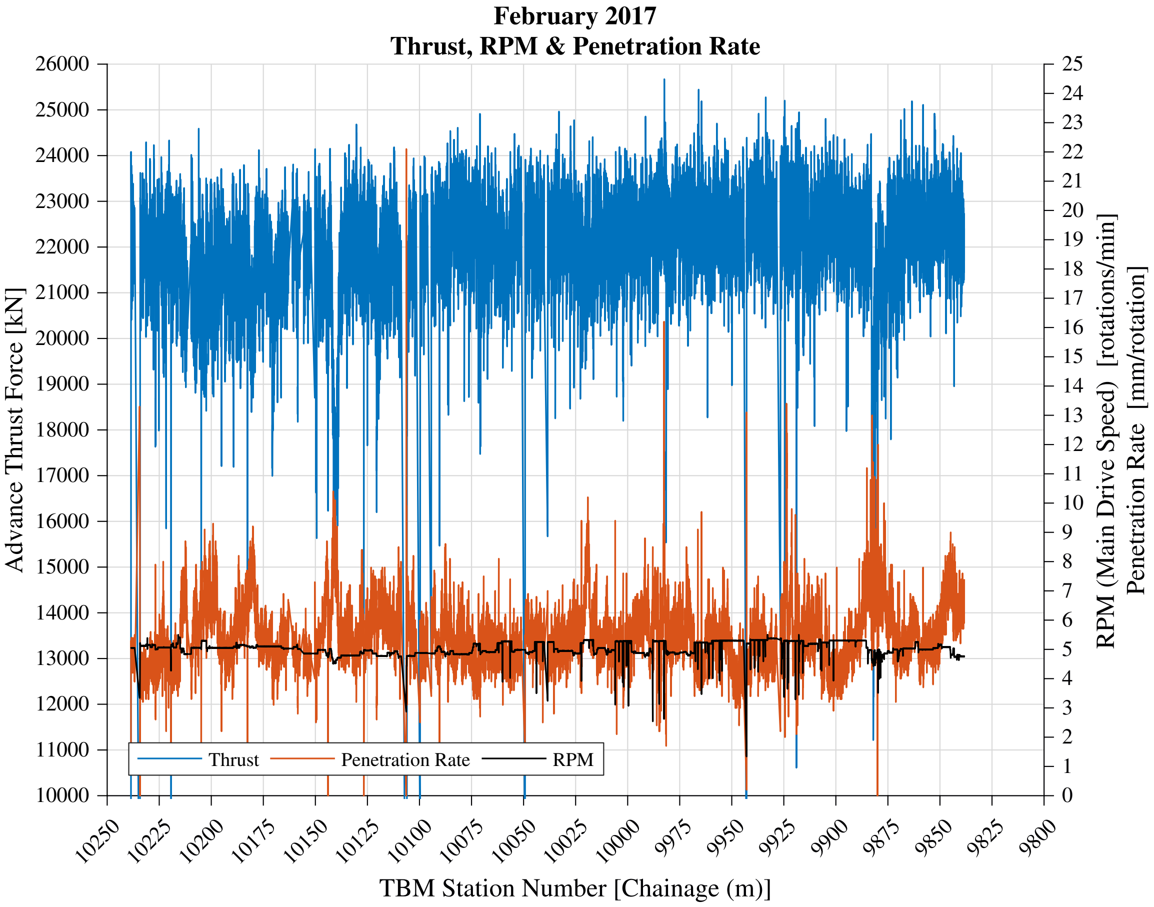


Figure 4.6: Example of TBM performance data for February 2017 without noise reduction

To better capture important patterns and signatures in the TBM performance data, the data were smoothened. Smoothening implies approximating a function to the data, which reduces noise and captures important patterns and signatures. There are multiple smoothing algorithms, moving average being a common one. To reduce noise in the filtered TBM performance data, the Savitzky-Golay noise filter in MATLAB was used. Different smoothing algorithms were considered but Savitzky-Golay noise filtering chosen as it is effective to data that varies rapidly and gentler to outliers in the data which were essential for the analysis. Savitzky-Golay is based on the least-squares fitting of polynomials over a specific sliding window of data points. The window is centered around the current data point, meaning that for a window of 1000 points, each point is a Savitzky-Golay fitting of the 500 previous points and the 500 consecutive. For the endpoints of the data, MATLAB adjusts the window depending on the data points available.

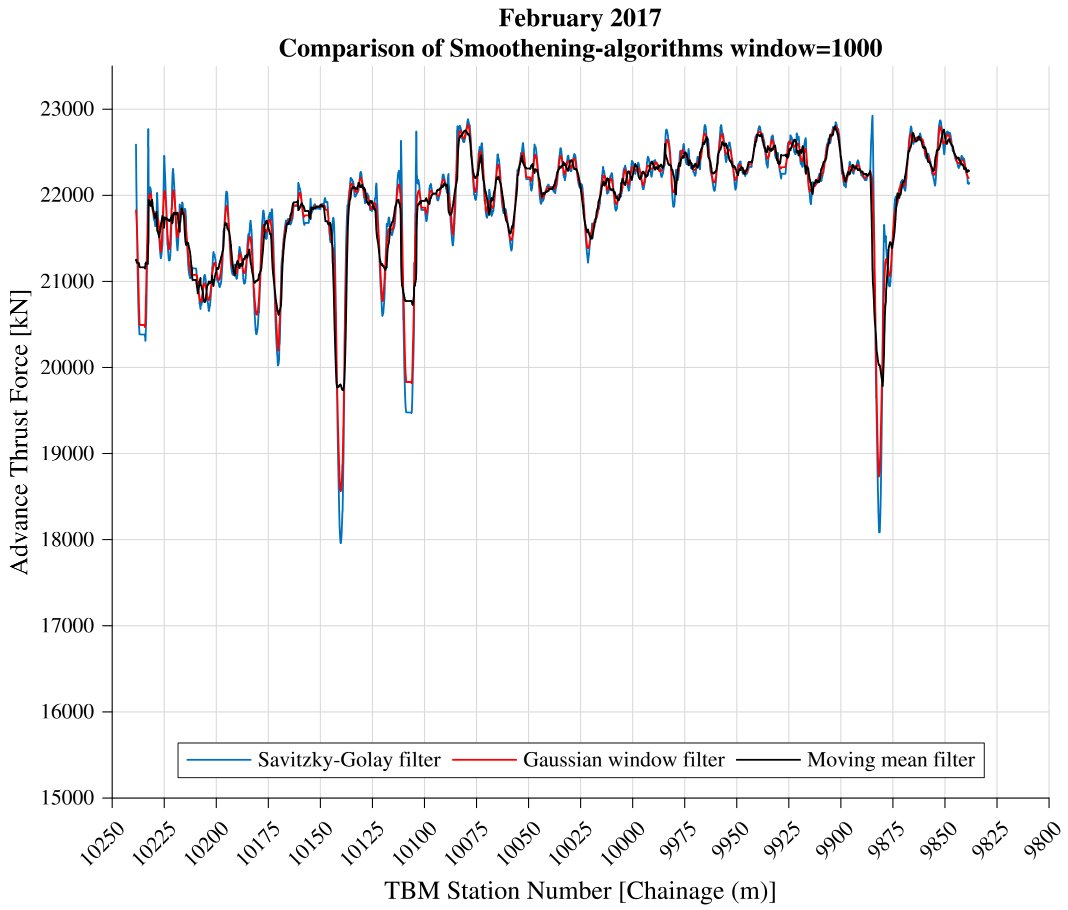


Figure 4.7: Comparison of three data-smoothening algorithms

A window of 500 data points from the filtered TBM performance data corresponds to approximately 2.5 meters of the tunnel in the filtered data. The result from reducing noise in the plot of TBM performance of February 2017 by a window of 500 can be seen from the following:

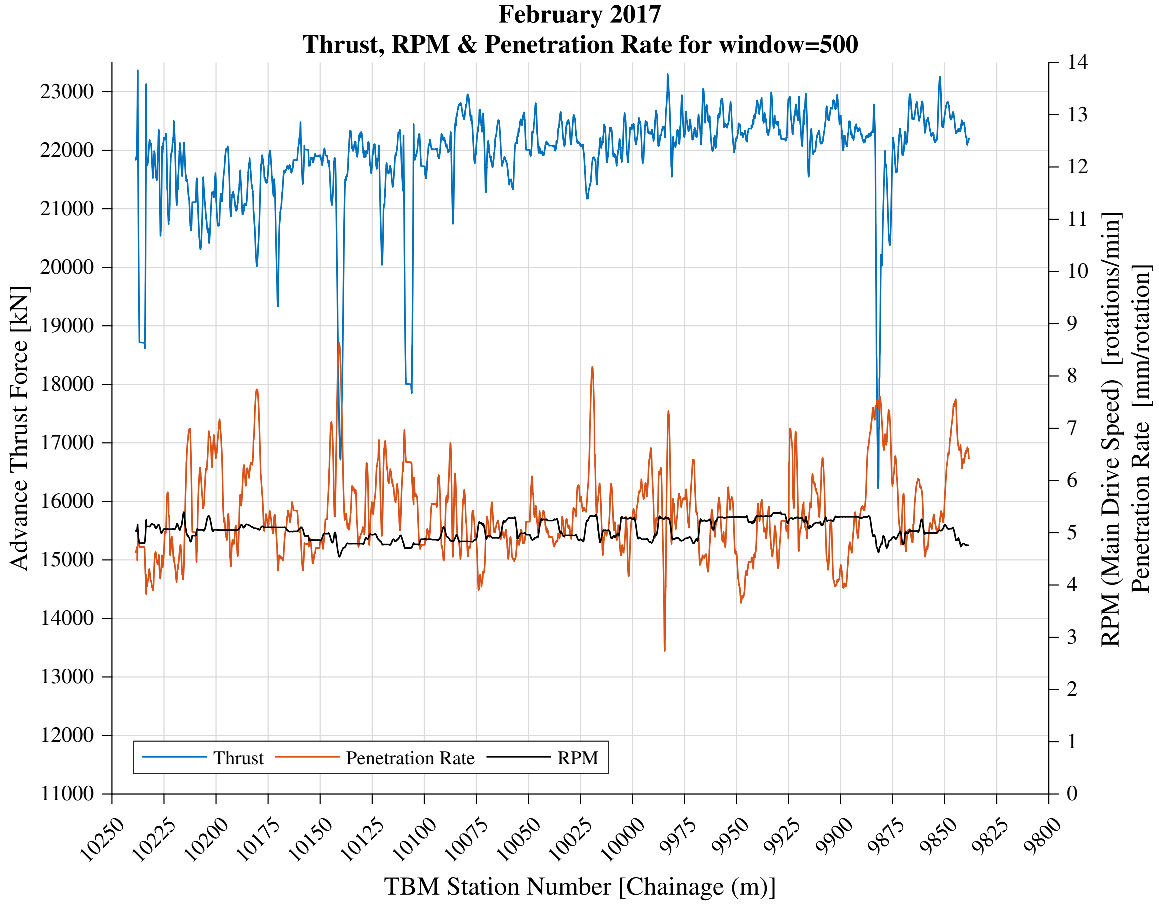


Figure 4.8: Example of TBM performance data for February 2017 noise reduced using Savitzky-Golay filtering

4.3.2 Plotting cutter data

Two cutter change parameters were used in the analysis, the cutter life measured in cubic meters per cutter and the number of cutter changes to the type of wear which constituted the cutter change. Bane NOR provided the cutter data of TBM Eufemia, recorded and presented on a monthly basis. Extra awareness was assigned the evaluation of results from the cutter data as it was informed that the data could contain errors in the recorded wear and in the macros. To calculate the average cutter life in cubic meters per cutter for each cutter change recording, the TBM Instantaneous Cutter Consumption Database of (Frostad, 2013) was used. Since the cutter change recordings display the monthly cutter consumption, the cutter life and TBM performance were plotted accordingly, meaning for each respective month presented as follows:

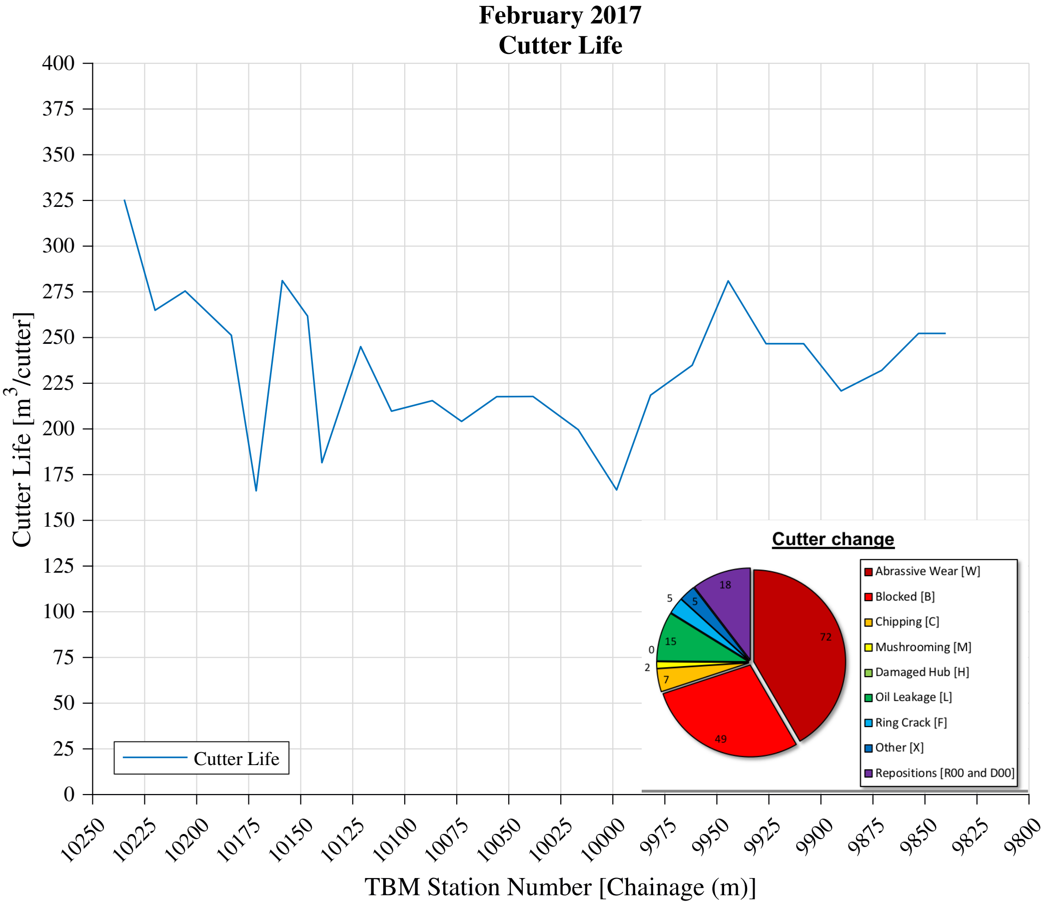
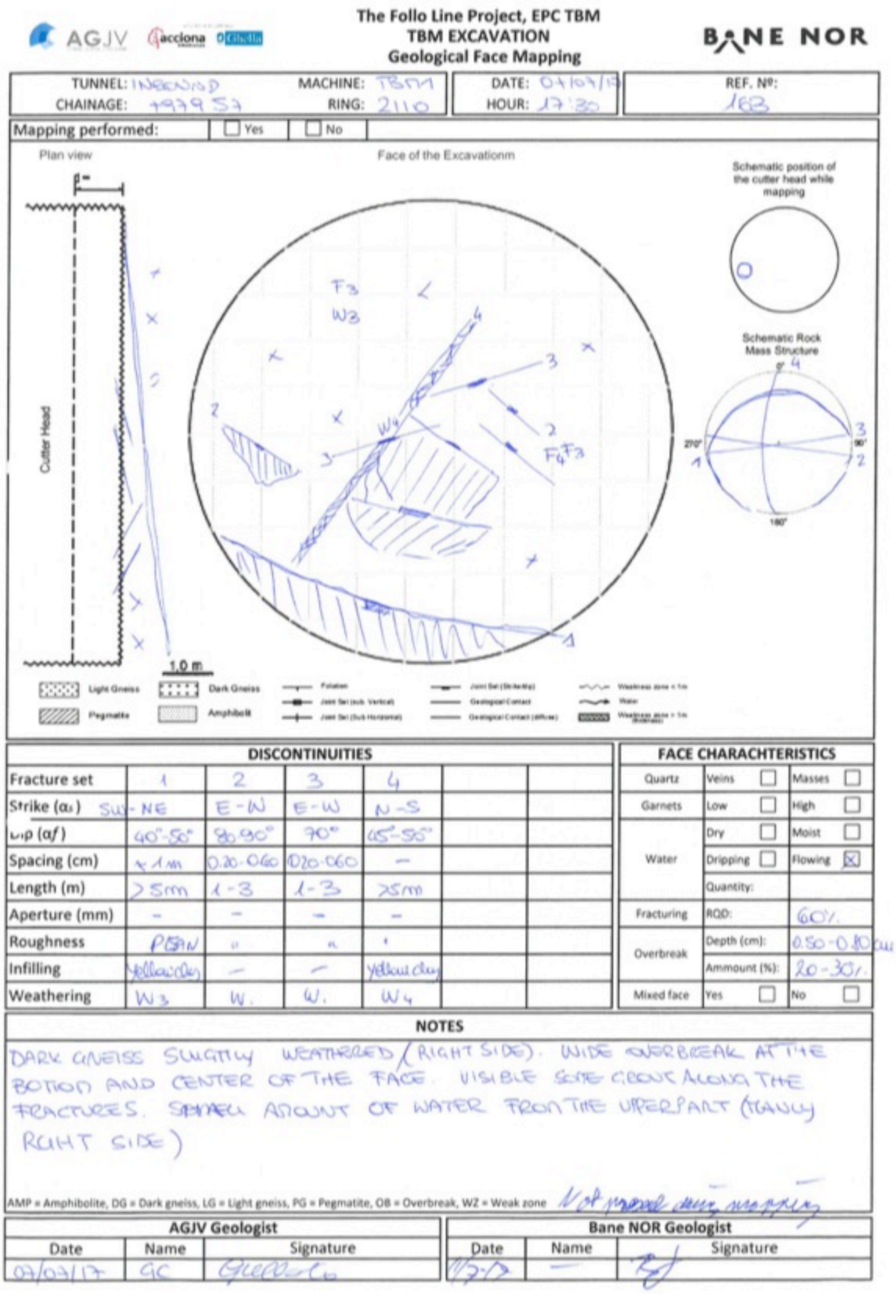


Figure 4.9: Cutter Life and Cutter consumption of February 2017

4.3.3 Comparison to Geological face mappings

Geological face mapping was made available by Bane NOR for some interesting chainages within the analyzed tunnel section. The geological face mappings contained a geological description of the current working face made by an engineering geologist on site, supported by photos of the working face. These mappings and photos were used in the analysis to further substantiate presumed MFC, but also to investigate some weakness zones and other interesting signatures where mapping was available for comparison. An example of the geological face mappings at the Follo Line project is attached.



The Follo Line Project, EPC TBM
TBM EXCAVATION
Geological Face Mapping

AGJV acciona Ghella BANE NOR

TUNNEL: INBOUND	MACHINE: TBM1	DATE: 04/04/17	REF. Nº:
CHAINAGE: 4979 57	RING: 2110	HOUR: 17:30	163

Mapping performed: ☐ Yes ☐ No

DISCONTINUITIES						
Fracture set	1	2	3	4		
Strike (αs)	SW-NE	E-W	E-W	N-S		
Dip (αf)	40°-50°	80-90°	70°	45°-55°		
Spacing (cm)	≈1m	0.20-0.60	0.20-0.60	–		
Length (m)	>5m	1-3	1-3	>5m		
Aperture (mm)	–	–	–	–		
Roughness	PLAN	"	"	"		
Infilling	yellow clay	–	–	yellow clay		
Weathering	W3	W.	W.	W4		

FACE CHARACHTERISTICS		
Quartz	Veins ☐	Masses ☐
Garnets	Low ☐	High ☐
Water	Dry ☐	Moist ☐
	Dripping ☐	Flowing ☒
	Quantity:	
Fracturing	RQD:	60%
Overbreak	Depth (cm):	0.50-0.80 cm
	Ammount (%):	20-30%
Mixed face	Yes ☐	No ☐

NOTES

DARK GNEISS SLIGHTLY WEATHERED (RIGHT SIDE). WIDE OVERBREAK AT THE BOTTOM AND CENTER OF THE FACE. VISIBLE SOME GROUT ALONG THE FRACTURES. SMALL AMOUNT OF WATER FROM THE UPPERPART (MAINLY RIGHT SIDE)

AMP = Amphibolite, DG = Dark gneiss, LG = Light gneiss, PG = Pegmatite, OB = Overbreak, WZ = Weak zone

Not mapped during mapping

AGJV Geologist			Bane NOR Geologist		
Date	Name	Signature	Date	Name	Signature
07/04/17	GC		11/7-17	–	

Figure 4.10: Example of geological face mapping at the Follo Line (Bane Nor)

4.3.4 Analyzing data

Analyzing the filtered and smoothened TBM performance data for the presence of MFC, it was decided to look at the data from approximately TBM station 10 000 to 3000. This was due to the northbound machines crossing over each other in the chainage area of 11 000 to 10 000 and the breakthrough of TBM Eufemia at 2890. For these areas along the tunnel chainage, the machine operational parameters seemed to be adjusted to achieve a gentler excavation progression, and the following recordings of TBM performance were thus considered non-representative to the analysis. As the cutter change recordings displayed the monthly cutter consumption, it was decided to analyze the TBM performance data for each month within the approximately chainage range of 10 000 to 3000. This range corresponded to analyzing the TBM performance recordings from the start of February 2017 to the end of August 2018, or more specifically the chainage from TBM station 10 238.6 to 2954.2.

Based on the theory of MFC presence in hard rock TBM tunneling, MFC should be visually observed as an evident reduction in penetration rate from reduction in thrust force and RPM. As no specific quantification of the level which one reduces these parameters when encountering geology of MFC significance is found, the suggestion by (Blindheim, Grov and Nilsen, 2002) is used as a reference when looking for MFC signatures. According to (Blindheim, Grov and Nilsen, 2002), a reduction in thrust force or both thrust and RPM by 10-15% would account for the undesirable impact loads experienced in MFC. Based on the ground characterizations, the TBM was assumed to have experienced similar rock mass properties along the tunnel section to be analyzed. With little change in rock mass properties, only signatures showing close to 10-15% reduction in the median thrust and -RPM were thus considered possible MFC. Further, as an evident reduction in penetration rate should follow the reduction of thrust and RPM according to theory, only signatures also showing a reduction in penetration rate were considered possible MFC. No specified constraints were set for the length of signatures to be considered as MFC.

The TBM performance was plotted using the described smoothening with a window of 1000 data points, equal to approximately 5 meters of excavated tunnel. Know weakness zones were marked in the plots according to the geological profile in APPENDIX–A. The signature of these weakness zones was addressed special awareness when analyzing as they could show similar behavior as expected for MFC. Torque as a performance parameter mentioned in theory was not considered in the analysis.

The following stepwise approach was used when analyzing the filtered data for the presence of MFC through visual investigation of TBM performance and cutter data plots:

1. Started by looking at the monthly cutter consumptions from the cutter data. Months with high numbers of cutters replaced due to the damage typically found in MFC according to theory was analyzed first, meaning wear patterns of the type; Blocked, Oil Leakage, Ring cracking, chipping and damaged hubs.

2. Looked to see if there were signatures with a significant reduction in thrust force and RPM (85-90% reduction from the median) correlated to a noticeable reduction in penetration rate within the months of interest. Zones of interest were marked out in the plots of TBM performance, including weakness zones.

3. Checked if zones considered to have MFC signature were followed by a reduction in average cutter life, by looking at cutter life within and in the aftermath of the marked zones from point 2.

4. Did a final check for the possibility of determining a correlation between TBM performance data and the presence of MFC, by controlling the marked zones to geological face mappings and photos made available by Bane NOR within the chainage of some of the marked zones.

4.4 Field trip

A field trip to the Follo Line project rig at Åsland was conducted in mid-March 2019. By mid-March, all the four TBM's had had their breakthrough and TBM work consisted of dismantling the machines. Due to D&B work on cross-passages between the northbound tunnel tubes, the tunnel from which TBM performance data was provided was not accessible for inspection. Instead, a trip through one of the southbound tunnel tubes was made by car from Åsland to the back rig of the respective TBM in Ski where the TBM could be inspected. The field trip was conducted with the intention of getting a first-hand insight on the extent and proportions of the project and TBM's. A meeting with Bane NOR was also carried out during the visit to discuss the chosen approach towards the problem statement, different questions, and the work conducted at the time.

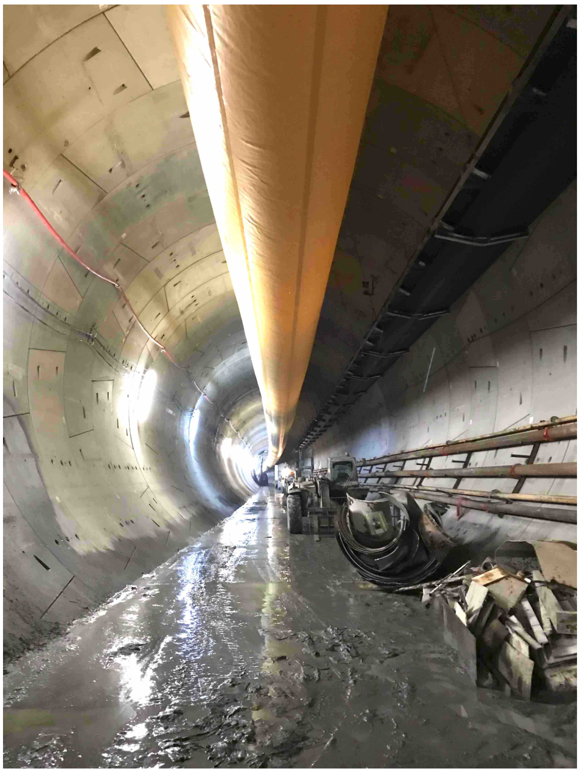


Figure 4.11: Finished tunnel lining in the inspected southbound tunnel tube (Field trip)

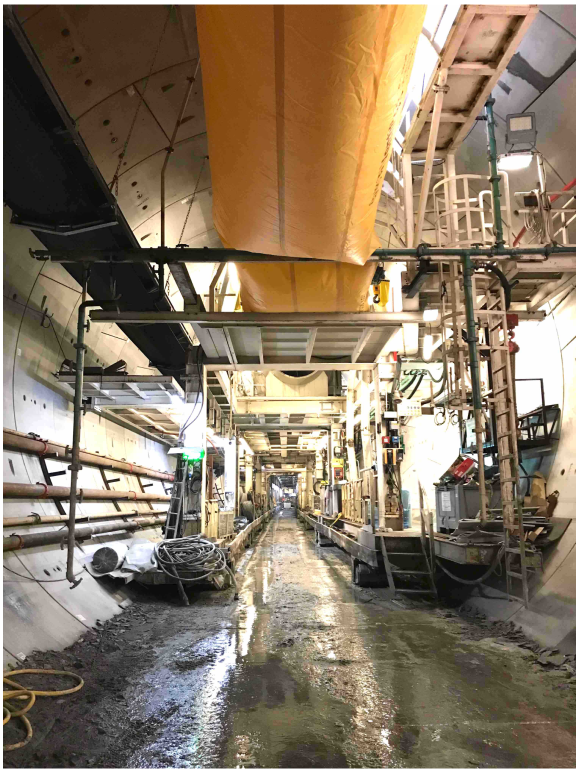


Figure 4.12: Back end of southbound TBM (Field trip)

Chapter 5

Results & Analyses

5.1 Results from literature

As there is no clear and unambiguous definition on Mixed Face Conditions, there are neither quantified guidelines on how to adjust the TBM operational parameters during excavation to best deal with problems and effects of MFC. Problems and effects encountered in MFC can also be comparable, or similar to, problems and effects found in other geological formations like blocky fractured rock, and from void areas present on the working face, hence making it difficult to distinguish these geological conditions in the TBM performance recordings. It is, however, found that common practice is to reduce thrust force and or RPM to minimize hazardous abnormal vibrations and excessive wear to cutters in MFC and that one should see a correlated reduction in penetration rate. It is according to the literature thus plausible to determine a correlation between TBM performance data and challenging geology like MFC but possibly not MFC exclusively. One suggestion related to MFC prediction in hard rock was found and used, saying that a reduction in thrust and or rpm of 10-15% would account for significant problems and effects of MFC.

5.2 Results from analysis of filtered data

5.2.1 Visual analysis of plots

Results from the visual analysis show the presumed MFC zones, known weakness zones, some questionable areas, and one longer hole in the data, marked along the specified tunnel section of each respective month.

- Presumed MFC zones are marked out by a red frame with a green transparent background
- Weakness zones by a dashed green frame with a transparent red background
- Questionable zones are marked with text and dashed frame.
- The dashed red arrows illustrate the median thrust and RPM, reduced by 10-15 %, set as the boundary for possible presence of MFC according to the chosen method.
- The dashed red arrow in the cutter life plot illustrates the median cutter life.

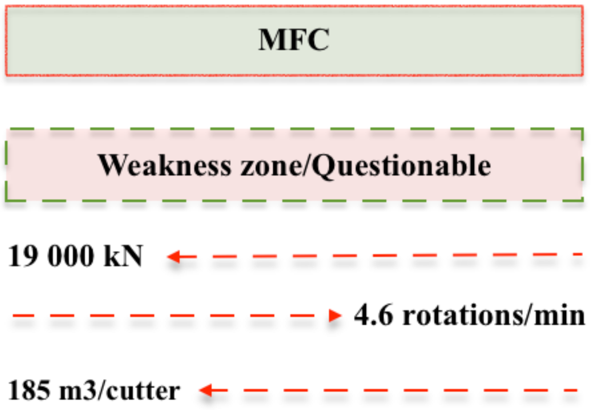
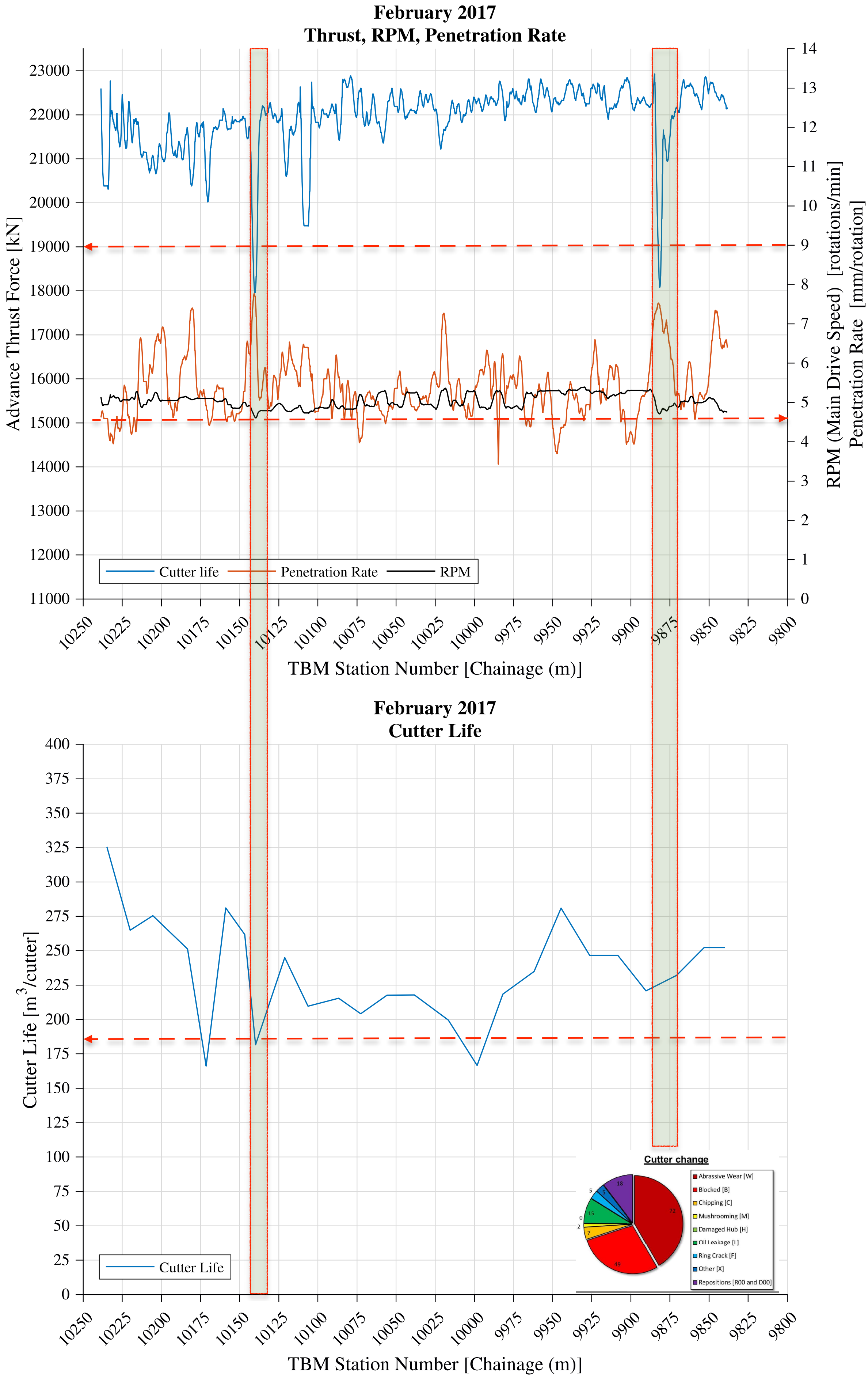
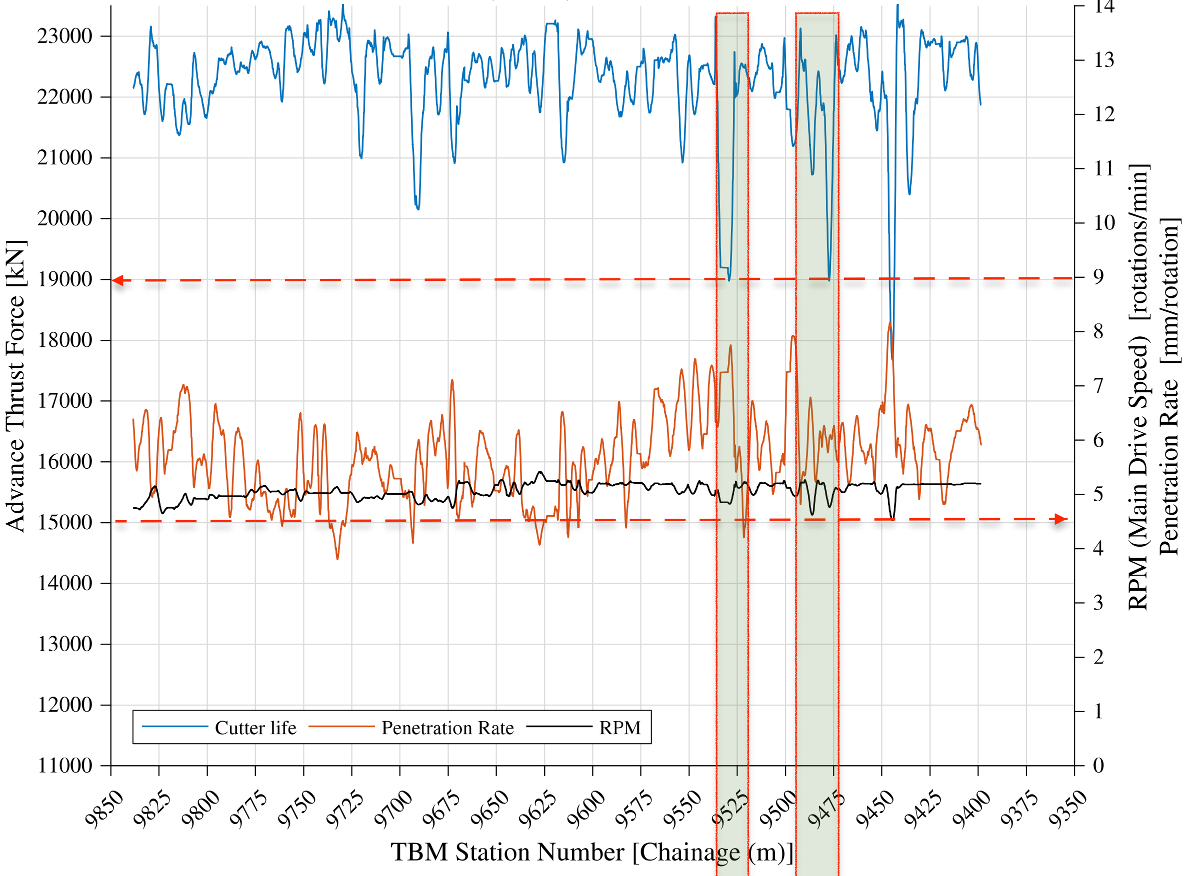
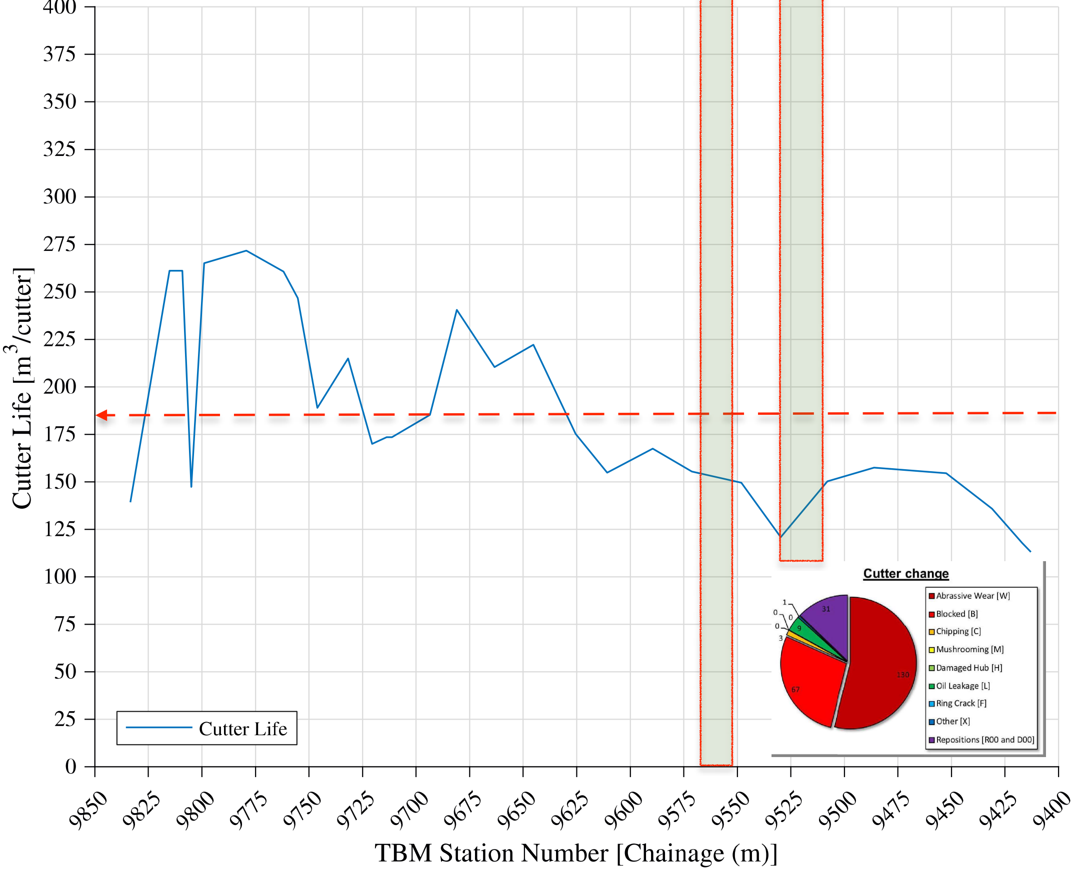


Figure 5.1: Overview of markers in the analysis

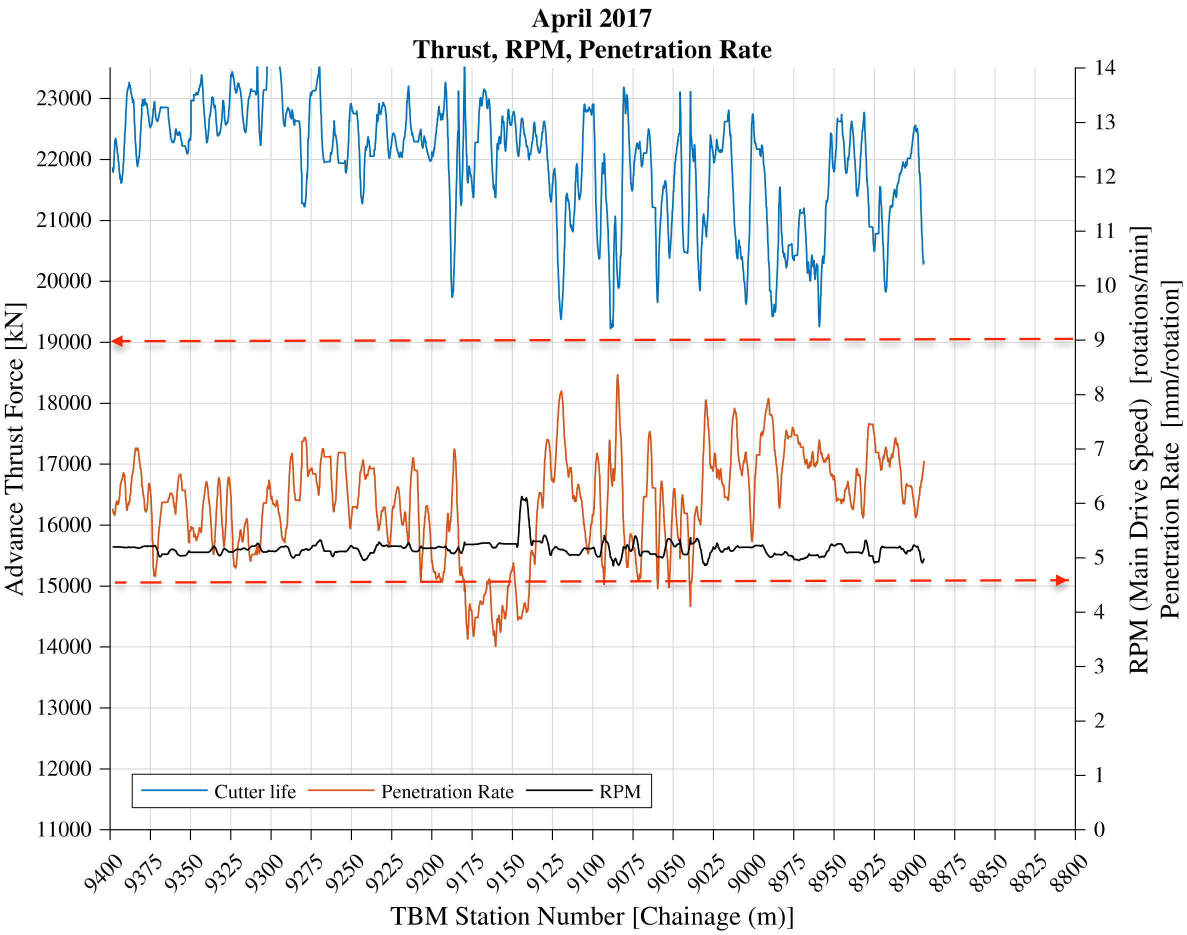

February 2017
Thrust, RPM, Penetration Rate
Advance Thrust Force [kN]
23000
22000
21000
20000
19000
18000
17000
16000
15000
14000
13000
12000
11000
RPM (Main Drive Speed) [rotations/min]
Penetration Rate [mm/rotation]
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Cutter life
Penetration Rate
RPM
10250
10225
10200
10175
10150
10125
10100
10075
10050
10025
10000
9975
9950
9925
9900
9875
9850
9825
9800
TBM Station Number [Chainage (m)]
February 2017
Cutter Life
Cutter Life [m^3/cutter]
400
375
350
325
300
275
250
225
200
175
150
125
100
75
50
25
0
Cutter Life
Cutter change
72
49
7
2
0
15
5
5
18
Abrassive Wear [W]
Blocked [B]
Chipping [C]
Mushrooming [M]
Damaged Hub [H]
Oil Leakage [L]
Ring Crack [F]
Other [X]
Repositions [R00 and D00]
10250
10225
10200
10175
10150
10125
10100
10075
10050
10025
10000
9975
9950
9925
9900
9875
9850
9825
9800
TBM Station Number [Chainage (m)]

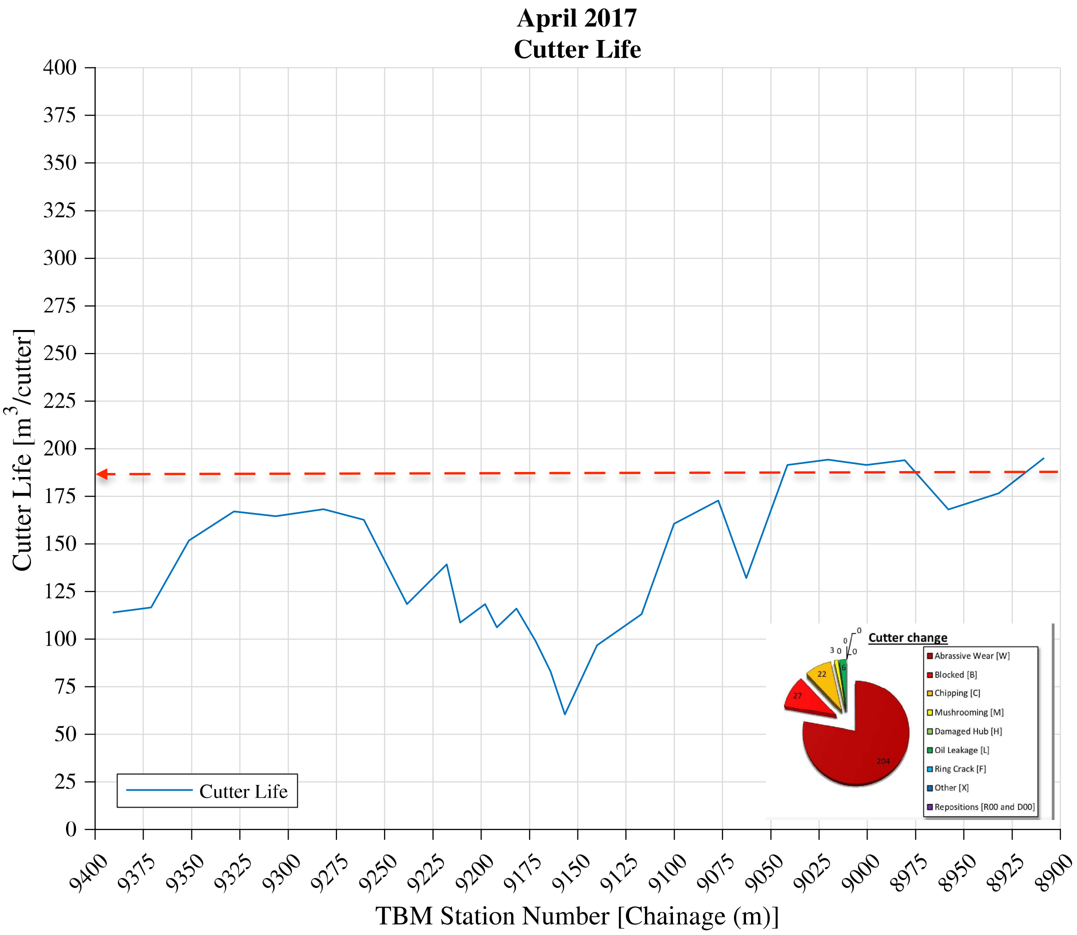


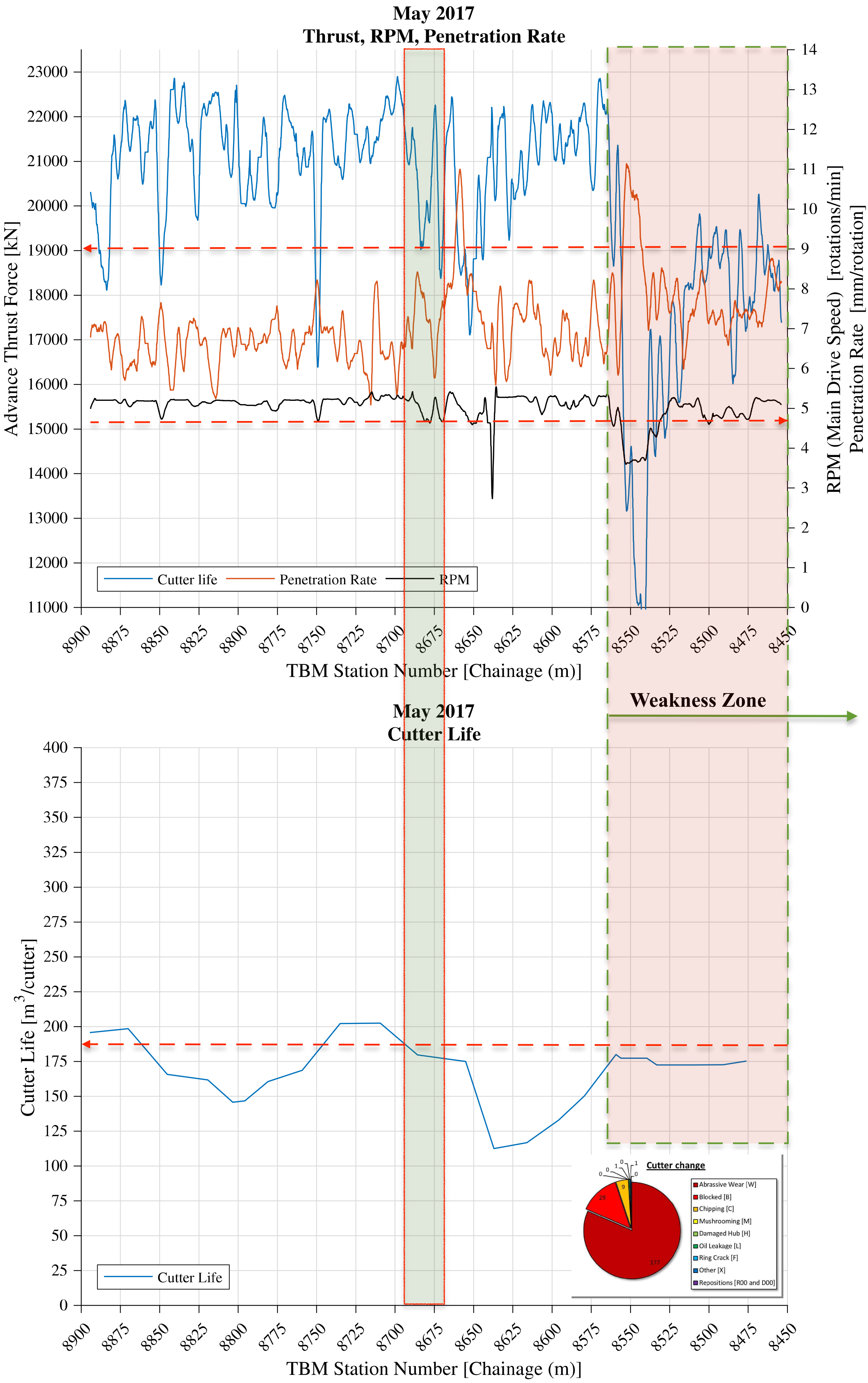
Mars 2017
Thrust, RPM, Penetration Rate

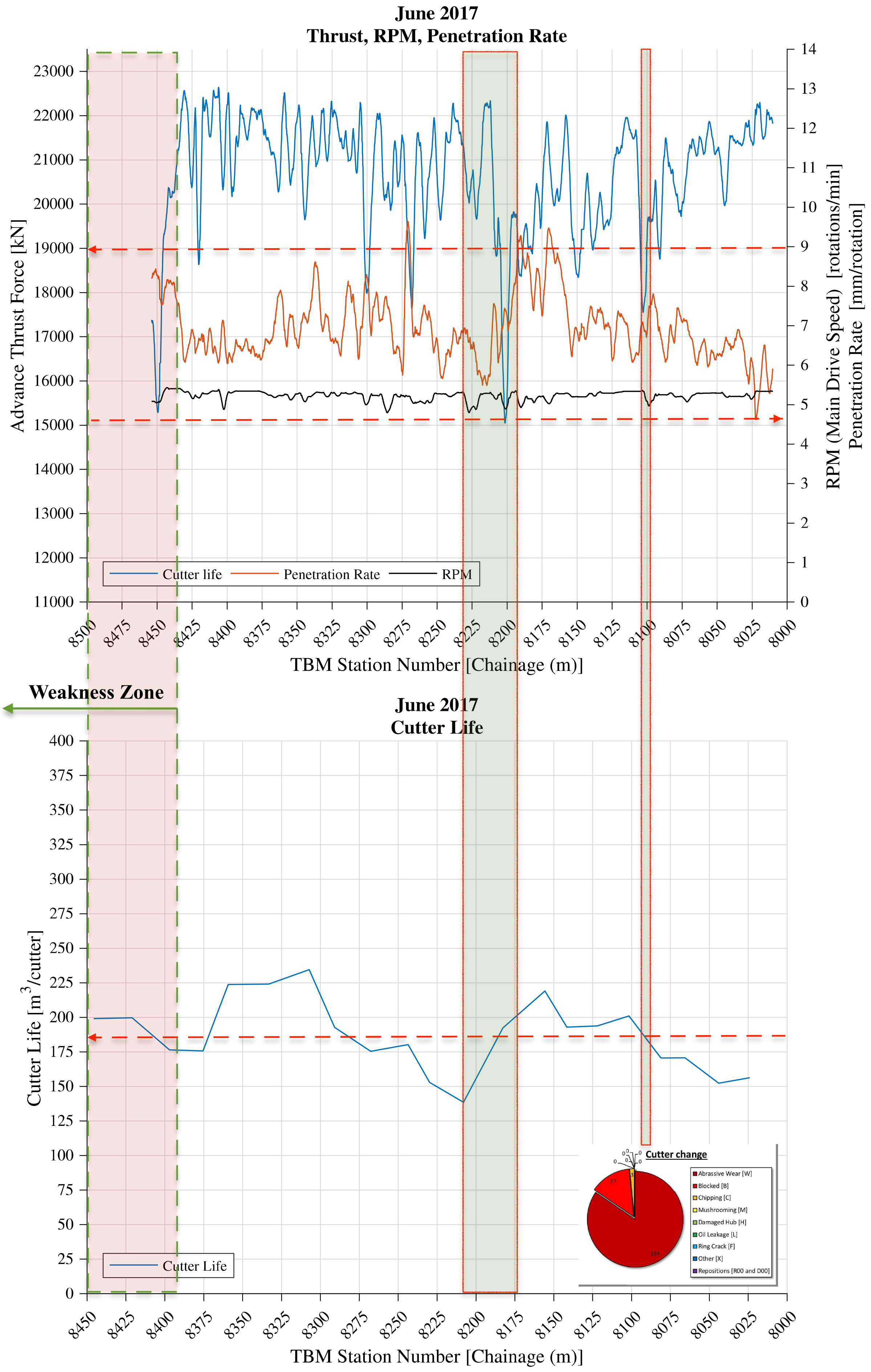


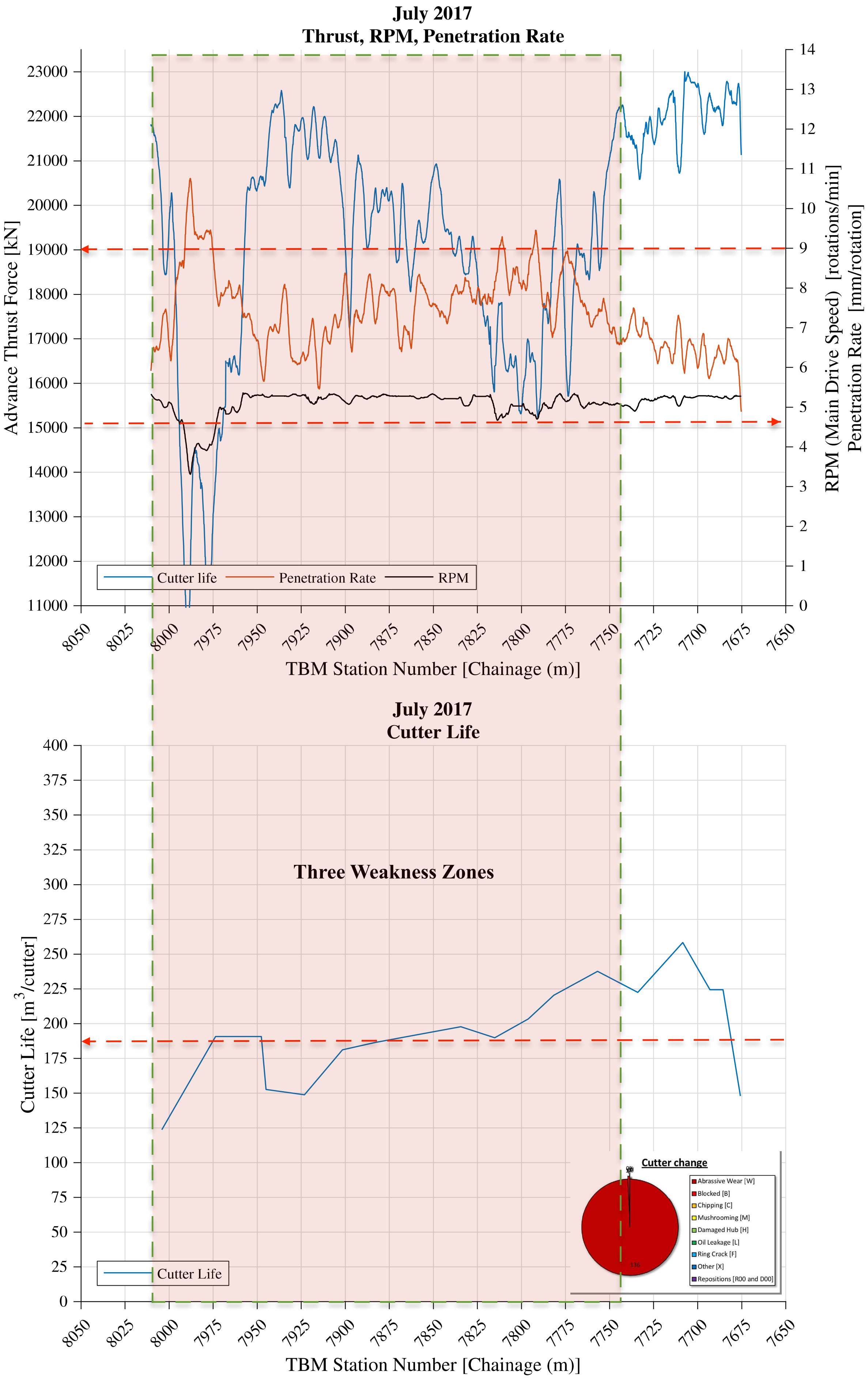
Mars 2017
Cutter Life


April 2017
Thrust, RPM, Penetration Rate


April 2017
Cutter Life

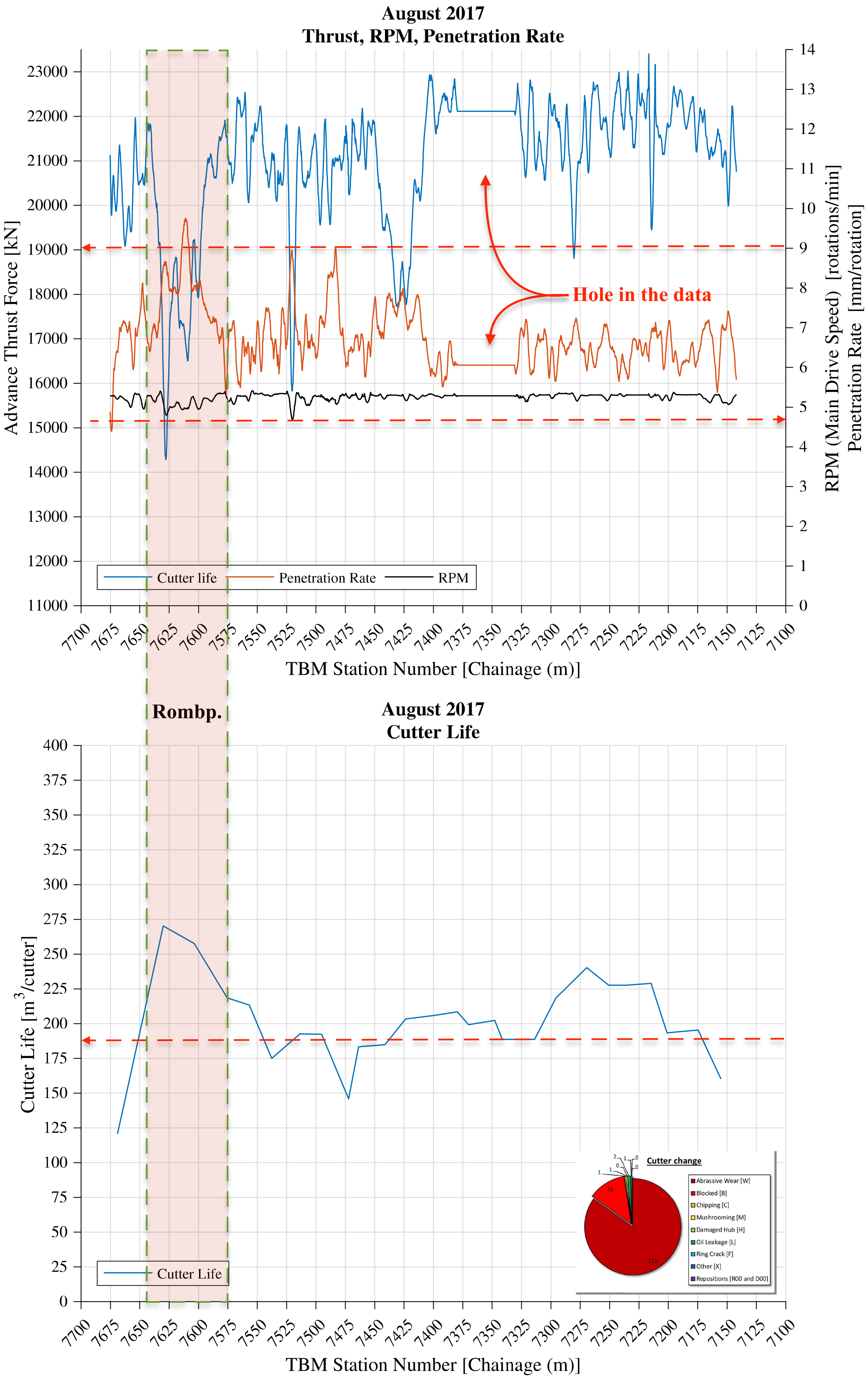

May 2017
Thrust, RPM, Penetration Rate
Advance Thrust Force [kN]
23000
22000
21000
20000
19000
18000
17000
16000
15000
14000
13000
12000
11000
RPM (Main Drive Speed) [rotations/min]
Penetration Rate [mm/rotation]
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Cutter life
Penetration Rate
RPM
8900
8875
8850
8825
8800
8775
8750
8725
8700
8675
8650
8625
8600
8575
8550
8525
8500
8475
8450
TBM Station Number [Chainage (m)]
Weakness Zone
May 2017
Cutter Life
Cutter Life [m^3/cutter]
400
375
350
325
300
275
250
225
200
175
150
125
100
75
50
25
0
Cutter Life
Cutter change
0
0
1
0
1
0
9
29
177
Abrasive Wear [W]
Blocked [B]
Chipping [C]
Mushrooming [M]
Damaged Hub [H]
Oil Leakage [L]
Ring Crack [F]
Other [X]
Repositions [R00 and D00]
8900
8875
8850
8825
8800
8775
8750
8725
8700
8675
8650
8625
8600
8575
8550
8525
8500
8475
8450
TBM Station Number [Chainage (m)]

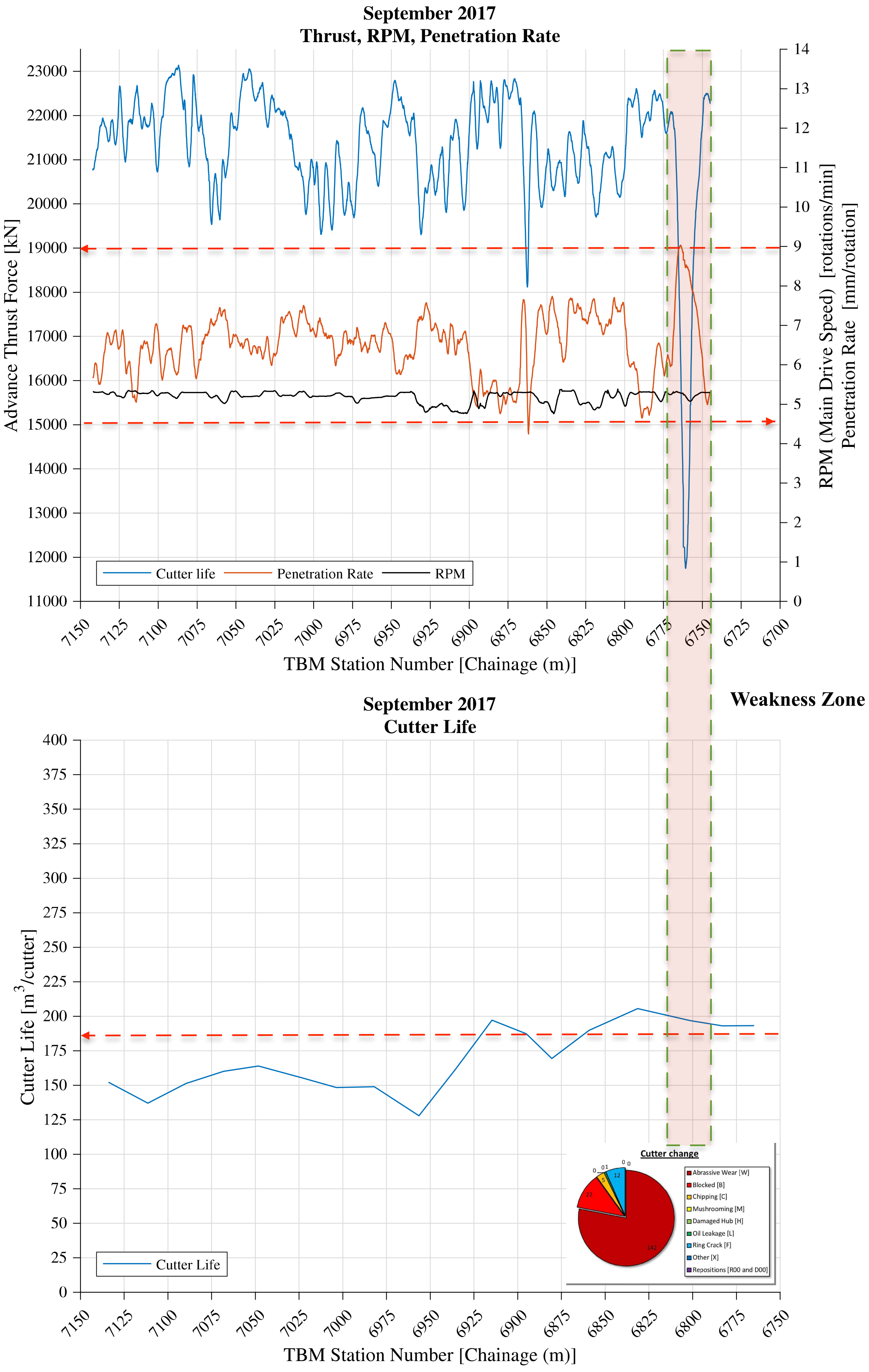

June 2017
Thrust, RPM, Penetration Rate
Advance Thrust Force [kN]
23000
22000
21000
20000
19000
18000
17000
16000
15000
14000
13000
12000
11000
RPM (Main Drive Speed) [rotations/min]
Penetration Rate [mm/rotation]
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Cutter life
Penetration Rate
RPM
8500
8475
8450
8425
8400
8375
8350
8325
8300
8275
8250
8225
8200
8175
8150
8125
8100
8075
8050
8025
8000
TBM Station Number [Chainage (m)]
Weakness Zone
June 2017
Cutter Life
Cutter Life [m^3/cutter]
400
375
350
325
300
275
250
225
200
175
150
125
100
75
50
25
0
Cutter Life
8450
8425
8400
8375
8350
8325
8300
8275
8250
8225
8200
8175
8150
8125
8100
8075
8050
8025
8000
TBM Station Number [Chainage (m)]
Cutter change
0
0
0
0
0
0
27
3
164
Abrassive Wear [W]
Blocked [B]
Chipping [C]
Mushrooming [M]
Damaged Hub [H]
Oil Leakage [L]
Ring Crack [F]
Other [X]
Repositions [R00 and D00]

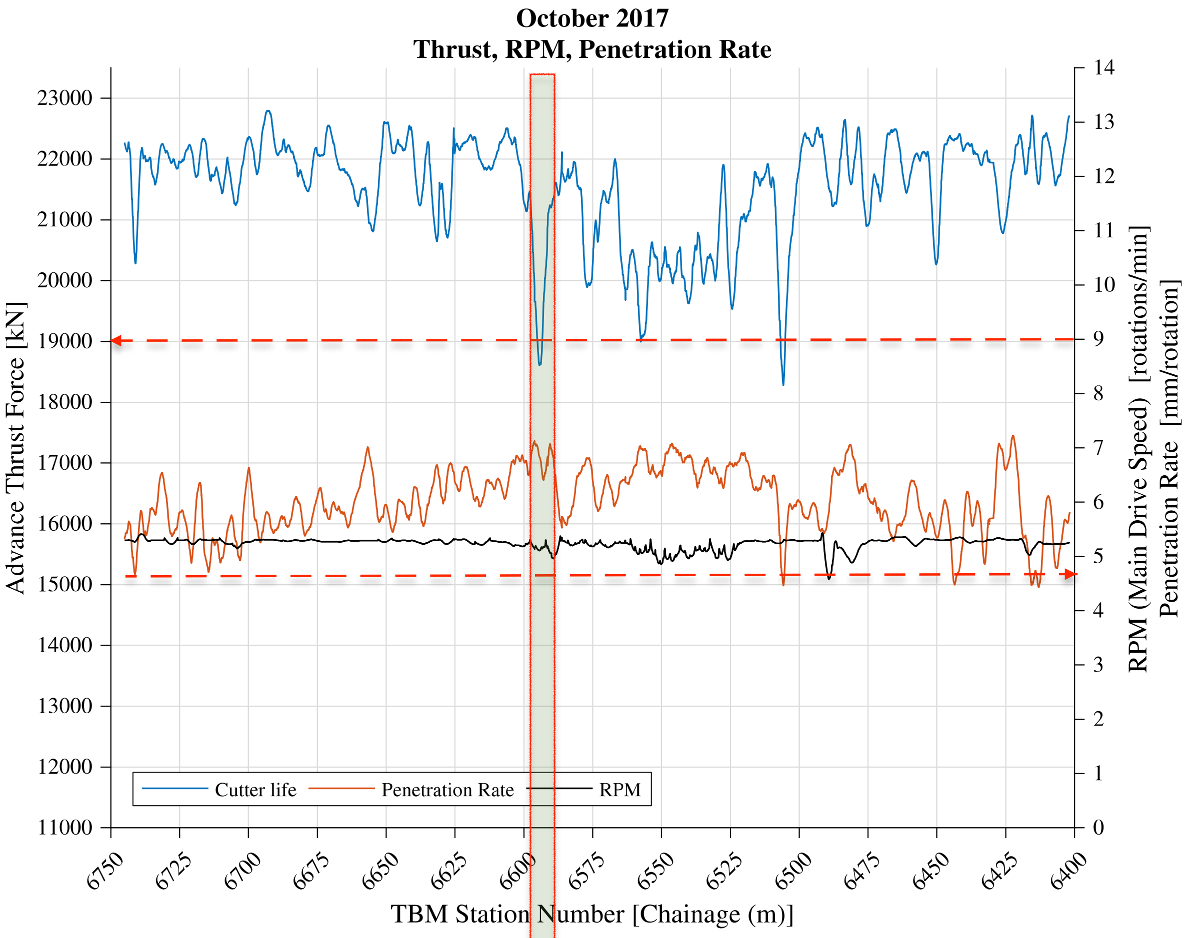


July 2017
Thrust, RPM, Penetration Rate

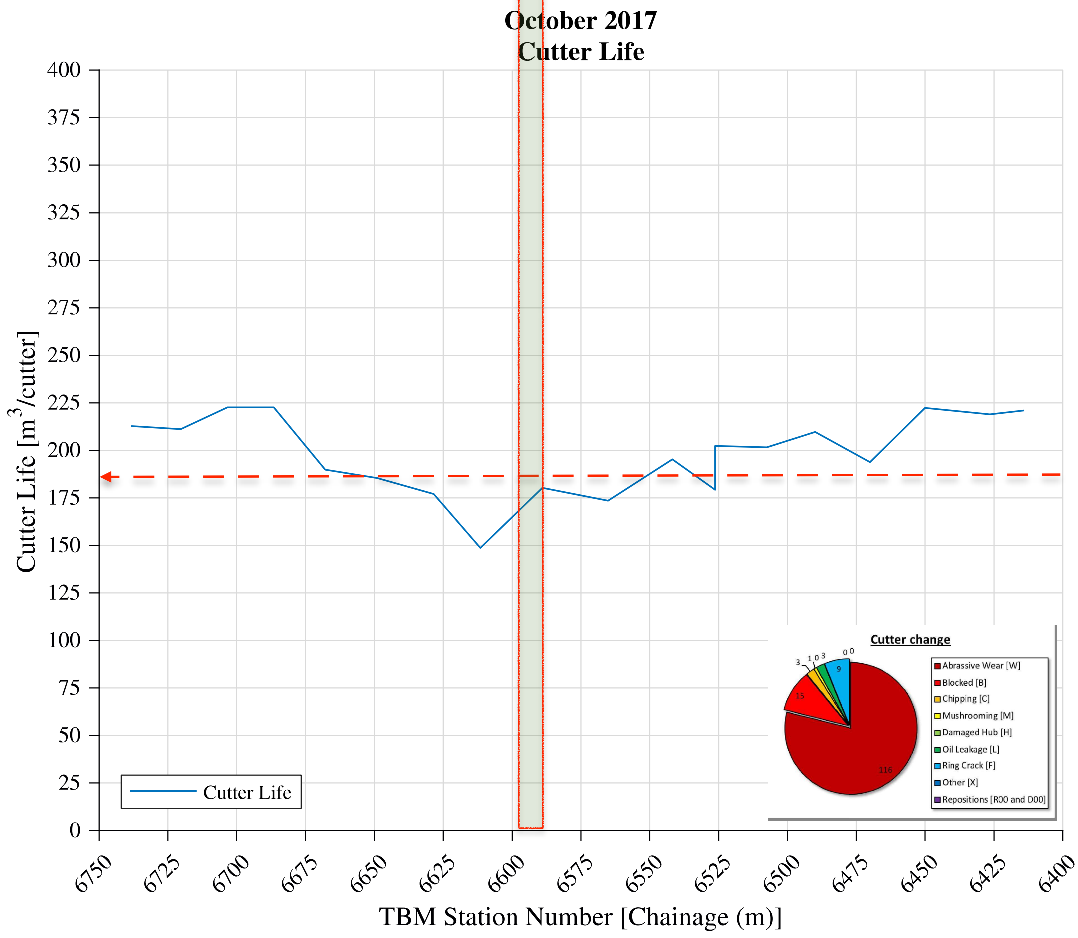
July 2017
Cutter Life


August 2017
Thrust, RPM, Penetration Rate
Advance Thrust Force [kN]
23000
22000
21000
20000
19000
18000
17000
16000
15000
14000
13000
12000
11000
RPM (Main Drive Speed) [rotations/min]
Penetration Rate [mm/rotation]
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Hole in the data
Cutter life
Penetration Rate
RPM
7700
7675
7650
7625
7600
7575
7550
7525
7500
7475
7450
7425
7400
7375
7350
7325
7300
7275
7250
7225
7200
7175
7150
7125
7100
TBM Station Number [Chainage (m)]
Rombp.
August 2017
Cutter Life
Cutter Life [m^3/cutter]
400
375
350
325
300
275
250
225
200
175
150
125
100
75
50
25
0
Cutter Life
Cutter change
174
26
1
1
0
2
1
0
0
Abrassive Wear [W]
Blocked [B]
Chipping [C]
Mushrooming [M]
Damaged Hub [H]
Oil Leakage [L]
Ring Crack [F]
Other [X]
Repositions [R00 and D00]
7700
7675
7650
7625
7600
7575
7550
7525
7500
7475
7450
7425
7400
7375
7350
7325
7300
7275
7250
7225
7200
7175
7150
7125
7100
TBM Station Number [Chainage (m)]

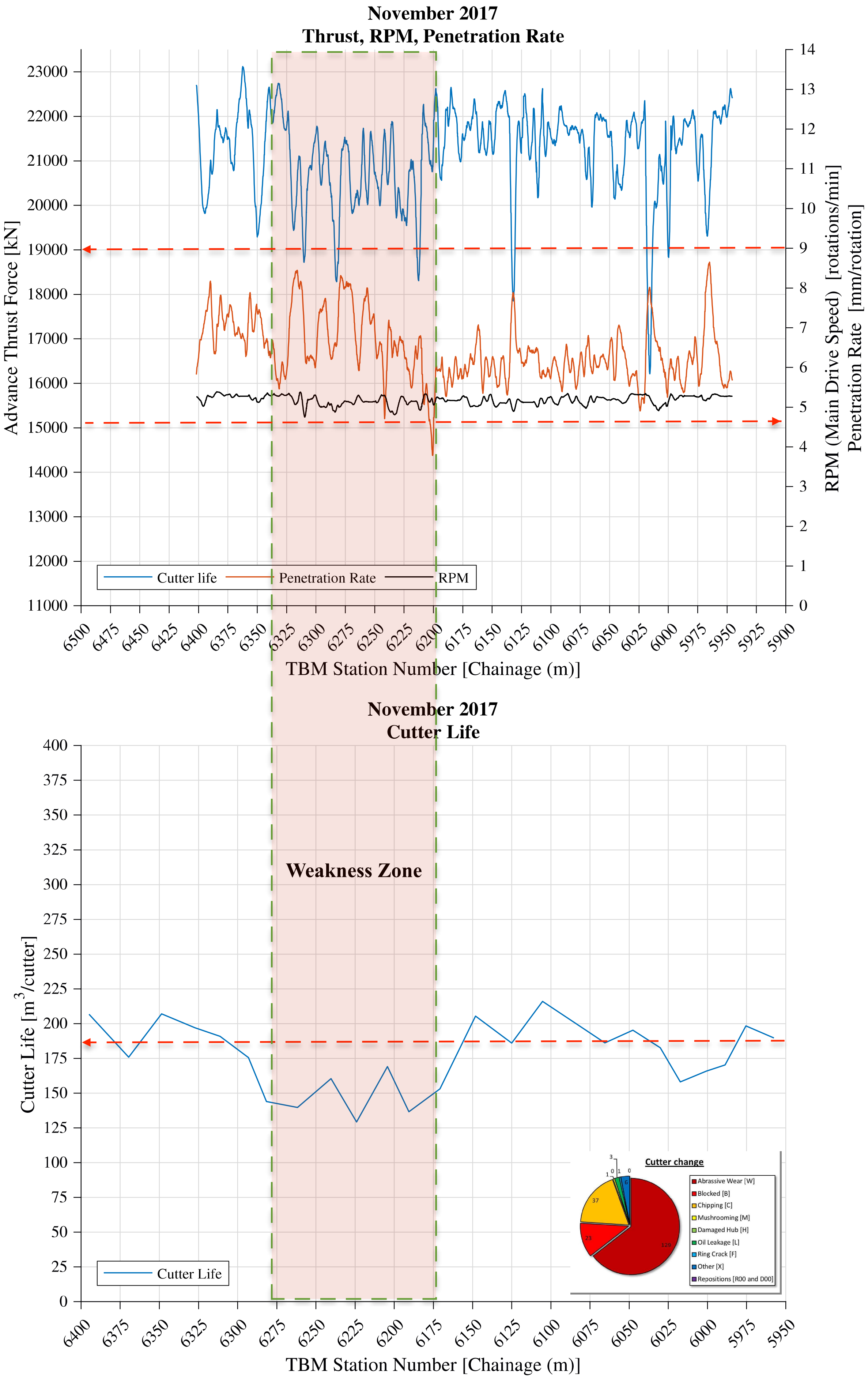

September 2017
Thrust, RPM, Penetration Rate
Advance Thrust Force [kN]
23000
22000
21000
20000
19000
18000
17000
16000
15000
14000
13000
12000
11000
RPM (Main Drive Speed) [rotations/min]
Penetration Rate [mm/rotation]
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Cutter life
Penetration Rate
RPM
7150
7125
7100
7075
7050
7025
7000
6975
6950
6925
6900
6875
6850
6825
6800
6775
6750
6725
6700
TBM Station Number [Chainage (m)]
Weakness Zone
September 2017
Cutter Life
Cutter Life [m^3/cutter]
400
375
350
325
300
275
250
225
200
175
150
125
100
75
50
25
0
Cutter Life
Cutter change
0
0 1
0 0
12
5
22
142
Abrassive Wear [W]
Blocked [B]
Chipping [C]
Mushrooming [M]
Damaged Hub [H]
Oil Leakage [L]
Ring Crack [F]
Other [X]
Repositions [R00 and D00]
7150
7125
7100
7075
7050
7025
7000
6975
6950
6925
6900
6875
6850
6825
6800
6775
6750
TBM Station Number [Chainage (m)]

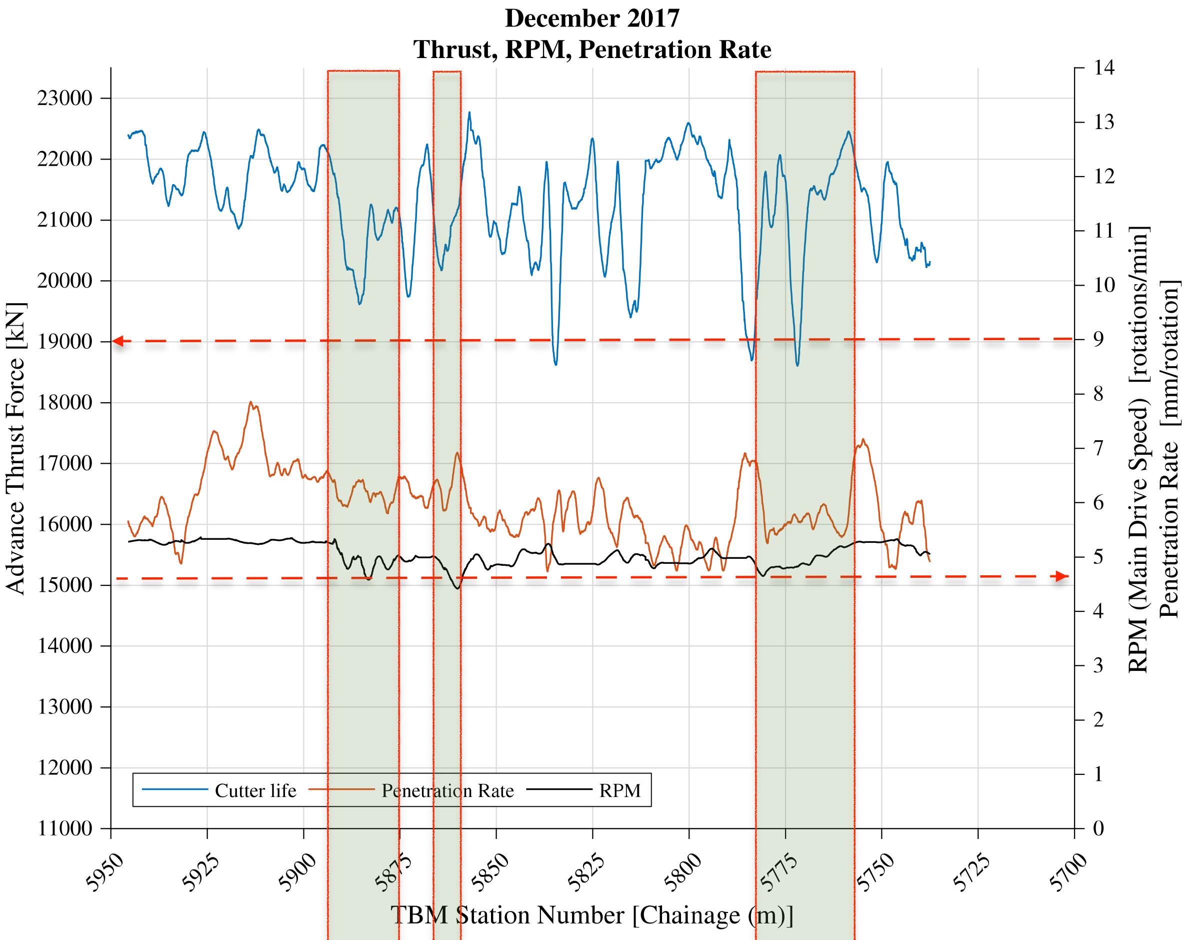


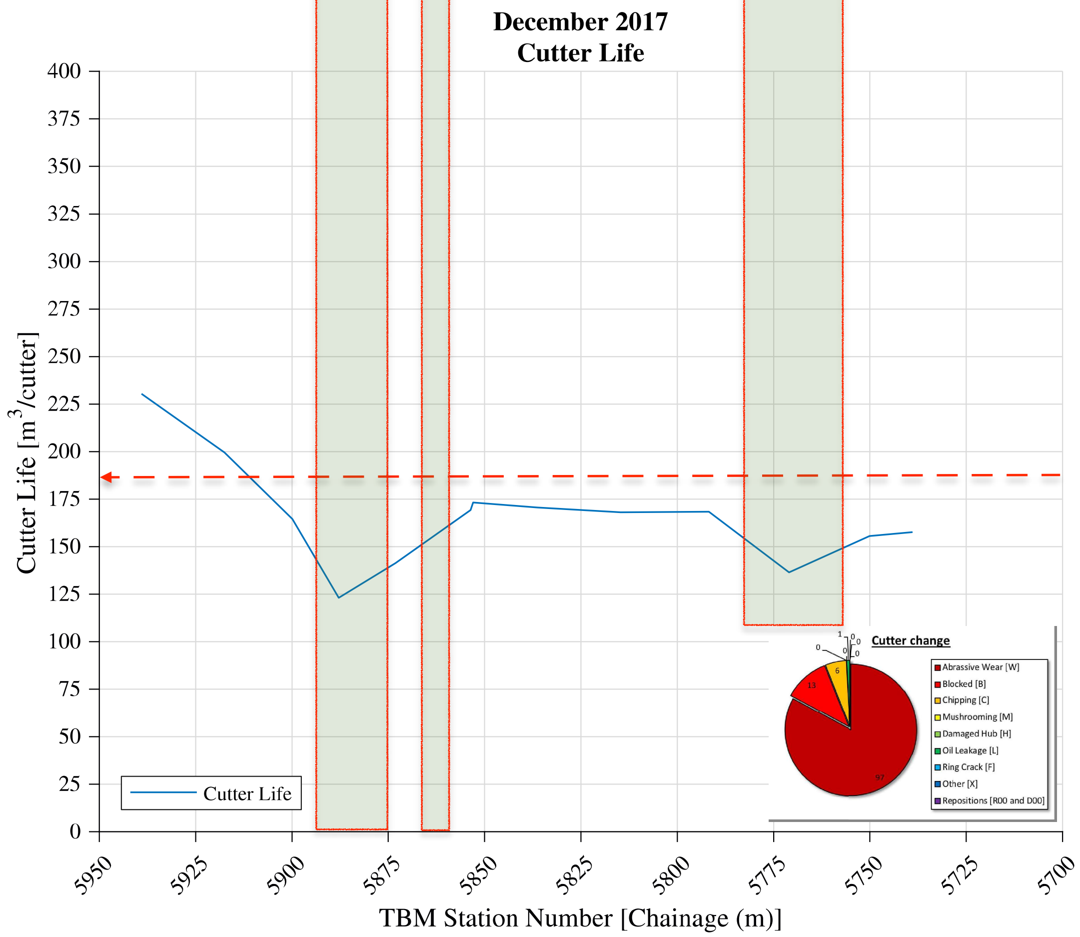
October 2017
Thrust, RPM, Penetration Rate

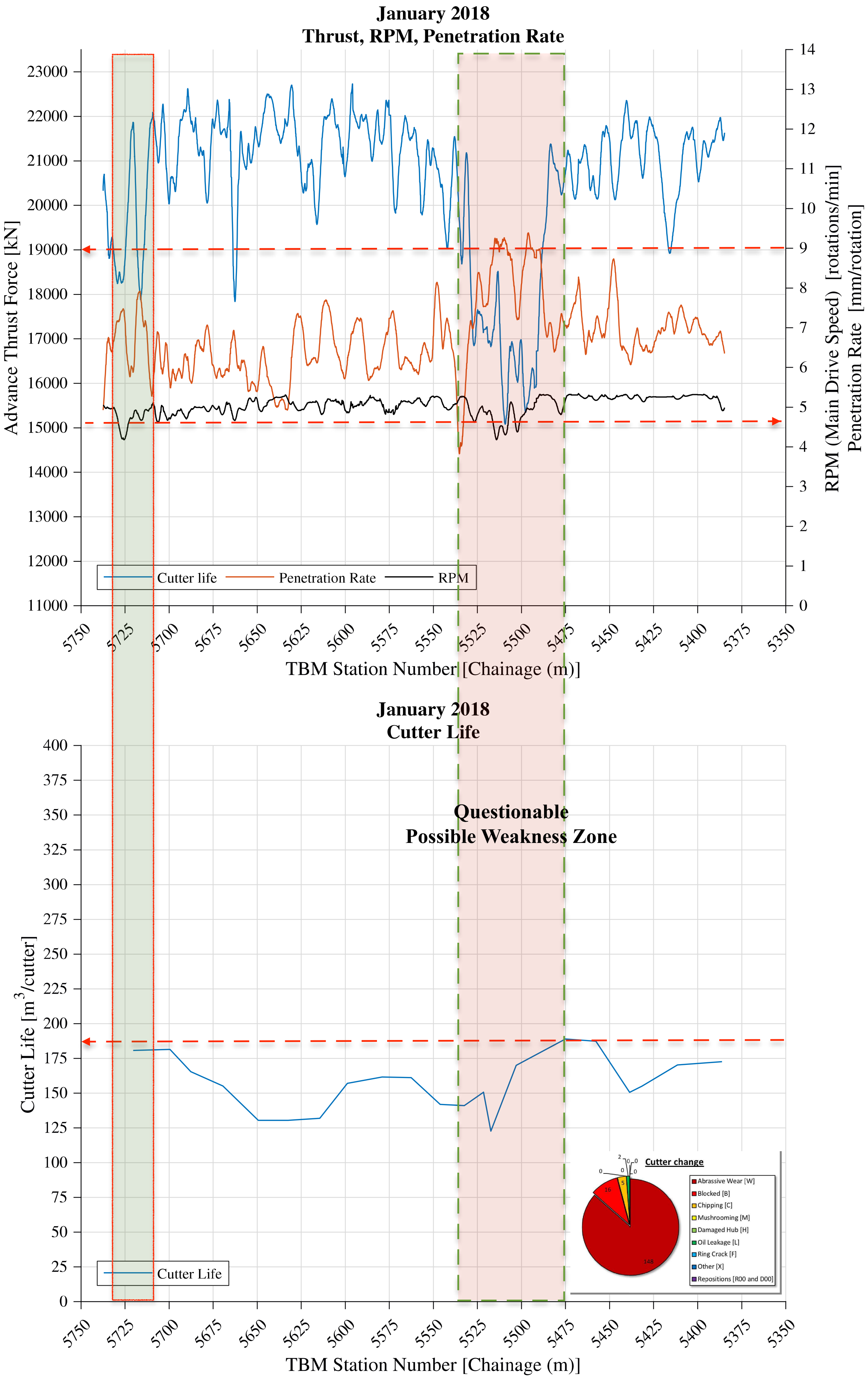


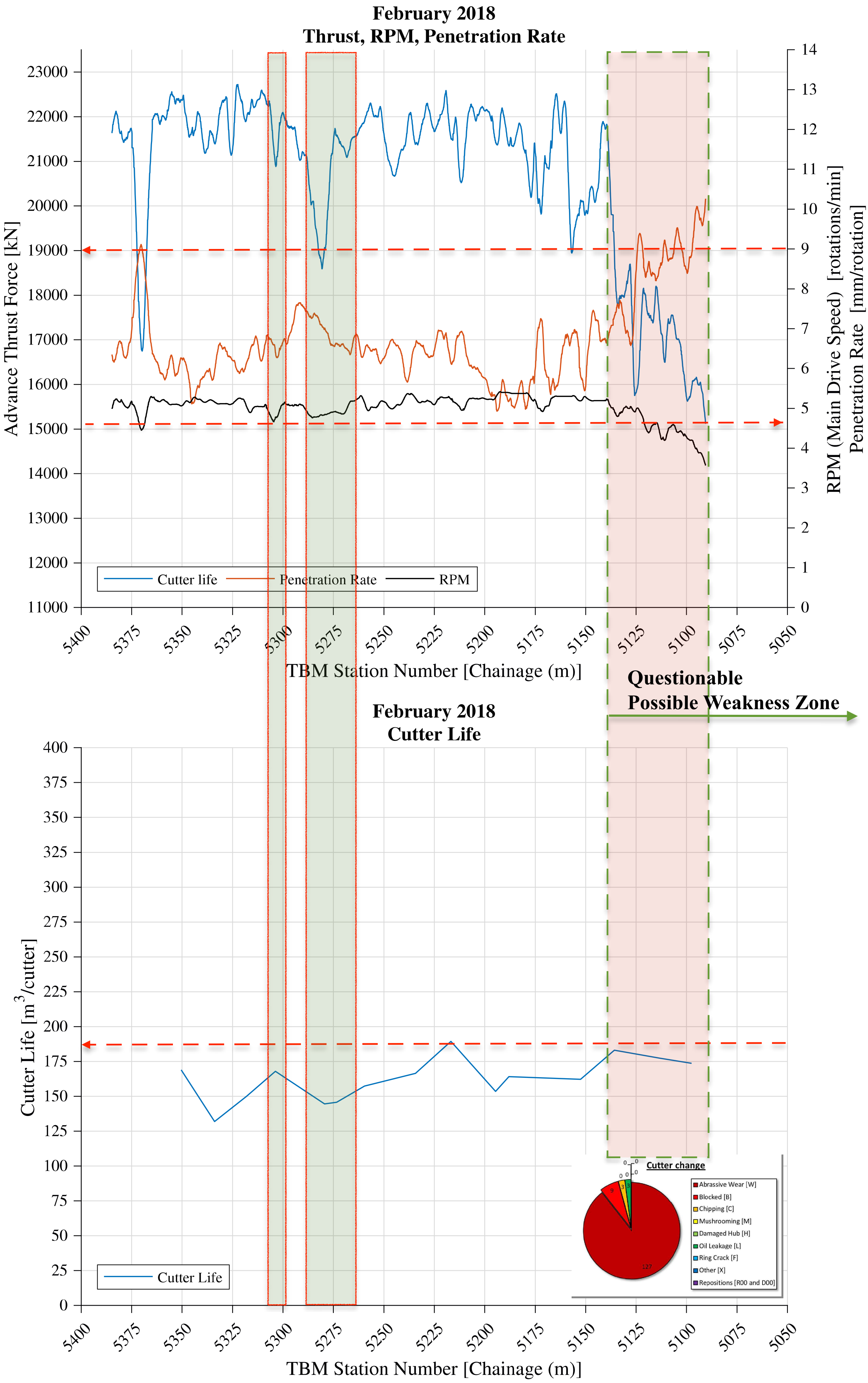
October 2017
Cutter Life

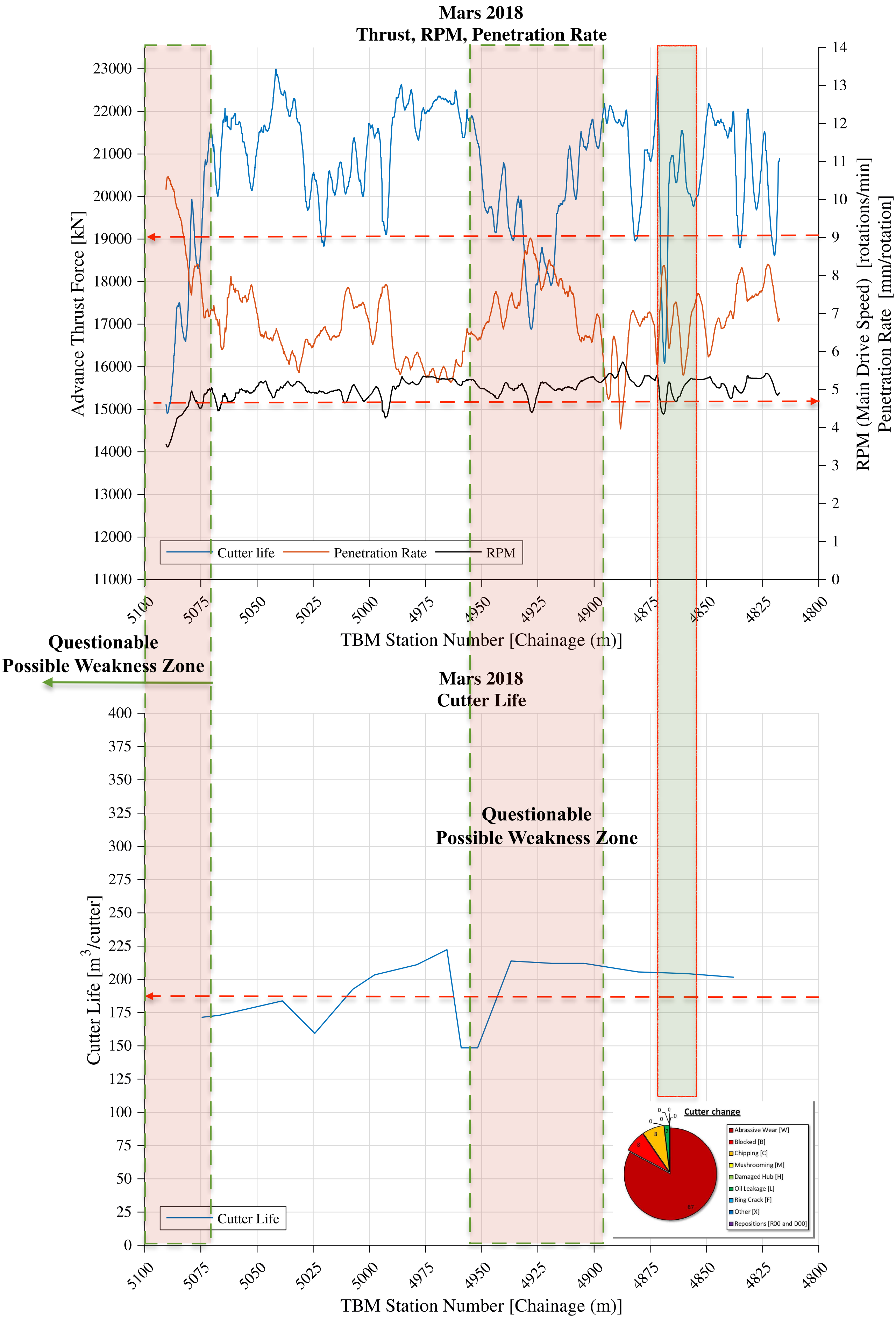

November 2017
Thrust, RPM, Penetration Rate
Advance Thrust Force [kN]
23000
22000
21000
20000
19000
18000
17000
16000
15000
14000
13000
12000
11000
RPM (Main Drive Speed) [rotations/min]
Penetration Rate [mm/rotation]
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Cutter life
Penetration Rate
RPM
6500
6475
6450
6425
6400
6375
6350
6325
6300
6275
6250
6225
6200
6175
6150
6125
6100
6075
6050
6025
6000
5975
5950
5925
5900
TBM Station Number [Chainage (m)]
November 2017
Cutter Life
Weakness Zone
Cutter Life [m³/cutter]
400
375
350
325
300
275
250
225
200
175
150
125
100
75
50
25
0
Cutter Life
Cutter change
3
1
0
1
0
6
37
23
129
Abrassive Wear [W]
Blocked [B]
Chipping [C]
Mushrooming [M]
Damaged Hub [H]
Oil Leakage [L]
Ring Crack [F]
Other [X]
Repositions [R00 and D00]
6400
6375
6350
6325
6300
6275
6250
6225
6200
6175
6150
6125
6100
6075
6050
6025
6000
5975
5950
TBM Station Number [Chainage (m)]


December 2017
Thrust, RPM, Penetration Rate
Advance Thrust Force [kN]
23000
22000
21000
20000
19000
18000
17000
16000
15000
14000
13000
12000
11000
RPM (Main Drive Speed) [rotations/min]
Penetration Rate [mm/rotation]
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Cutter life
Penetration Rate
RPM
5950
5925
5900
5875
5850
5825
5800
5775
5750
5725
5700
TBM Station Number [Chainage (m)]

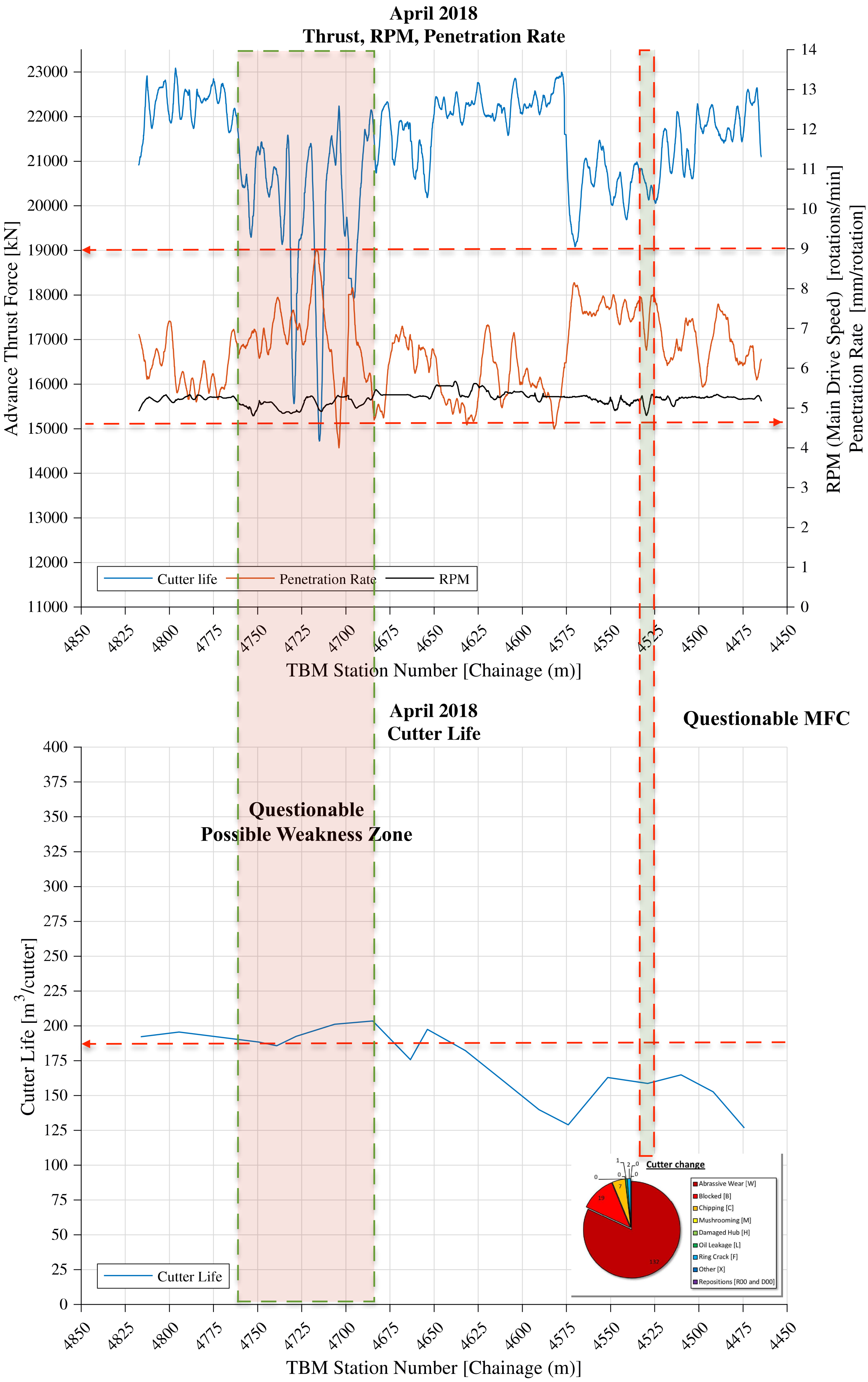

December 2017
Cutter Life
Cutter Life [m^3/cutter]
400
375
350
325
300
275
250
225
200
175
150
125
100
75
50
25
0
Cutter Life
Cutter change
97
13
6
1
0
Abrassive Wear [W]
Blocked [B]
Chipping [C]
Mushrooming [M]
Damaged Hub [H]
Oil Leakage [L]
Ring Crack [F]
Other [X]
Repositions [R00 and D00]
5950
5925
5900
5875
5850
5825
5800
5775
5750
5725
5700
TBM Station Number [Chainage (m)]

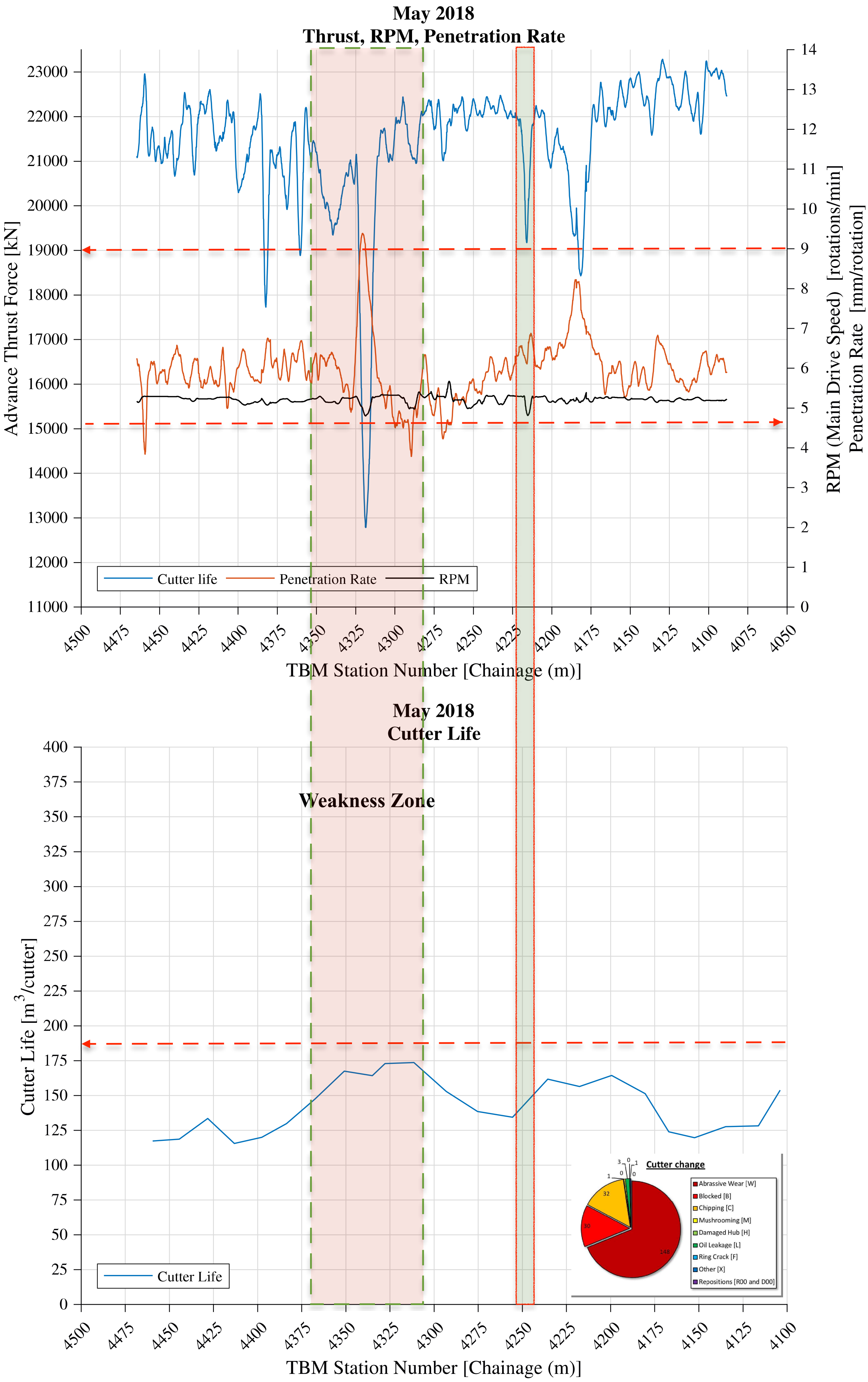

January 2018
Thrust, RPM, Penetration Rate
Advance Thrust Force [kN]
23000
22000
21000
20000
19000
18000
17000
16000
15000
14000
13000
12000
11000
RPM (Main Drive Speed) [rotations/min]
Penetration Rate [mm/rotation]
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Cutter life
Penetration Rate
RPM
5750
5725
5700
5675
5650
5625
5600
5575
5550
5525
5500
5475
5450
5425
5400
5375
5350
TBM Station Number [Chainage (m)]
January 2018
Cutter Life
Cutter Life [m^3/cutter]
400
375
350
325
300
275
250
225
200
175
150
125
100
75
50
25
0
Questionable
Possible Weakness Zone
Cutter Life
Cutter change
2
0
0
0
0
0
16
5
148
Abrassive Wear [W]
Blocked [B]
Chipping [C]
Mushrooming [M]
Damaged Hub [H]
Oil Leakage [L]
Ring Crack [F]
Other [X]
Repositions [R00 and D00]
5750
5725
5700
5675
5650
5625
5600
5575
5550
5525
5500
5475
5450
5425
5400
5375
5350
TBM Station Number [Chainage (m)]

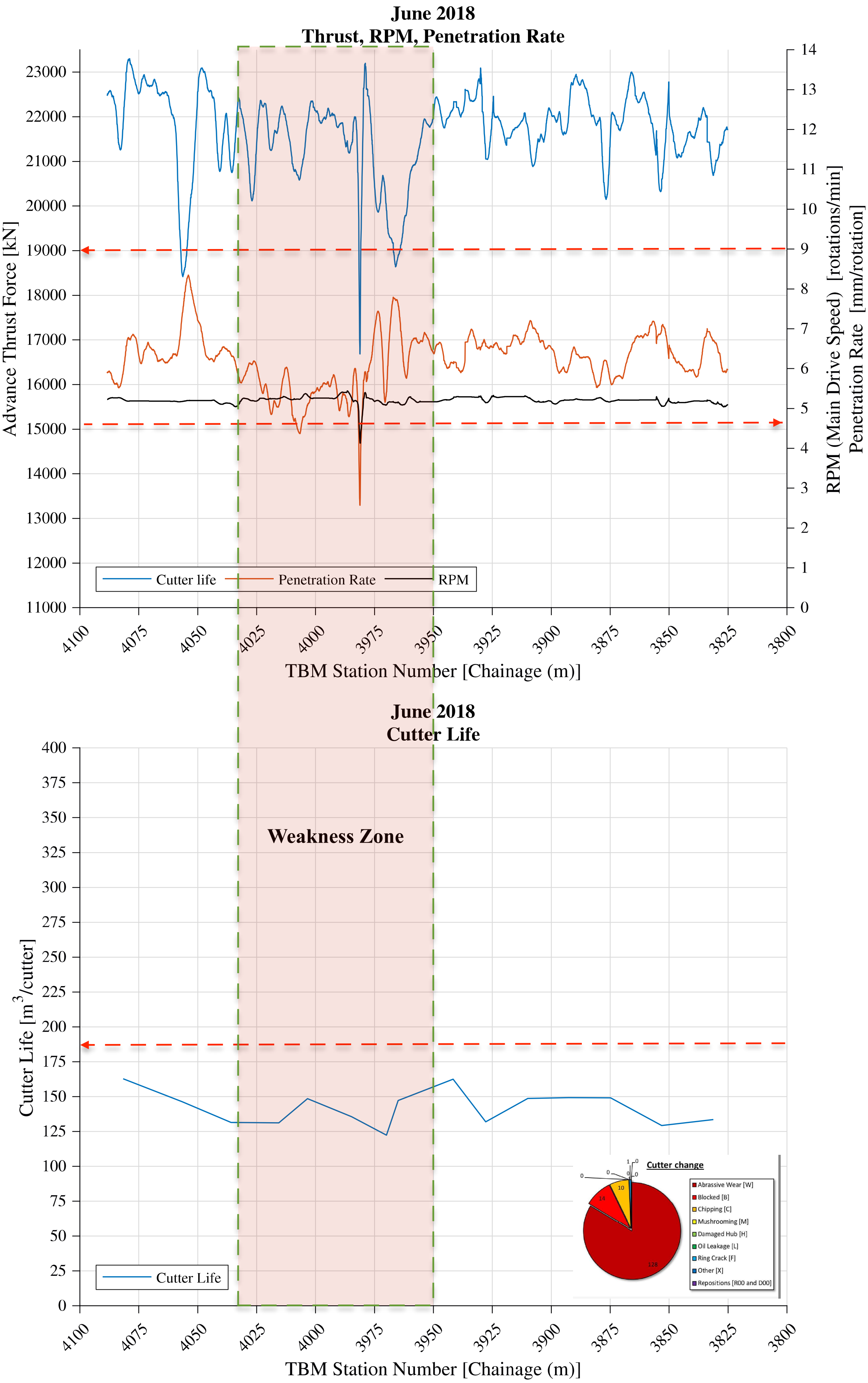

February 2018
Thrust, RPM, Penetration Rate
Advance Thrust Force [kN]
23000
22000
21000
20000
19000
18000
17000
16000
15000
14000
13000
12000
11000
RPM (Main Drive Speed) [rotations/min]
Penetration Rate [mm/rotation]
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Cutter life
Penetration Rate
RPM
5400
5375
5350
5325
5300
5275
5250
5225
5200
5175
5150
5125
5100
5075
5050
TBM Station Number [Chainage (m)]
Questionable
Possible Weakness Zone
February 2018
Cutter Life
Cutter Life [m^3/cutter]
400
375
350
325
300
275
250
225
200
175
150
125
100
75
50
25
0
Cutter Life
Cutter change
127
9
3
3
0
0
0
0
0
Abrasive Wear [W]
Blocked [B]
Chipping [C]
Mushrooming [M]
Damaged Hub [H]
Oil Leakage [L]
Ring Crack [F]
Other [X]
Repositions [R00 and D00]
5400
5375
5350
5325
5300
5275
5250
5225
5200
5175
5150
5125
5100
5075
5050
TBM Station Number [Chainage (m)]

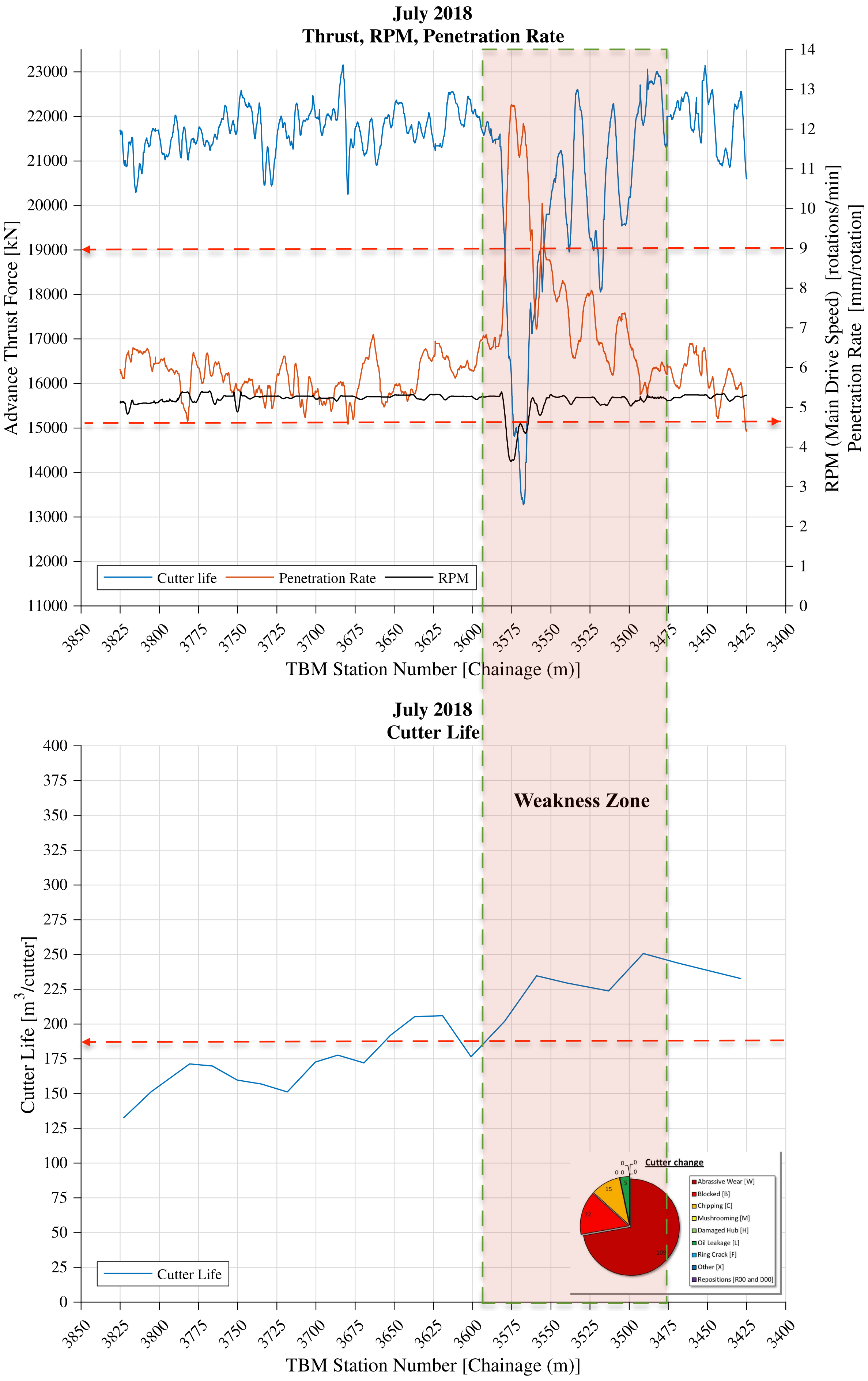


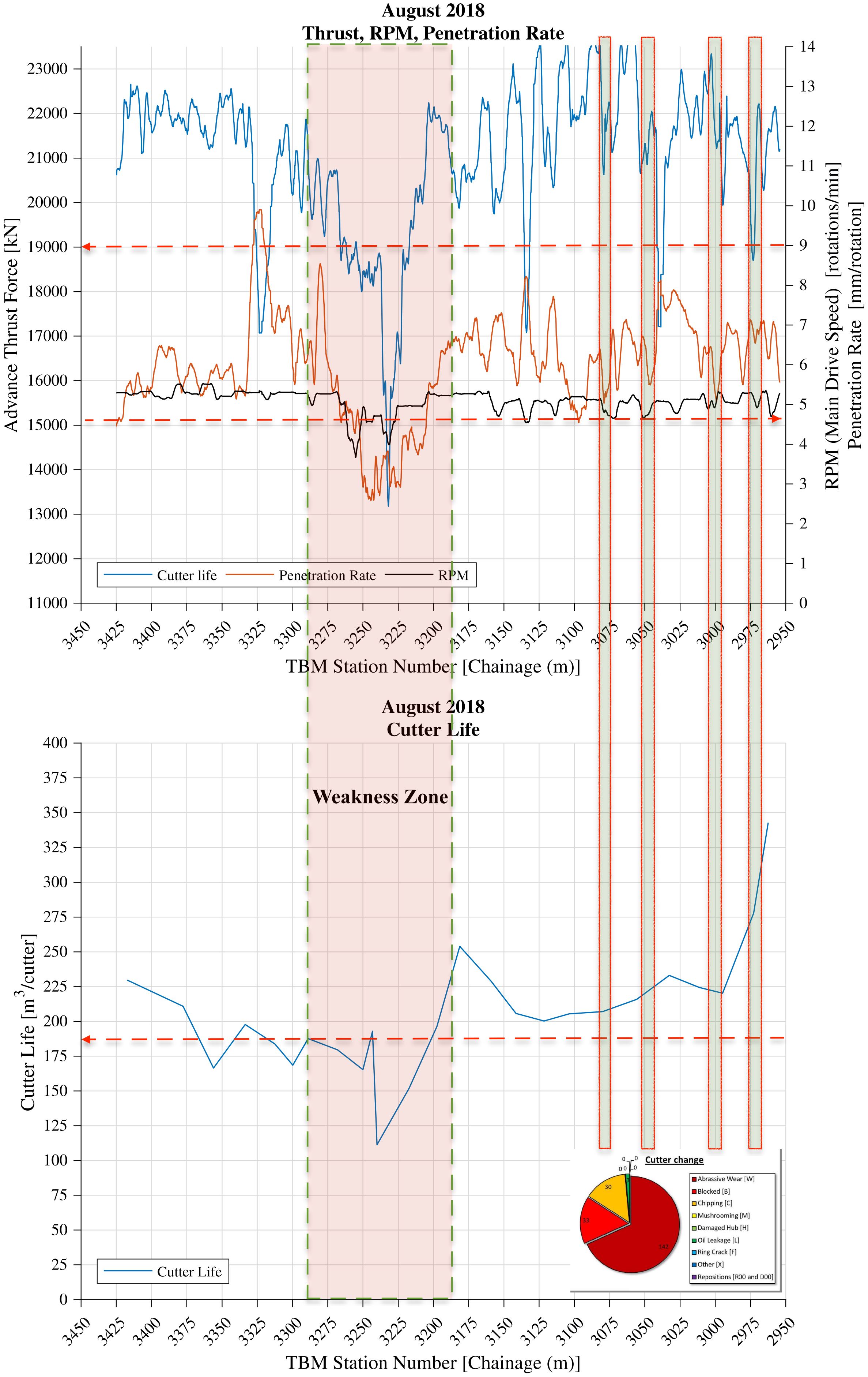
Mars 2018
Thrust, RPM, Penetration Rate
Advance Thrust Force [kN]
23000
22000
21000
20000
19000
18000
17000
16000
15000
14000
13000
12000
11000
RPM (Main Drive Speed) [rotations/min]
Penetration Rate [mm/rotation]
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Cutter life
Penetration Rate
RPM
5100
5075
5050
5025
5000
4975
4950
4925
4900
4875
4850
4825
4800
TBM Station Number [Chainage (m)]
Questionable
Possible Weakness Zone
Mars 2018
Cutter Life
Cutter Life [m^3/cutter]
400
375
350
325
300
275
250
225
200
175
150
125
100
75
50
25
0
Questionable
Possible Weakness Zone
Cutter Life
Cutter change
0
0
0
0
0
8
8
2
87
Abrassive Wear [W]
Blocked [B]
Chipping [C]
Mushrooming [M]
Damaged Hub [H]
Oil Leakage [L]
Ring Crack [F]
Other [X]
Repositions [R00 and D00]
5100
5075
5050
5025
5000
4975
4950
4925
4900
4875
4850
4825
4800
TBM Station Number [Chainage (m)]


April 2018
Thrust, RPM, Penetration Rate
Advance Thrust Force [kN]
23000
22000
21000
20000
19000
18000
17000
16000
15000
14000
13000
12000
11000
RPM (Main Drive Speed) [rotations/min]
Penetration Rate [mm/rotation]
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Cutter life
Penetration Rate
RPM
4850
4825
4800
4775
4750
4725
4700
4675
4650
4625
4600
4575
4550
4525
4500
4475
4450
TBM Station Number [Chainage (m)]
April 2018
Cutter Life
Questionable MFC
Questionable
Possible Weakness Zone
Cutter Life [m^3/cutter]
400
375
350
325
300
275
250
225
200
175
150
125
100
75
50
25
0
Cutter Life
Cutter change
Abrassive Wear [W]
Blocked [B]
Chipping [C]
Mushrooming [M]
Damaged Hub [H]
Oil Leakage [L]
Ring Crack [F]
Other [X]
Repositions [R00 and D00]
132
19
7
0
1
2
0
0
0
4850
4825
4800
4775
4750
4725
4700
4675
4650
4625
4600
4575
4550
4525
4500
4475
4450
TBM Station Number [Chainage (m)]


May 2018
Thrust, RPM, Penetration Rate
Advance Thrust Force [kN]
23000
22000
21000
20000
19000
18000
17000
16000
15000
14000
13000
12000
11000
RPM (Main Drive Speed) [rotations/min]
Penetration Rate [mm/rotation]
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Cutter life
Penetration Rate
RPM
4500
4475
4450
4425
4400
4375
4350
4325
4300
4275
4250
4225
4200
4175
4150
4125
4100
4075
4050
TBM Station Number [Chainage (m)]
May 2018
Cutter Life
Weakness Zone
Cutter Life [m^3/cutter]
400
375
350
325
300
275
250
225
200
175
150
125
100
75
50
25
0
Cutter Life
Cutter change
148
30
32
1
0
3
0
1
0
Abrasive Wear [W]
Blocked [B]
Chipping [C]
Mushrooming [M]
Damaged Hub [H]
Oil Leakage [L]
Ring Crack [F]
Other [X]
Repositions [R00 and D00]
4500
4475
4450
4425
4400
4375
4350
4325
4300
4275
4250
4225
4200
4175
4150
4125
4100
TBM Station Number [Chainage (m)]


June 2018
Thrust, RPM, Penetration Rate
Advance Thrust Force [kN]
23000
22000
21000
20000
19000
18000
17000
16000
15000
14000
13000
12000
11000
RPM (Main Drive Speed) [rotations/min]
Penetration Rate [mm/rotation]
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Cutter life
Penetration Rate
RPM
4100
4075
4050
4025
4000
3975
3950
3925
3900
3875
3850
3825
3800
TBM Station Number [Chainage (m)]
June 2018
Cutter Life
Weakness Zone
Cutter Life [m^3/cutter]
400
375
350
325
300
275
250
225
200
175
150
125
100
75
50
25
0
Cutter Life
Cutter change
128
14
10
0
0
0
1
0
0
Abrasive Wear [W]
Blocked [B]
Chipping [C]
Mushrooming [M]
Damaged Hub [H]
Oil Leakage [L]
Ring Crack [F]
Other [X]
Repositions [R00 and D00]
4100
4075
4050
4025
4000
3975
3950
3925
3900
3875
3850
3825
3800
TBM Station Number [Chainage (m)]


July 2018
Thrust, RPM, Penetration Rate
Advance Thrust Force [kN]
23000
22000
21000
20000
19000
18000
17000
16000
15000
14000
13000
12000
11000
RPM (Main Drive Speed) [rotations/min]
Penetration Rate [mm/rotation]
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Cutter life
Penetration Rate
RPM
3850
3825
3800
3775
3750
3725
3700
3675
3650
3625
3600
3575
3550
3525
3500
3475
3450
3425
3400
TBM Station Number [Chainage (m)]
July 2018
Cutter Life
Weakness Zone
Cutter Life [m^3/cutter]
400
375
350
325
300
275
250
225
200
175
150
125
100
75
50
25
0
Cutter Life
Cutter change
0
0
0
0
0
0
5
15
22
109
Abrasive Wear [W]
Blocked [B]
Chipping [C]
Mushrooming [M]
Damaged Hub [H]
Oil Leakage [L]
Ring Crack [F]
Other [X]
Repositions [R00 and D00]
3850
3825
3800
3775
3750
3725
3700
3675
3650
3625
3600
3575
3550
3525
3500
3475
3450
3425
3400
TBM Station Number [Chainage (m)]


August 2018
Thrust, RPM, Penetration Rate
Advance Thrust Force [kN]
23000
22000
21000
20000
19000
18000
17000
16000
15000
14000
13000
12000
11000
RPM (Main Drive Speed) [rotations/min]
Penetration Rate [mm/rotation]
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
Cutter life
Penetration Rate
RPM
3450
3425
3400
3375
3350
3325
3300
3275
3250
3225
3200
3175
3150
3125
3100
3075
3050
3025
3000
2975
2950
TBM Station Number [Chainage (m)]
August 2018
Cutter Life
Weakness Zone
Cutter Life [m^3/cutter]
400
375
350
325
300
275
250
225
200
175
150
125
100
75
50
25
0
Cutter Life
Cutter change
142
33
30
0
0
0
0
0
Abrasive Wear [W]
Blocked [B]
Chipping [C]
Mushrooming [M]
Damaged Hub [H]
Oil Leakage [L]
Ring Crack [F]
Other [X]
Repositions [R00 and D00]
3450
3425
3400
3375
3350
3325
3300
3275
3250
3225
3200
3175
3150
3125
3100
3075
3050
3025
3000
2975
2950
TBM Station Number [Chainage (m)]

The presence and influence of the weakness zones are clearly evident in the plotted TBM performance recordings, and the signatures also show behavior that to a certain extent coincides with signatures considered to correlate with MFC, however to a greater magnitude than the criterions set for the possible presence of MFC along the studied tunnel section. Besides the weakness zones, TBM performance recordings in eleven out of the considered nineteen months contain zones marked with signatures that fall within the criterions set for the possible correlation between TBM performance and the presence of MFC. Looking through the data, there are areas where thrust reduces by the criterion set for MFC, but no significant reduction is seen in the recorded RPM. There are also sections where thrust and RPM reduce by the criterion, but no correlating reduction is seen in the recorded penetration rate. These cases are not marked as MFC but are considered interesting. The approximate total length of the zones marked as MFC is measured to 355 meters, corresponding to 4.8% of the analyzed tunnel length. If the whole approximate length of weakness zones is included, the total length of MFC is 1640 meters, corresponding to 22.5% of the analyzed tunnel length.

The average and median cutter consumption registered with descriptions of wear typically experienced in MFC is respectively 22.7% and 18.4%. Only five out of the nineteen examined months is registered with consumption of cutters higher than 30%, due to the cutters being blocked, cracked, chipped, having oil leakage or damaged hubs. The respective months are February 2017, Mars 2017, November 2017, May 2018, and August 2018. Out of these five months, not taking the excavated length into account, there are only the two first and the last month where more than one zone of potential MFC is marked. Most of the zones marked as MFC correlates with a registered cutter life close to, or below the median cutter life. Further, it is also evident that most of the marked zones are followed by a reduction in the calculated cutter life for cutter changes recorded in the aftermath of the marked zones. The calculated cutter life thus substantiates the possible correlation between TBM performance and the presence of MFC in the analysis, but the number of changed cutters and the recorded cutter wear show little to no correlation to the presumed presence of MFC.

5.2.2 Comparative analyses of geological face mapping and tunnel face photos

The results from comparing interesting signatures in the filtered and analyzed TBM performance data to available geological face mappings are presented according to the position of the assessed mappings along the tunnel chainage. All face mappings available within zones marked as MFC were assessed, together with some weakness zones and one of the questionable zones:

8559-8555-8540-8493

Comprises mappings in the area of a known marked weakness zone. The first recorded mapping at chainage 8559 is just outside of the signature of the weakness zone, and the filtered performance data does not show any significance of MFC. The mapping describes the presence of a small area with soft brown clay on the upper right side of the working face, which most likely is due to the weakness zone ahead. The 8555 mapping is of greater interest as it describes a portion of the working consisting of blocky fractured rock to sandy conditions, occurring as an overbreak in the upper part of the working face. This description is similar to what one would expect in MFC of type RSI, but the performance data show an increase in the recorded penetration rate compared to the performance before encountering the weakness zone and is thus not considered MFC. Following, the next two mappings show photos of geology with fractured rock and voids which substantiates the increase in recorded penetration rate but not the presence of MFC.

8204-8082

8204 is within a presumed but vague MFC signature that stretches over 30 meters, showing varying thrust. The mapping describes small weakness zones, that give big over breaks, but no typical MFC geology. Photos show voids which might be the reason for increased penetration in the end of the signature, and the presence of MFC is not substantiated. 8082 show a layer banded pegmatite within gneiss, substantiating a correlation between MFC of Layer Banded Rock type to the recorded TBM performance.

6738-6688-6649-6629-6612

Five consecutive face mappings conducted in the 126 meters ahead of a marked zone of presumed MFC. Mapping 6649-6612 does not show any signs of MFC, substantiating the recorded TBM performance which shows a continues signature of normal excavation as expected for these mappings. 6738 and 6688 are described to show presence of layered amphibolite, and small deviations are seen in the thrust and penetration recordings. These deviations are not enough to qualify as MFC, and the corresponding photos show a stable working face with smooth kerfs.

5888

Marked as MFC with reduced TBM performance and corresponding low cutter life. Face mapping describes a pegmatite body and ampphibolite dyke on the working face. Hard to see presence of MFC from photos. Maybe MFC of LBR type, but not possible to substantiate.

5720

Vague signature of MFC as penetration rate varies within the marked zone. The working face is described to be consisting of gneiss with a band of fractured weak rock with some clay, but not assessed to be weakness zones. Hard to observe MFC from the corresponding photos. May be MFC of RSI type, but not possible to substantiate.

5304-5318

Marked as MFC due to a clear drop in recorded RPM. Penetration and thrust is reduced, however, thrust not to the boundary set for MFC to be presumed. 5304 describes a layered dyke of quartz between two dykes of ampphibolite in the gneiss, and 5318 shows ampphibolite dykes in gneiss. The dykes are visual from the corresponding photos, especially the quartz dyke. The face mappings thus substantiate MFC of the type LBR.

5098-5078

Two geological face mappings within a zone marked as questionable and possibly a weakness zone as the penetration rate increases. Thrust and RPM reduces significantly within this zone. From the photos it is hard to see clear kerfs and to substantiate the geology as possible MFC. The description of 5078 shows a registered weakness in the upper left side of the working face, together with banded dykes of pegmatite and ampphibolite. For 5098, the geology is described as highly fractured (blocky), which might be the reason for the increase in penetration rate. MFC is not substantiated in this questionable zone.

4859

Zone marked as MFC and the face mapping describes the working face to consist of gneiss with a marked area of ampphibolite to the lower right side of the face. The TBM performance signature is vague as both the penetration and thrust varies within the marked zone. From the photos it is also hard to substantiate the presence of MFC.

2973-2962

Marked as the last zone of MFC within the studied tunnel section. Thrust and RPM reduces to the conditions set for MFC to be presumed. Both face mappings show ampphibolite dykes crossing the working face from the upper right to lower left side, through the center. The dykes are evident from the photos and MFC of LBR type is evaluated to be substantiated.

The available face mappings substantiate the presence of MFC as interpreted for the marked zones showing the most evident signatures of MFC according to the boundaries set for the analysis. These zones are all assumed to be MFC of LBR type, and the corresponding photos show layer banded dykes of different rock mass on the working face, with the most evident being the quartz dyke seen from mapping at chainage 5318. For the zones marked as vague MFC, weakness zones, and questionable, the face mappings mostly describe working faces with the presence of fractured rock and some clay. The fracturing and presence of voids are likely to be the reason for the TBM performance recordings to show varying thrust and RPM, followed by increased penetration rate. Expecting to observe the presence of MFC of the type RSI in the transitions to and from weakness zones and possibly in the vague MFC zones, the geological face mapping substantiates the analysis of the TBM performance data by indicating the absence of real MFC in these zones.

Chapter 6

Discussion

6.1 The presence of MFC in TBM performance from literature

From the ground characterizations provided by Bane NOR, the rock mass was categorized as having low to very low drillability and high to very high strength, with the behavior of unsupported full-face excavation. This is well within the qualifications of hard rock conditions, and together with the descriptions of the rock mass properties one should assume MFC to occur as the type LBR and or RSI defined by (Tóth *et al.*, 2013). According to Bane NOR, MFC was expected and further exemplified to occur both as LBR and RSI; *"Mixed face conditions are likely to occur. An example of mixed face may be a very hard amphibolite with UCS of 250 MPa mixed with gneiss with UCS of 100 MPa. Another example may be a combination of solid rock and a weakness zone."*. Dykes or sills on the working face containing the "very hard ampphibolite", is covered by the description of LBR in the literature, and the combination of solid rock and weakness zones by the descriptions of RSI.

No descriptions were found in the literature regarding differences between the TBM performance signatures recorded from MFC of either the type RSI or from LBR. Looking to (Tóth *et al.*, 2013) as the most recent literature to suggest a definition of MFC, RSI is described to be characterized by the distinct difference in material properties between rock and soil on the working face, recognizing that unfilled karst can be considered as an extreme case of RSI. It is thus possible to argue that voids or open fracture sets in an otherwise homogeneous rock mass can be interpreted as MFC, with air constituting the "soft soil." If so, the full length of the weakness zones may be characterized as MFC as they are described as heavily jointed rock mass with minimal soil content or as crushed zones with clay transformations. Since the TBM performance signatures of the weakness zones deviate to a much greater magnitude than MFC zones presumes elsewhere along the studied tunnel section, a possible correlation between signatures in TBM performance data and the presence of MFC is more evident if the rock mass in weakness zones are categorized as MFC.

Characterizing the weakness zones as MFC has a significant effect on the total percentage of MFC occurrence along the studied tunnel section, increasing from approximately 4.8% to 22.5% of the total length. Looking at the very approximate assumption of 4.8% MFC from the criterions of reduction in thrust and RPM by (Blindheim, Grov and Nilsen, 2002), it is likely that one would see an increase in presumed MFC percentage along the tunnel if criterions were set less conservative. Less conservative could be understood as a 10-15% reduction in thrust only, with or without a reduction in the correlating penetration rate. As the primary countermeasure in MFC is to reduce the thrust, it is expected to see a reduction in penetration rate, followed by a possible project delay. Although not being defined to affect TBM performance solely in a negative way, it is evident in the literature that MFC is addressed to affect the TBM performance in a negative manner. This is further the reason for not addressing zones as MFC where penetration rate increases, even if thrust and or RPM reduces significantly, a reduction in cutter life is observed, and cutters changes show increased recordings of wear typical in MFC. Addressing MFC in such a manner might mean that possible correlations between MFC and TBM performance remain undetected when analyzing and may also be a general reason for misinterpretations of MFC.

6.2 Filtering

An extensive amount of the project work implied the development of the filtering code in MATLAB. The extent of- and the criterions set for the filtering operation was established in the early phase of the Thesis work, being adjusted and improved from the original code developed during the fall of 2018. Development of the code did, however, show to be a continuous and time-consuming task throughout the work on the Thesis, with most of the time being allocated to the processes of debugging and testing. The validity of such a filtering code is dependent upon extensive testing and preferably on multiple datasets. The code has been tested firmly to the TBM performance data available, where it has shown to work as intended, but the lack of testing to other TBM performance datasets is further regarded as a weakness affecting the overall validity of the code.

From the filtering code, error recordings, holes in the data, and downtime on the logging system were found, confirming the information given by Bane NOR on the need for filtering. The most considerable uncertainties found within the code, are the constraints set for the filtering operation of each of the TBM parameters evaluated. The allowed jump in the recordings of TBM station numbers and timestamp were respectively set to 1 meter and 1 minute. These criterions were assumed to be reasonable, and confirmed with Bane NOR during the field trip, but has no justification to literature or other scientific sources. The criterions set for filtering of unrealistic recordings are also partly based on reasonable assumptions, which are set based on the statistical distribution of the recordings and not evaluated to possible literary sources.

Filtering the raw TBM performance of 1 648 904 recorded data rows, the filter code removes 71 873 rows equivalent to 4.36% of the raw data. The total number of rows being filtered as unrealistic or as error recordings is 425 rows, which makes up only a fraction of the rows filtered from being recorded outside the actual boring operation. When applying a smoothening algorithm to the filtered data to reduce noise, it can thus be discussed and investigated how much effect there is from filtering the raw data for such recordings. Lengthening the moving window of the applied smoothening algorithm, the impact of such recordings will be reduced, and maybe even reduced exponentially.

Little scientific information was found in the literature regarding the influence of smoothening TBM performance recordings for analysis. A window of 1000 data points, equivalent to 1000 rows or approximately 5 meters were used in the analysis, and it is difficult to visually say if this window is suitable or if it covers up essential signatures in the data. A longer window, containing more data points, could have eased the process of analyzing and could also reduce the chance of misinterpreting the data. Assuming that the filter is accurate and valid, a last but essential factor to be addressed when evaluating results from applying the filtering code, is the fact that the quality of the output from computer programs depends on the quality of the input. The author has not been able to evaluate the quality of the provided raw TBM performance data or the logging system to other datasets or systems, which would have been beneficial to the overall assessment of the code validity.

6.3 Results and analysis

Based on the described literature and method, 20 zones were marked out in the filtered TBM performance data with a signature assumed to be correlating with the presence of Mixed Face Conditions on the working face. Most of these zones correlate with a reduction in the cutter life, calculated from the program named TBM Instantaneous Cutter Consumption Database of (Frostad, 2013), which substantiated the possibility of determining a correlation between TBM performance data and the presence of MFC. Due to the cutter data possibly containing errors in the recorded wear and the macros, and not knowing the validity of the program used to calculate cutter life, extra awareness was addressed to the cutter life results. The cutter life results seemed reasonable, but it was found that some of the performance signatures marked as MFC correlate with the point of cutter changes. Addressing this issue with Bane NOR, it was agreed that this could be due to a reduction of the operational parameters ahead of planned halts, possibly meaning that some of the marked performance signatures were misinterpreted as MFC. The influence of this possible non-representative data ahead of planned halts was not investigated and thus not assessed in the filtering code, weakening the validity of the marked results and further the possibility of determining a correlation between MFC presence and particular TBM performance signatures.

Due to the possible misinterpretation of signatures as MFC from the above, and the uncertainty around the validity of cutter life calculations, geological face mappings were considered as an additional validation and possible substantiation of the marked MFC and weakness zones. Results from analyzing face mappings available within or close to interesting signatures showed promising for the most explicit MFC signatures marked. These signatures were substantiated as MFC of type LBR according to the geological description in the mappings. The face mappings could not substantiate any MFC of the type RSI, which was assumed to possibly occur in the transition to or from weakness zones as described by Bane NOR. In the transition to the weakness zones, only the weakness zone marked in August 2018 showed a correlating reduction in penetration rate from the reduction in thrust and rpm assumed for MFC presence. Since the boundaries set for MFC to be present in the performance data required a correlating reduction in penetration rate and the fact that face mappings describe the geological conditions as fractured with some clay, no presence MFC could be determined. Interestingly, it can still be discussed if these performance recordings and face mappings of weakness zones describe a visual difference between MFC and geological conditions that show the same problems and effect as MFC. If so, TBM performance data can be used to distinguish signatures of possible MFC from geology like blocky fractured rock and rock mass with voids, making it possible to exclude the presence of MFC by determining the presence of these other geological conditions.

Chapter 7

Conclusion

Addressing Mixed Face Conditions as a sensitive and highly discussed topic in the TBM-tunneling industry, especially when actualized in relation to additional costs and claims, the problem statement in this Thesis was established through the actualization of the topic in recent Norwegian TBM projects. The problem statement was adequately pursued through the following scope:

- Gather an up to date knowledge on MFC in hard rock and its presence in TBM-tunneling.
- Development of a filter in MATLAB to clean the unfiltered TBM performance data so that analysis is possible.
- Analyze the TBM performance data for a correlation between TBM performance data and the presence of MFC, substantiating using cutter data and literature.

7.1 Conclusion

The research has gained an up to date knowledge on Mixed Face Conditions in hard rock and its presence in TBM-tunneling through literary searches on the topic in international journals and by utilizing TBM and cutter tool life data from the recently finished Follo Line tunnel for the analysis of its presence in filtered TBM performance data.

A TBM raw-data filtering code has successfully been developed in MATLAB, giving the opportunity to effectively remove non-representative data and error recordings in raw TBM performance data. Through the filtering operation, the position of holes in the recorded data, non-representative recordings, and error recordings is revealed and stored for the possibility of inspection. Data to be filtered out is further removed, and the result is a dataset of filtered TBM performance recordings, containing data solely from the actual boring operation, ready for analysis.

The possibility of determining a correlation between TBM performance data and the presence of Mixed Face Conditions on the working face was researched through analyzes of literature and filtered TBM performance data. The analysis of performance data was also substantiation from cutter tool life data and geological face mappings.

According to literature, it was found plausible to determine a correlation between TBM performance data and challenging geology like Mixed Face Conditions in hard rock TBM tunneling, but not Mixed Face Conditions exclusively. It was also found that literature interprets Mixed Face Conditions as rock mass that affects the TBM performance negatively as a reduced penetration rate is expected when Mixed Face Conditions is present. No scientific quantification was found on the extent to which one should reduce operational performance parameters to handle problems and effects of Mixed Face Conditions, but some findings in the literature suggested that a 10-15% reduction of thrust and or RPM would be reasonable to account for Mixed Face Conditions due to different rock types alone. This suggestion further worked as the basis for the visual analysis of TBM performance data from the Follo Line Project.

Through the analysis of filtered TBM performance data from the Follo Line project, it was found plausible to determine a correlation between TBM performance signatures and the presence of Mixed Face Conditions of the type Layer Banded Rock in shielded hard rock tunneling, but not from TBM performance data exclusively. To determine the presence of Mixed Face Conditions with a certain degree of accuracy, it was found that TBM performance data must be substantiated using cutter data records, geological face mappings, and other factors relating to MFC. The approximate total length of Mixed Face presence was found to be 355 meters, corresponding to 4.8% of the analyzed section in the tunnel studied.

7.2 Further Work

The Follo Line is an interesting project for the study of Mixed Face Conditons in hard rock as there is a significant amount of data available from four different TBM's and thus a good basis of data for further work on the topic of Mixed Face Conditons. It is suggested that performance data from all four TBM's are analyzed, as well as the validity of the raw-data and logging systems used. Further analysis should assign more time to substantiate performance signatures from geological face mappings, with particular awareness applied to weakness zones showing a reduction in penetration rate correlating to a reduction in thrust and RPM. Since Mixed Face Conditons of the type Layer Banded rock were presumed and substantiated, it would be interesting to study the correction factor suggested by (Steingrimsson, Grøv and Nilsen, 2002). The cutter data and cutter life should also be reviewed to confirm the validity. Recordings of the performance parameter torque, hydrogeological properties and mechanical properties of the excavated rock mass are assumed to hold valuable information to the interpretation of the TBM performance data signatures and should be evaluated in further studies.

The effect and need for comprehensive filtering should be studied in accordance with the effect of smoothening the TBM performance data to better interpret the data visually. If the filter code is to be used in further studies, the effect of adjustments to operational parameters ahead of planned halts should be investigated firmly. The validity of the filter code would further benefit from testing on other datasets, preferably data from the second northbound TBM as a first test. A scientific review of the filter-criterions should also be included in further studies if the code is to be used.

Since the primary indication of Mixed Face Conditons and other geological formations that constitute similar effects and problems is abnormal vibrations, studies on the topic of vibrations in TBM tunneling could hold valuable information on the quantification of Mixed Face Conditons. A suggestion is to record accelerations during excavation to establish a database of characteristic vibration signatures for different cutter head designs, cutter diameters and machine makes and models. Abnormal vibration could then possibly be related to Mixed Face Conditons or other problematic conditions on the working face in a more scientific way, minimizing the chance of misinterpretations and disputes in the industry.

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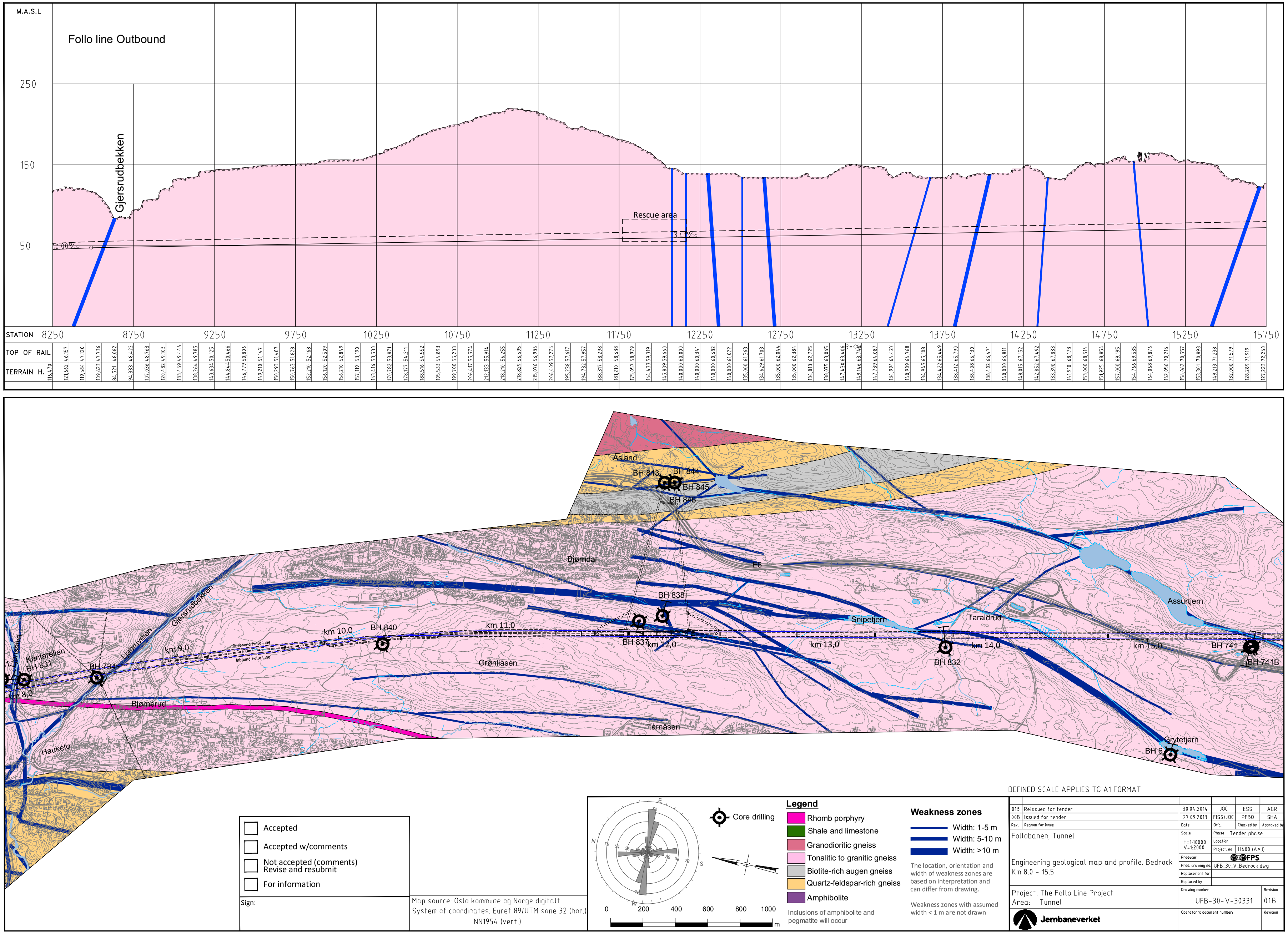
Appendices

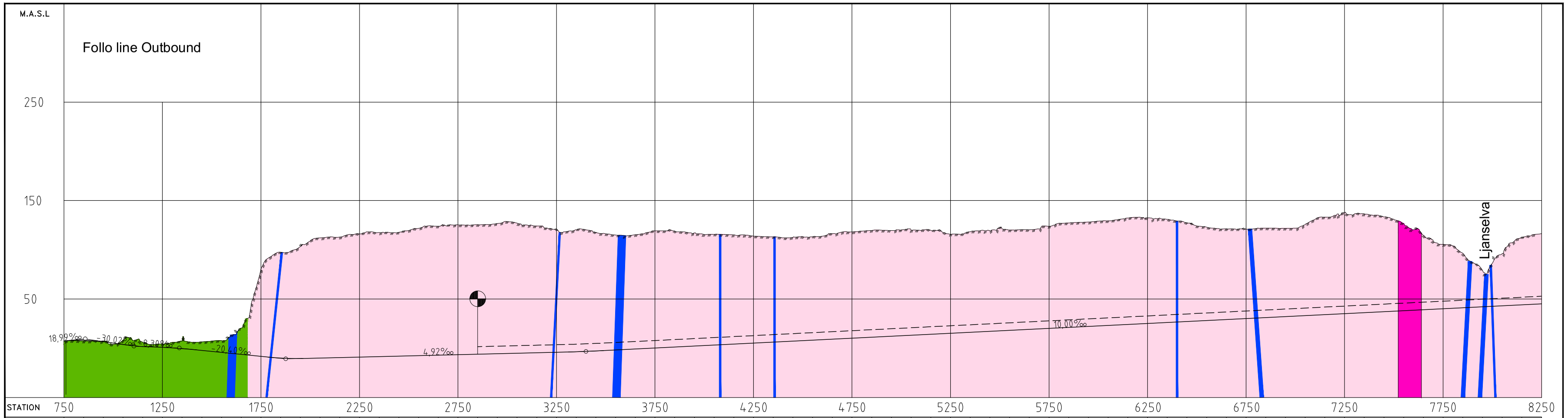
A – Geological profiles for northbound machines

B – Filtering code

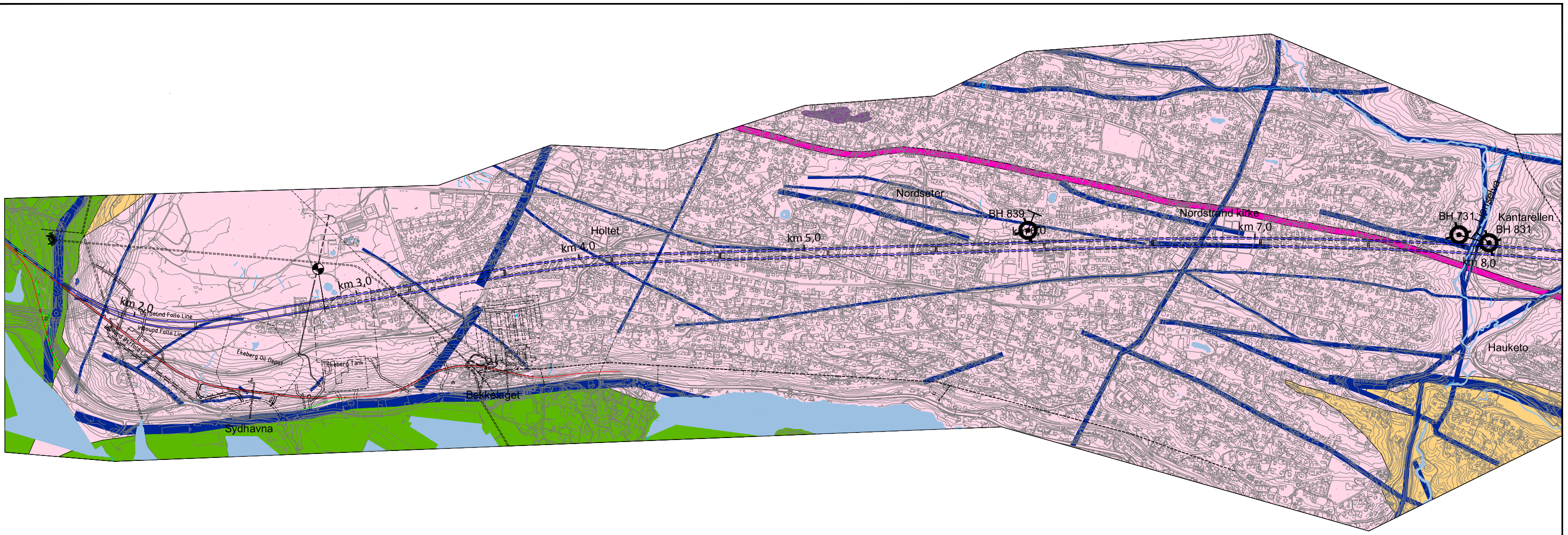
APPENDIX – A


M.A.S.L
250
150
50
Follo line Outbound
Gjersrudbekken
Rescue area
3.4 ‰
STATION
8250
8750
9250
9750
10250
10750
11250
11750
12250
12750
13250
13750
14250
14750
15250
15750
TOP OF RAIL
TERRAIN H.
Åsland
BH 843
BH 844
BH 845
BH 846
Bjørndal
E6
BH 838
BH 837
km 12,0
Snipetjern
Taraldrud
km 13,0
BH 832
km 14,0
Assurtjern
km 15,0
BH 741
BH 741B
Grytetjern
BH 6
Tårnåsen
Grønliåsen
km 11,0
BH 840
km 10,0
km 9,0
Gjersrudbekken
Liabruveien
Kanalarellen
BH 831
BH 734
km 8,0
Bjørnerud
Hauketo
Outbound Follo Line
Inbound Follo Line
Core drilling
Legend
Rhomb porphyry
Shale and limestone
Granodioritic gneiss
Tonalitic to granitic gneiss
Biotite-rich augen gneiss
Quartz-feldspar-rich gneiss
Amphibolite
Inclusions of amphibolite and pegmatite will occur
Weakness zones
Width: 1-5 m
Width: 5-10 m
Width: >10 m
The location, orientation and width of weakness zones are based on interpretation and can differ from drawing.
Weakness zones with assumed width < 1 m are not drawn
0
200
400
600
800
1000
m
☐ Accepted
☐ Accepted w/comments
☐ Not accepted (comments) Revise and resubmit
☐ For information
Sign:
Map source: Oslo kommune og Norge digitalt
System of coordinates: Euref 89/UTM sone 32 (hor.)
NN1954 (vert.)
DEFINED SCALE APPLIES TO A1 FORMAT
01B Reissued for tender 30.04.2014 JOC ESS AGR
00B Issued for tender 27.09.2013 EISS/JOC PEBO SHA
Rev. Reason for issue Date Orig. Checked by Approved by
Follobanen, Tunnel
Engineering geological map and profile. Bedrock
Km 8.0 - 15.5
Scale H=1:10000 V=1:2000
Phase Tender phase
Location
Project. no 11400 (AAJ)
Producer
Prod. drawing no. UFB_30_V_Bedrock.dwg
Replacement for
Replaced by
Project: The Follo Line Project
Area: Tunnel
Drawing number UFB-30-V-30331
Revision 01B
Operator's document number:
Revision
Jernbaneverket

Follo line Outbound



STATION	TOP OF RAIL	TERRAIN H.
750		7,210
	8,334	7,210
	6,733	7,210
	3,735	8,170
	1,711	6,006
1250	0,881	4,210
	-0,232	7,219
	-2,168	6,470
	-4,208	7,476
	-6,248	20,507
1750	-8,288	80,370
	-10,076	97,597
	-10,465	103,105
	-9,977	112,064
	-9,485	113,045
2250	-8,993	116,053
	-8,500	117,486
	-8,008	117,803
	-7,516	121,738
	-7,024	123,979
2750	-6,532	125,509
	-6,040	125,517
	-5,548	126,668
	-5,056	127,004
	-4,564	124,210
3250	-4,072	120,505
	-3,577	120,358
	-2,827	117,746
	-1,830	115,009
	-0,830	115,282
3750	0,170	119,210
	1,169	119,137
	2,169	117,154
	3,169	115,608
	4,169	115,204
4250	5,168	113,893
	6,168	113,210
	7,168	112,530
	8,167	113,233
	9,167	116,268
4750	10,167	118,150
	11,167	119,643
	12,166	119,632
	13,166	119,963
	14,166	119,678
5250	15,165	115,679
	16,165	118,210
	17,165	119,141
	18,165	120,025
	19,164	120,312
5750	20,164	123,801
	21,164	127,268
	22,163	128,259
	23,163	129,371
	24,163	132,210
6250	25,163	132,388
	26,162	130,956
	27,162	127,322
	28,162	123,031
	29,162	121,211
6750	30,161	120,901
	31,161	122,040
	32,161	121,757
	33,160	125,425
	34,160	133,185
7250	35,160	137,867
	36,160	136,722
	37,159	133,341
	38,159	126,703
	39,159	114,851
7750	40,158	105,464
	41,158	96,495
	42,158	78,966
	43,158	96,101
	44,157	112,507
8250	45,157	116,471

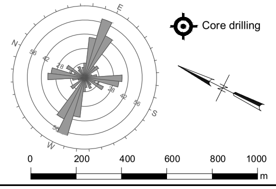


DEFINED SCALE APPLIES TO A1 FORMAT

☐ Accepted
☐ Accepted w/comments
☐ Not accepted (comments) Revise and resubmit
☐ For information

Sign:

Map source: Oslo kommune og Norge digitalt
System of coordinates: Euref 89/UTM sone 32 (hor.)
NN1954 (vert.)



Core drilling

Legend

🟪	Rhomb porphyry
🟩	Shale and limestone
🟥	Granodioritic gneiss
▨	Tonalitic to granitic gneiss
⬜	Biotite-rich augen gneiss
🟨	Quartz-feldspar-rich gneiss
🟪	Amphibolite

Inclusions of amphibolite and pegmatite will occur

Weakness zones

—	Width: 1-5 m
—	Width: 5-10 m
—	Width: >10 m

The location, orientation and width of weakness zones are based on interpretation and can differ from drawing.

Weakness zones with assumed width < 1 m are not drawn

Rev.	Reason for issue	Date	Orig.	Checked by	Approved by
01B	Reissued for tender	30.04.2014	JOC	ESS	AGR
00B	Issued for tender	27.09.2013	EISS/JOC	PEBO	SHA

Follobanen, Tunnel

Engineering geological map and profile. Bedrock
Km 2.85 - 8.0

Scale: H=1:10000 V=1:2000
Phase: Tender phase
Location:
Project. no: 11400 (AAJ)
Producer: FPS
Prod. drawing no.: UFB_30_V_Bedrock.dwg
Replacement for:
Replaced by:

Project: The Follo Line Project
Area: Tunnel

Drawing number: UFB-30-V-30330
Revision: 01B

Jernbaneverket

Operator's document number:
Revision:

APPENDIX – B

```
%                TBM performance rawdata filter code
%                       Written by Even Iddeng
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
function [Data,Time,Filterdata,FilterTime]=Filter_TBM_Rawdata(filename)
%filename='Rawdata.txt';
tic
% close all       %Close all open figuers
%
% clc             %Clears command window
% clear           %Clears workspace

A = importdata(filename,'\t');
%Imports rawdata from file of format 'Filendame.txt' to the struct A.
%Importdata separates the data columns in the rawdata by their spacing.
%Raw data is tabulator spaced and \t telles importdata to separate by
%tabulator. Timestamp column in rawdata does not contain real numbers and A
%becomes a struct containing a table of real numbers for perfomance data
%and a cell array containing the Timestamp.

dbstop if error         %Jump into debuger if error in code
Data = A.data;          %Define Data as matrix of real numbers in A
Text = A.textdata(:,1); %Define Text as matrix of text cells in A
Text(1,:)  = [];        %Removes first row of headerlines in Text matrix
Filterdata = A.data;    %Define Filterdata matrix equal to Data matrix
Time = Text;            %Defines Time matrix equal to Text matrix

%Overview of the different data in the different columns of Time and Data
%matrix:

        %Time(:,1)       = dd.mm.yyyy HH:MM:SS    [24 hour clock]

        %Filterdata(:,1) = ringnumber             [number]
        %Filterdata(:,2) = Main drive speed       [rotations/min]
        %Filterdata(:,3) = Advance speed          [mm/min]
        %Filterdata(:,4) = VMT_TBM_station        [station number (m)]
        %Filterdata(:,5) = Advance thrust force   [kN]
        %Filterdata(:,6) = Main drive torque      [kNm]
        %Filterdata(:,7) = Penetration            [mm/rotation]


%% Filter on unrealistic TBM_station numbers and retraction of the TBM
%For-loop looks through data, filtering out station numbers outside the
%boundaries of the dataset and sudden jumps in station number. Station
%number is sinking over the length of the data and all stations with a
%difference greater than the allowable JumpLength from the previous station
%is filtered out. Only interested in performance data from production, all
%performance data from retraction of the machine is removed to make a
%continous set of only real boring operation data. Code uses Data to locate
%rows which are to be filtered and filters data in the Filterdata matrix.

% Filtering of unrealistic TBM stations

OutData=1;      %counter
ErrorCount=1;   %counter
JumpLength=1;   %1 meter
```

```
for i=2:(length(Data)-1)

    if     (Data(i,4)>Data(1,4)) || (Data(i,4)<Data(length(Data),4))
           StationOutsideData(OutData,:) = [i Data(i,4)];
           OutData=OutData+1;       %Store unreal stations
           Filterdata(i,4)=0;
           %If TBM station is higher than the starting station number or
           %lower than the last station number it is filtered out

    elseif (Data(i,4)<(Data(i-1,4)-JumpLength)) && (Data(i,4)<Data(i+1,4))
           StationError(ErrorCount,:) = [i Data(i,4)];
           ErrorCount=ErrorCount+1; %Store Error positions
           Filterdata(i,4)=0;
           %Station number found within the range of the highest and lowest
           %station, but loggd at incorrect position is filtered out
    else
    end
end


% Filtering of data rows from retraction of the machine
count=1;    %counter
i=2;        %index
while i<=length(Data)
 if Data(i,4)>=Data(length(Data),4) && Data((i-1),4)<Data(i,4)
    %If Staton is within the range of the dataset and the previous station
    %is lower than the current, retraction is registered

    for  j=i:length(Data)
       %Look through Data from the point of registered retraction i
      if   Data((i-1),4)<Data(length(Data),4) && Data(j,4)>Data((i-2),4)
           %If retraction in Data is registered due to ErrorStations, check
           %with i-2 to control if real restraction is detected or not

           StationRectraction(count,:) = [j Data(j,4)]; %Store retraction
           count=count+1;
           Filterdata(j,4)=0; %Filter out if real retraction

      elseif Data((i-1),4)>=Data(length(Data),4) && Data(j,4)>Data((i-2),4)
           %Registeres real retraction in Data

           StationRectraction(count,:) = [j Data(j,4)]; %Store retraction
           count=count+1;
           Filterdata(j,4)=0; %Filter out real retraction

      else
           break
           %If above criterias are not met, break out for-loop.
      end
    end
  i=j;
 else
 end
 i=i+1;
end

%All station to be filtered out has been set to zero in Filterdata.
NumZeroStation = sum(Filterdata(:,4)==0);   %Number zero stations
ZeroRowStation  = find(Filterdata(:,4)==0); %Row number of zero stations

%Sets all rows in Filterdata equal to zero if station is zero.
```

```
%Similarly equal rows are set empty in Time vector
for n=1:length(ZeroRowStation)
    Filterdata(ZeroRowStation(n),:)=0;
    Time(ZeroRowStation(n),1)={''};
end

%Empty rows in Time and zero-rows in Filterdata is removed
Filterdata = Filterdata(any(Filterdata ~= 0,2),:); %Removes all "zero-rows"
Time = Time(~any(cellfun('isempty', Time), 2), :); %Removes all empty cells


%% Reveling jumps and the length of jumps present in Filterdata
count=1;      %counter
JumpLength=1; %Jumplength in station number is set to 1 meter
for i=2:length(Filterdata)
    if (Filterdata(i,4) >=  Filterdata(length(Filterdata),4)   && ...
       (Filterdata((i-1),4)>Filterdata(length(Filterdata),4))  && ...
       (Filterdata((i-1),4)-Filterdata(i,4))>JumpLength)

     StationsJumpFilter(count,:) = [i Filterdata(i,4) (Filterdata(i-1,4)...
     -Filterdata(i,4)) (Filterdata(i-1,1)-Filterdata(i,1))]; %Store Jump
     count=count+1;

     %Checks if jump in TBM station is greater than 1 meter, then store
     %these positions, the real length of jump and check change of ring
     %number. Store results in vector StationsJumpFilter
    else
    end
end


%% Filter on Timestamps when detecting halts in production

%Converts date and time string in Time vector to double (real numbers) as
%number of days and decimal time since refrence year January 1st 0000 = 1
%Time cell array vector is converted to double vector time_number
%To detect halts in production, jumps in the Timestamp of more than 1
%minute is detected. When halt is detected, check if real halt or possible
%downtime on the logging system.

time_number=datenum(Time,'dd.mm.yyyy HH:MM:SS');
format long     %Shows more digits in time_number
JumpLength=1; %Allowed jump in station number
Minutes=3;      %Time length which should be filtered out set to 3min
AllowedTimeDif=datenum(['0/0/0000 0:0',num2str(1),':00']);     % 1min
MaxFilterTimeLength=datenum(['0/0/0000 0:0',num2str(Minutes),':00']); %3min
FilterTime=time_number;
%FilterTime equals time_numbers and time_number is used as referance for
%calculations.

%Filtering of Timestamps
count=1;    %Counter
Haltcount=1;%Counter
for i=2:length(Time)
    TimeIndex=(i);          %Index
    PrevTimeIndex=(i-1);    %Index timestamp in previous row
    PrevTime    = time_number(PrevTimeIndex);    %Previous timestamp
    CurrentTime = time_number(TimeIndex);
    if CurrentTime>PrevTime+AllowedTimeDif
       %Finds jumps in Timestamp greater than 1 min
```

```
      if (Filterdata(PrevTimeIndex,4)-Filterdata(TimeIndex,4))>...
         JumpLength && (Filterdata(TimeIndex,1)-(Filterdata...
         (PrevTimeIndex,1)))>1
         %Check if real halt or possible downtime on loggingsystem by
         %controling jumps in ring number and Station

         TimeStationError(count,:) = [TimeIndex Filterdata(TimeIndex,4)];
         %Store possible downtime positions
         count=count+1;

      else %Real halt in production
           if i<=18 %control if halt is within first 18 rows in Time vector
           ThrustForceMedian=median(Filterdata(1:PrevTimeIndex,5));
           PenetrationMedian=median(Filterdata(1:PrevTimeIndex,7));
           %Check median Thrust force and Penetration for available data

           else
           ThrustForceMedian=median(Filterdata(...
                                     (PrevTimeIndex-18):PrevTimeIndex,5));
           PenetrationMedian=median(Filterdata(...
                                     (PrevTimeIndex-18):PrevTimeIndex,7));
           %Check median of Thrust force and Penetration from last 18 rows
           %equivalent to approx. 3 min of production

           end

           %Filter out all rows where Thrust force and Penetration has not
           %reached the percentage performance target of 80% resumed
           %performance from before the halt. If target is not reached
           %within 3 minutes, the loop breaks and all data within 3 minutes
           %successive to a halt is filtered out

           TargetMean=0.8;   %Target set to 80% of performance mean

           FilterTime(TimeIndex)=0;           %Retraction data set to 0
           ValidIndex=0;     %ValidIndex to start new counting of signals

           while (Filterdata(TimeIndex+ValidIndex,5)<TargetMean*...
                 ThrustForceMedian)  ||
(Filterdata(TimeIndex+ValidIndex,7)<...
                 TargetMean*PenetrationMedian)

                 ValidIndex = ValidIndex+1;     %Update index
                 ValidTime  = time_number(TimeIndex+ValidIndex);

                 if ValidTime-CurrentTime>MaxFilterTimeLength
                    break
                 end

           end
                 ValidIndex=ValidIndex+PrevTimeIndex;
                 FilterTime(TimeIndex:ValidIndex)=0;
                 LengthFilt=(Filterdata(TimeIndex,4)-...
                                Filterdata(ValidIndex,4));
                 %Timestamps within non representative data is set to 0

            TimeHaltFilt(Haltcount,:)=[TimeIndex Filterdata(TimeIndex,4)...
            Filterdata(ValidIndex,4) LengthFilt];
            Haltcount=Haltcount+1;
       end
```

```
    else
    end
end

%All Timestamps to be filtered out has been set to zero in FilterTime.
NumZerosTimestamp = sum(FilterTime()==0);   %Number of zero Timestamps
ZeroRowsTimestamp = find(FilterTime()==0);  %Row number of zero Timestamp

%Sets all rows in FilterDate equal to zero where Timestamp is zero.
%Similarly equal rows are set empty in Time vector
for m=1:length(ZeroRowsTimestamp)
    Filterdata(ZeroRowsTimestamp(m),:)=0;
    FilterTime(ZeroRowsTimestamp(m),:)=0;
    Time(ZeroRowsTimestamp(m),1)={''};
end

%Empty rows in Time and zero-rows in Filterdata and FilterTime is removed
Filterdata = Filterdata(any(Filterdata ~= 0,2),:); %Removes all "zero-rows"
FilterTime = FilterTime(any(FilterTime ~= 0,2),:); %Removes all "zero-rows"
Time = Time(~any(cellfun('isempty', Time), 2), :); %Removes all empty cells


%% Filter of unrealistic non-representative recordings of performance data

%Based on the following criterions, unrealsitc performance recordings are
%filter out of the data. Advance speed recordings higher than 75 mm/min,
%Advance thrust force lower than 3550 kN equivalent to 50 kN/cutter and
%Penetration rates higher than 25 mm/rotation makes the filter criterions.

count=1;
for i=1:length(Filterdata)
    if    Filterdata(i,3)>75 || Filterdata(i,5)<3550 || Filterdata(i,7)>25

        Unrealistic(count,:) = [i Filterdata(i,4) Filterdata(i,3) ...
                                      Filterdata(i,2) Filterdata(i,5)];
        %Store recordings which are filtered out as unrealistic
        count=count+1;
        Filterdata(i,4)=0;

    else

    end
end

%All station to be filtered out has been set to zero in Filterdata.
NumZeroStation = sum(Filterdata(:,4)==0);   %Number zero stations
ZeroRowStation  = find(Filterdata(:,4)==0); %Row number of zero stations

%Sets all rows in Filterdata equal to zero if station is zero.
%Similarly equal rows are set empty in Time vector
for p=1:length(ZeroRowStation)
    Filterdata(ZeroRowStation(p),:)=0;
    FilterTime(ZeroRowStation(p),:)=0;
    Time(ZeroRowStation(p),1)={''};
end

%Empty rows in Time and zero-rows in Filterdata is removed
Filterdata = Filterdata(any(Filterdata ~= 0,2),:); %Removes all "zero-rows"
FilterTime = FilterTime(any(FilterTime ~= 0,2),:); %Removes all "zero-rows"
```

```
Time = Time(~any(cellfun('isempty', Time), 2), :); %Removes all empty cells


toc%Ends stopwatch and displays calcualtion time


        %Time(:,1)       = dd.mm.yyyy HH:MM:SS    [24 hour clock]

        %Filterdata(:,1) = ringnumber             [number]
        %Filterdata(:,2) = Main drive speed       [rotations/min]
        %Filterdata(:,3) = Advance speed          [mm/min]
        %Filterdata(:,4) = VMT_TBM_station        [station number (m)]
        %Filterdata(:,5) = Advance thrust force   [kN]
        %Filterdata(:,6) = Main drive torque      [kNm]
        %Filterdata(:,7) = Penetration            [mm/rotation]



%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                            May 2019
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
end
```

Even Lein Iddeng

Full Face Tunnel Boring in Hard Rock Conditions - Detection and Influence of Mixed Face Conditions

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