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Evaluation and Optimisation of Small-Diameter Tunnel Boring Machines in Hard Rock

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Abstract

The use of small-diameter tunnel boring machines (TBMs) in hard rock is becoming more widespread due to the growing demand for new and longer utility tunnels that include sewer, stormwater, freshwater and hydropower systems, as well as tunnels for cables and casings for pipelines carrying natural gas or hydrogen. These utility tunnel projects often have to overcome diverse geological conditions, including small overburden, weathered rock, rock-soil transitions, and intact or fractured rock with high strength and abrasiveness. Due to stricter safety regulations, the technique of hard rock pipe jacking is becoming increasingly vital in the utility tunnelling industry. Using the example of a 530-m-long utility tunnel with an outer diameter of 2.2 m in France, which serves as a casing tunnel for a gas pipeline in the context of France's energy transition, the first part of this thesis presents and discusses the methods and challenges involved in analysing data for small-diameter pipe jacking projects. In order to better understand the global challenges associated with performance analysis and prediction of utility tunnelling projects, a database has been created in the second part that includes 37 hard rock projects with TBM outer diameters between 1 and 5 m, as well as more than 70,000 m of tunnel alignments, with a median drive length of less than 500 m. As most of the existing penetration prediction models have been developed for large-diameter TBMs, this is the first time different approaches for predicting small-diameter TBM penetration, their implications and guidelines for practical application are given. The third part of the work addresses the question of how such small TBMs can become even faster in hard rock by exposing the rock to microwaves and weakening it. Therefore, a comprehensive geotechnical testing program was conducted on over 700 microwave-irradiated and non-irradiated specimens, which included granite and three different strength grades of concrete. Microwave pre-conditioning of rocks involves utilising selective heating to cause differential volumetric expansion in minerals, which leads to the formation of micro- and macrofractures in rock and strength reduction ratios of over 50%. Following on from the question of how fast small TBMs in hard rock are today and how this can best be predicted, the use of microwave pre-conditioning proves to be a highly promising method for decreasing the strength of rock and therefore increasing cutting rates, with the ability to significantly boost the advance rates and profitability of future mechanised hard rock tunnel boring and mining equipment.

Kurzfassung

Der Einsatz von Tunnelbohrmaschinen (TBMs) mit kleinem Durchmesser in Gesteinen mit hohen Festigkeiten wird aufgrund der wachsenden Nachfrage nach neuen und längeren Versorgungstunneln für Abwasserkanäle, Regenwasser-, Süßwasser- oder Wasserkraftanlagen sowie Kabeltunneln und Hüllrohren für Gas- oder Wasserstoffpipelines immer bedeutender. Bei diesen Tunnelbauvorhaben für Versorgungsunternehmen müssen oft die unterschiedlichsten geologischen Bedingungen überwunden werden, darunter geringe Überdeckungen, verwittertes Gestein, Festgestein-Lockergesteins-Übergänge sowie intaktes oder gestörtes Gestein mit hoher Festigkeit und Abrasivität. Aufgrund strengerer Sicherheitsvorschriften ist die Technologie des Hartgestein-Rohrvortriebs in der Tunnelbauindustrie zunehmend weit verbreitet. Am Beispiel eines 530 m langen Versorgungstunnels mit einem Außendurchmesser von 2,2 m in Frankreich, der im Rahmen der Energiewende als Hülltunnel für eine Gaspipeline dient, werden im ersten Teil dieser Arbeit die Methoden und Herausforderungen bei der Analyse von Daten von Rohrvortriebsprojekten mit kleinen Durchmessern vorgestellt und diskutiert. Zum besseren Verständnis der Herausforderungen im Zusammenhang mit der Leistungsanalyse und Penetrationsvorhersage von Tunnelbauprojekten mit kleinen Durchmessern wurde im zweiten Teil eine Datenbank erstellt, die 37 Hartgesteinsprojekte mit Durchmessern zwischen 1 m und 5 m, mehr als 70.000 m Tunnel, sowie eine Vortriebslänge von weniger als 500 m pro Projekt (Median) umfasst. Da die meisten vorhandenen Modelle zur Penetrationsvorhersage für TBMs mit großem Durchmesser entwickelt wurden, werden zum ersten Mal verschiedene Ansätze zur Vorhersage des Vortriebs für TBMs mit kleinem Durchmessern sowie ihre Auswirkungen und Empfehlungen für die praktische Anwendung vorgestellt. Im dritten Teil dieser Arbeit wird untersucht, wie die Vortriebsgeschwindigkeit von TBMs mit kleinen Durchmessern im Festgestein erhöht werden kann. Dazu wurde ein umfangreiches geotechnisches Untersuchungsprogramm an über 700 Proben, darunter Granit und Beton mit drei verschiedene Festigkeitsklassen, durchgeführt und diese Proben mit Mikrowellen bestrahlt. Bei diesem Ansatz wird durch selektive Erwärmung eine unterschiedliche Volumenexpansion in den Mineralien hervorgerufen, die zur Bildung von Mikro- und Makrorissen im Gestein und zu einer Festigkeitsminderung von über 50 % führt. Ausgehend von der Frage, wie hoch die Vortriebsgeschwindigkeiten kleiner TBMs in Gesteinen hoher Festigkeit heute tatsächlich sind und wie dies am besten vorhergesagt werden kann, erweist sich der Einsatz der Mikrowellen-Vorkonditionierung als vielversprechende Methode zur Verringerung der Festigkeit eines Gesteins und damit zur Erhöhung der Schneidraten, was die Vortriebsgeschwindigkeit und Rentabilität künftiger Tunnelbau- und Bergbaumaschinen erheblich steigern könnte.

Résumé

L’utilisation de tunneliers de petits diamètres adaptés aux roches dures est de plus en plus répandue en raison de la demande croissante de nouveaux tunnels de service publique. Ces tunnels sont destinés à la construction d’égouts, de conduites de transport d’eau pluviale, d’eau douce, de conduites forcées pour la production d’hydroélectricité, ainsi qu’à l’installation de gazoducs ou de pipelines pour transporter l’hydrogène. Ces projets de construction de tunnels pour l’extension de réseaux publics nécessitent souvent de surmonter des conditions géologiques très variées, notamment des roches homogènes ou fragmentées présentant une résistance et une abrasivité élevées. En raison de haut standards de sécurité, la technique de forage par microtunnelier en roche dure est de plus en plus répandue dans l'industrie de la construction de tunnels. La première partie de ce travail s’appuie sur l'exemple d'un tunnel d'approvisionnement de 530 m de long et d'un diamètre extérieur de 2,2 m réalisé dans le cadre de la transition énergétique en France, servant de tunnel d'enveloppe pour un gazoduc. La seconde partie de ce travail présente et développe les méthodes et les défis liés à l'analyse des données de projets de creusement de tunnels de petit diamètre. Afin de mieux comprendre les défis liés à l'analyse des performances et à la prédiction de la vitesse de réalisation de ce type de projets, une base de données a été créée, comprenant entre autre, plus de 70.000 m de tunnels d’une longueur médiane de creusement inférieure à 500 m par projet, provenant de 37 projets, réalisés en roche dure avec des diamètres compris entre 1 et 5 m. Sachant que la plupart des modèles existants de prévision de vitesse d’avance ont été développés pour les tunneliers de grand diamètre, le rapport présente pour la première fois différentes approches de prévision de la pénétration pour les tunneliers de petit diamètre, leurs effets et les recommandations pour l'application pratique de ces dernières. La troisième partie du travail abordera l’optimisation des petits tunneliers, afin de les rendre plus rapides dans les roches dures et compactes. Pour ce faire, un vaste programme d'essais géotechniques a été mené sur plus de 700 échantillons, composés entre autres de granit et de béton de trois classes de résistance différentes, partiellement irradiés par micro-ondes. Dans cette approche, le chauffage sélectif de l’échantillon provoque une expansion volumique locale dans les minéraux. Celle-ci entraîne la formation de microfissures et de macrofissures dans la roche et ainsi une diminution de la résistance de plus de 50 %. L’usage d’un tel traitement sur des roches dures, dans le but d’en abaisser leur dureté locale et superficielle semble être une méthode prometteuse. Grâce à celle-ci, les vitesses de forages actuelles des tunneliers peuvent être sensiblement augmentées tout en maintenant leur usure à un niveau économiquement acceptable.

Abbreviations

Abbreviation	Description
AI	Artificial intelligence
AVN	Small-diameter slurry TBM with cone crusher (Automatische Vortriebsmaschine Nass)
CSM	Colorado School of Mines
DBI	Detailed borehole information
DGGT	German Geotechnical Society
EDX	Energy dispersive X-ray spectroscopy
EPB	Earth pressure balance
HDD	Horizontal directional drilling
HGA	Homogeneous geotechnical area
IJS	Interjack station
ISRM	International Society of Rock Mechanics
LCM	Linear cutting machine
ML	Machine learning
MW	Microwave
NTNU	Norwegian University of Science and Technology
PJ	Pipe jacking
SEM	Scanning electron microscope
SL	Segment lining
TBM	Tunnel boring machine
XRD	X-ray diffraction

Symbols

Symbol	Unit	Description
BTS	MPa	Brazilian tensile strength
CAI	-	CERCHAR abrasivity index
C_p	$kJ/(kg \cdot K)$	Specific heat capacity
D	mm	Cutterhead diameter
e	%	Electrothermal efficiency
e_f	$W \cdot s^{1/2}/(m^2 \cdot K)$	Thermal effusivity
F_n	kN	Cutter thrust force
FPI	$(kN/cutter)/(mm/rev)$	Field penetration index
F_r	kN	Cutter rolling force
HOME	%	Heat over microwave energy
ID	mm	Inner diameter
k	$W/(m \cdot K)$	Thermal conductivity
K_i	-	Correction factor
LAC	g/t	LCPC abrasivity coefficient
LBC	%	LCPC breakability coefficient
M	kNm	Torque
m	kg	Mass
MAPE	%	Mean average percentage error
OD	mm	Outer diameter
ρ_b	g/cm^3	Dry bulk density
PLI	MPa	Point load index
PR	mm/rev	Penetration rate
P_{sample}	kW	Specific performance
Rev	min^{-1}	Revolution speed
RMCI	MPa	Rock mass cuttability index
RMSE	mm/rev	Root mean square error
RQD	%	Rock quality designation
RQDc	-	RQD class
RT_c	-	Rock type code
T	K	Temperature
t	s	Time
UCS	MPa	Uniaxial compressive strength
WOME	% $per\ kWh/t$	Weakening over microwave energy

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1 Introduction

In times of increasing urbanisation, higher standards of living, the push to build an emission-neutral society, and in the wake of steadily rising commodity prices, the market for small-diameter tunnel boring machines (TBMs) promises a bright future, especially in hard rock. Small-diameter TBMs have always been and are still overshadowed by large TBMs, but offer at least as much growth potential (KUESEL 1996; MAIDL et al. 2012; ONG et al. 2022). The small-diameter range is as fascinating as it is complex because it includes all infrastructure tunnels except the ones for traffic applications (i.e. for people, cars or trains of any kind), most TBM types which are well known from larger diameters and with pipe jacking another very challenging but versatile lining method (STERLING 2020; SCHMÄH et al. 2021). Small-diameter TBMs nowadays offer mechanised solutions for projects in hard rock which some years ago were not considered to be feasible (HUNT & DEL NERO 2009; LANG 2017). Furthermore, these machines are considered to be substantially safer and more environmentally friendly than comparable conventional technologies. Projects and recent research focus more and more on sustainability considerations related to tunnelling job sites (GALLEHER & STIFT 2004; NAJAFI & KIM 2004; MATTHEWS et al. 2015; HUANG et al. 2015; VALDENEBRO & GIMENA 2018; LUO et al. 2020; LU et al. 2020b; ONG et al. 2022). For example, an analysis of a planned tunnelling project in Texas, USA, has revealed that the CO_2 footprint of trenchless technology is six times less than a comparable conventional cut and cover method (HUANG et al. 2015; TAVAKOLI et al. 2017). Thus, carbon footprint, energy consumption and social acceptance may be decisive factors for the realisation of underground projects and strongly drive the growth behind the increased use of trenchless technologies (LU et al. 2020b; STERLING 2020; VAN DOORN et al. 2021; HALLIN et al. 2021).

Usually, small-diameter TBMs are considered to range up to approximately 5 m in outer diameter. TBMs below this diameter are generally also called utility TBMs and are preferably used for the construction of sewer, stormwater, freshwater or hydropower tunnels, as well as pipeline casing and cable tunnels for hydrocarbons, hydrogen, fibre optic and electricity lines. Depending on the project-specific and geological conditions, utility tunnels in rock can be constructed with different mechanised technologies such as slurry-TBMs, earth pressure balance (EPB) TBMs, single- and double-shield TBMs, gripper TBMs or partial-face TBMs (MAIDL et al. 2012; GIRMSCHEID 2013). They certainly offer a truly exciting field of research, especially in their interaction with hard rocks, because, due to the smaller project size and often very high complexity, little to no attention is regularly paid to these smaller projects (SHEIL et al. 2016; SCHMÄH & PETERS 2018; ONG et al. 2022). Most of these small-diameter projects in hard rock are characterised by poor geotechnical data and little project information, which makes it extremely difficult for those not directly involved in the project to familiarise themselves with the subject matter. Much knowledge is distributed among individuals in a few companies. Therefore, it is not surprising that very limited published literature is available on that subject (FRIANT

& ABBOTT 1994; BARLA et al. 2006; SHEIL et al. 2016; TANG et al. 2021; LANG & LEHMANN 2022). However, due to the above-mentioned trends, it is necessary for a wide range of project participants, such as clients, designers, consultants, machine manufacturers and, of course, the construction and mining companies, to acquire knowledge about the interaction of such utility TBMs with hard rock. This particularly includes the question of how fast such small-diameter TBMs can advance in hard rocks, how excavation tools can be used most efficiently and how this can be predicted, and how the tunnelling or mining performance of such hard rock cutting machines could be significantly increased in the future.

1.1 Definition of terms

As indicated before, this work and the attached papers deal with small TBMs and their interaction with hard rock. In the field of small TBMs and their projects, different terms are used, which will be explained briefly to avoid possible confusion. In addition to various machine techniques, for the operation of which reference should be made to the relevant standard literature, there are also several spoil removal methods which are best explained in KUESEL (1996), STEIN (2003), MAIDL et al. (2012) and WEHRMEYER (2018).

- **Utility tunnelling:** Utility tunnelling is a term defining the purpose of the tunnel to be built. It describes tunnels for the construction of sewer, stormwater, freshwater or hydropower applications as well as cable and pipeline casing tunnels for hydrocarbons, hydrogen, fibre optic and electricity lines. The majority of these tunnels require TBMs with an outer diameter of 0.3 to 5 m. Above this diameter, most tunnels are traffic tunnels built for train and car applications.

- **Segment lining:** Segment lining is the lining of a tunnel with precast elements installed in a ring (MAIDL et al. 2012). The principle of ground excavation by TBM and consecutive ring building is the most important lining method for large-diameter tunnels. In small tunnel diameters of up to 5 m outer diameter, numerous projects have been carried out worldwide using the segmental lining method (SCHMÄH et al. 2021). However, the minimum diameter for segmental tunnels is increasing due to restrictions imposed by stricter safety regulations.

- **Pipe jacking:** Pipe jacking is a frequently applied tunnel construction and lining method. It is gaining importance not only for long-distance projects but also for inner diameters above 3 m, where segmental lining was preferred in the past. Prefabricated pipes, mostly made of concrete or steel are pushed through the ground from a launch shaft or starting point. A TBM is installed in front of the pipe string to remove the spoil. Pipe jacking is generally applied from 0.3 m to 4.0 m inner diameter. However, more and more larger diameter and non-circular pipe jacking projects are being executed

(STERLING 2020; ONG et al. 2022). Further information on pipe jacking in hard rock is given in LEHMANN et al. (2023c).

- **Trenchless:** Trenchless technology is the construction of pipelines with little or no excavation on the surface. It is characterised by the fact that it does not interfere with traffic, causes little noise and leaves a small ecological footprint. According to the construction objectives, trenchless technology can be classified into trenchless installation and renewal technology, and renewal technology can be further divided into repair technology and replacement technology. Besides pipe jacking, trenchless installation also includes impact moling, pipe reaming, horizontal auger drilling, HDD, and microtunnelling. According to LU et al. (2020b), the only replacement technique is pipe bursting.

- **Microtunnelling:** Microtunnelling is a subtype of the pipe jacking method, which describes the operatorless and remote-controlled operation of a tunnel boring machine in non-person entry diameters. According to STERLING (2020), microtunnelling is furthermore characterised by the small tunnel size and the ability to control the support of the excavation face.

Detailed information on the practical applications of small-diameter TBMs in hard rock is given in LEHMANN et al. (2024).

1.2 Research motivation

In science and industry, empirical, semi-empirical and theoretical penetration prediction models are used for penetration and advance rate estimation of TBMs. The best-known and most commonly used models in hard rock are from the Colorado School of Mines (CSM model; ROSTAMI & OZDEMIR (1993) and ROSTAMI (1997)) and from the NTNU in Trondheim (BRULAND 1998; MACIAS 2016). Other hard rock penetration models are from BÜCHI (1984), GEHRING (1995), ALBER (2000), BARTON (2000), YAGIZ (2006), GONG & ZHAO (2009), HASSANPOUR et al. (2011), FARROKH et al. (2012), PALTRINIERI et al. (2016), WILFING (2016), ENTACHER & ROSTAMI (2019), WANG et al. (2020), JING et al. (2021) and SISSINS & PARASKEVOPOULOU (2021) and XU et al. (2021a) among others. In addition, some attempts have been made to estimate the penetration rate in mixed ground or with mixed face conditions (GENG et al. 2016; MACIAS et al. 2020; GOODARZI et al. 2021). Most of the aforementioned models assume a large number of mechanical and especially geotechnical parameters, which are often not available at all or incomplete, especially for projects with small-diameter TBMs (OD < 5 m). Furthermore, a follow-up and analysis of the excavation data in connection with the geological information are only carried out for large projects, if at all (CAPIK et al. 2017; ARMETTI et al. 2018b).

For this reason, a database is required with all relevant geotechnical and machine data characterising a project. Even though there is extensive literature on large-diameter tunnels, including case studies and performance prediction approaches, there is little to almost no literature for small-diameter TBMs (KLEIN et al. 1995; THURO & BRODBECK 1998; DELISIO et al. 2013; ARMETTI et al. 2018a; RISPOLI et al. 2020; CARDU et al. 2021). It gets even worse for pipe jacking projects, where published papers are very scarce and only cover low-strength rocks and soil (SOFIANOS et al. 2004; SHEIL et al. 2016; DENG et al. 2022). Data quality, variability and cleaning are key for meaningful algorithms, e.g. for performance prediction or predictive maintenance (ERHARTER & MARCHER 2021; XIAO et al. 2022). To date, no such methodology of data pre-processing for further analysis has been published.

The CSM model of ROSTAMI (1997) or a slightly modified version of it, which takes into account the small diameter of the machines and the reduced thrust force, is often used for the penetration prediction of TBMs with small diameters. The most important reasons for using the CSM model are, on the one hand, the simple application and, on the other hand, the geotechnical input parameters (uniaxial compressive strength - UCS, Brazilian tensile strength - BTS and Cerchar abrasivity index - CAI), which are common worldwide and especially available for smaller projects (CARTER & MARINOS 2020). The CSM model provides mechanically meaningful results, which are, moreover, fundamentally independent of the machine technology. The CSM model has hardly been developed further, especially in recent years, and has been evaluated only sporadically on a few projects in the large-diameter range (FARROKH et al. 2012; XIA et al. 2018). Field experience from numerous pipe jacking projects shows that the CSM model tends to overestimate the jacking rate at low compressive strengths, while it tends to underestimate it at high compressive strengths (SHIMADA et al. 2004; SHEIL et al. 2016). Furthermore, construction companies report that the performance of segment lining projects is often not predicted correctly. A systematic comparison of the calculated performance with the actual performance achieved on projects often does not take place.

Although using penetration prediction models for the corresponding geology and deployed TBMs will not only substantially increase the planning accuracy of existing small-diameter TBMs in hard rock but it also adds efficiency to the entire tunnelling job site. Hard rock excavation in mechanised tunnelling has changed only slightly in technical terms since the first hard rock TBMs of The Robbins Company in the 1950s (MUIRHEAD & GLOSSOP 1968). The rock is still made to chip by means of cutting tools such as disc cutters and high thrust forces. In order to keep up with the trend towards ever greater mechanisation and automation in construction and mining in general, and in underground mining in particular, hard rock TBMs will not only have to be able to drive autonomously in the future but will also have to be capable of significantly higher advance rates with less wear and tear (ZHENG et al. 2016; SIFFERLINGER et al. 2017). This could not only result in significantly shorter construction site times, energy savings, simpler design of the TBMs and lower costs, but a much broader range of applications for the machines appears possible, especially in the small-diameter TBM market segment and mining (ALTINDAG 2003; TIRYAKI & DIKMEN 2006; GHORBANI et al. 2023). In addition to the optimisation of the operating style and the cutting concept of existing TBMs, another possible solution to the problem is to significantly reduce the strength of the rock mass before the mechanical excavation process by pre-conditioning the rock (ZHENG et al. 2016; ZHENG 2017; CHENG et al. 2020). In general, this raises the question of how hard rock can be mined mechanically in the medium term in a more sustainable, faster and cost-efficient manner (SIFFERLINGER et al. 2017). The most promising technical solution for this problem currently is microwave rock pre-conditioning (LAURIELLO & FRITSCH 1974; HASSANI et al. 2008; MEISELS et al. 2015; TEIMOORI & HASSANI 2020; GAO et al. 2022; YAO & YAO 2023). This approach involves utilising selective heating to induce differential volumetric expansion in the minerals, which leads to the formation of micro- and macrofractures in rock, a decrease in rock strength and, therefore – at least in theory - increased tunnelling and mining rates.

1.3 Research questions and objectives

Considering the trends towards more underground infrastructure and increasing resource extraction, research on the interaction between such infrastructure-building machines and the surrounding rock mass is becoming increasingly important. It is of major importance for the planning and execution of a tunnelling project to know the anticipated performance of the job site and the TBM itself. Therefore, it is not only crucial to be able to compare the upcoming projects with previously executed projects and their challenges but also to accurately predict the performance of TBMs in advance. The following research questions, whose investigation is deemed necessary to shed light on the above-mentioned topics, will be examined within the scope of this dissertation project:

- What are the key factors leading to successful small-diameter hard rock projects? What are typical performance parameters, and what are the limits of pipe jacking machines in hard rock? What are the important steps for data preparation and analysis handling with data from small-diameter TBMs, i.e. pipe jacking machines? What could a data cleaning procedure look like for future AI-based applications like predictive maintenance algorithms or automated geology detection?
- What is the current performance in terms of the penetration rate of state-of-the-art small-diameter TBMs in hard rocks? Is there a difference between the performance in different rock types? What other key factors influence and differentiate the performance of both segment lining and pipe jacking projects? How can the performance of small-diameter hard rock TBMs be predicted? Which model best predicts the penetration rate of segment lining and pipe jacking projects? What are the limitations of existing and newly developed models?
- How can the performance of small-diameter TBMs in hard rock be increased? What will hard rock cutting look like in the future? How can the strength of rock be artificially reduced? How does rock pre-conditioning with microwave irradiation influence the strength of granite and concrete? How do the geotechnical parameters vary, and how does this influence the performance of hard rock cutting technologies?

First, the current performance of such TBMs in hard rock must be recorded and analysed. For this purpose, data were collected from hard rock TBM projects all over the world, in as diverse geological conditions as possible and using different machine technologies. Especially hard rock pipe jacking has become particularly crucial in the industry due to stricter safety regulations (LEHMANN et al. 2023c). To illustrate the methods and challenges involved in analysing data for small-diameter pipe jacking projects, the 530-m-long and 2.2-m-outer-diameter Landivisiau utility tunnel in Brittany, France, is examined. It is a protective casing tunnel for a gas pipeline as part of France's transition to clean energy. The procedures, data analysis, and difficulties encountered in a small-diameter pipe jacking project are discussed using this specific example.

The aim of the second part of this dissertation is to present the current state-of-the-art with regard to the actual penetration of small-diameter TBMs in different hard rock ground conditions and to compare the results with industry-standard penetration prediction models. For this purpose, international tunnelling projects of different construction companies and TBM manufacturers have been evaluated and compared with respect to their machine parameters, such as penetration, driving speed, torque, rotational speed and contact force. Furthermore, the influence of different geotechnical parameters on the tunnelling performance is determined, and thus the most important, performance-relevant parameters for small TBMs are worked out (THURO et al. 2015; WILFING et al. 2016). The actually achieved parameters are compared with the results of the CSM model and other conventional penetration prediction models. Guidelines for the practical application of existing models are given, and new approaches for penetration prediction with regression models and a machine learning model are proposed, which lead to more precise penetration prediction for small-diameter TBMs in hard rock.

Depending on their size, hard rock TBMs reach economic limits in very strong rocks. However, large parts of the surface of our planet consist of very strong to extremely strong rocks, i.e. large parts of Scandinavia and North America. Additionally, many important open-cut and underground mines are in similar rock conditions and today beyond the technical boundaries of conventional mechanized rock cutting equipment. However, the construction and mining companies would be very interested in such equipment to improve safety, automation and efficiency. As stated before, the penetration of a TBM inversely correlates with the rock strength, meaning that a lower rock strength would result in an increase in TBM advance speed. The TBM performance is also dependent on joint spacing and rock mass quality. These parameters could be controlled and artificially reduced by the application of alternative rock pre-treatment methods. Micro- and macrocracks can be artificially induced by methods like high-power lasers, high-pressure water jets, activated tools or microwaves (SIFFERLINGER et al. 2017; PEDULLA 2021; RUI & ZHAO 2021; ZHANG et al. 2022; ZHAO & DAI 2023). As the rock strength decreases, less thrust needs to be applied to induce chipping. Furthermore, altered rocks generally have a lower abrasivity, which results in less wear and, ultimately, in a much more cost-effective deployment of TBMs in hard rock projects. An overview of alternative hard rock cutting and pre-damaging methods is given in LEHMANN et al. (2023d).

Microwave technology has found diverse applications over the past few decades. Recently, there has been a notable and increasing interest in the use of microwaves in hard rock breakage and mineral processing. Microwave irradiation could be fast and very effective in pre-fracturing rocks by destroying their microstructure (XU et al. 2021b). It is considered a safe, environmentally friendly and automation-ready technology (TEIMOORI & HASSANI 2020). Deploying microwave irradiation in hard rock tunnelling could be a game changer for the tunnelling and mining industry.

The aim of the third part of this dissertation is to provide an overview of the current state of research into alternative or supportive mining methods and which of these methods currently appears to be the most promising. A special focus is on microwave pre-treatment of rocks and how such a technique could be employed in hard rock cutting machines. For this purpose, the pre-treatment or heating of the rocks with microwave irradiation, similar to the fire-setting frequently practised in ancient mining, plays a decisive role. A proposed approach involves the installation of microwave antennas on the cutter head of a TBM with the aim of subjecting the tunnel face to microwave irradiation prior to excavation (FENG et al. 2022). Empirical evidence indicates that the response of rocks containing diverse mineral compositions to microwaves is considerably influenced by variations in their thermo-physical and dielectric properties (TEIMOORI & HASSANI 2020).

Considering existing literature, which rocks can be pre-treated best and the suitable microwave parameters are summarised. Furthermore, it will be shown which power is necessary to significantly reduce the strength of rocks with microwave irradiation to develop a holistic, economic concept for mining of hard rocks.

1.4 Structure of the dissertation

The thesis is a publication-based dissertation containing the cumulative inclusion of three accepted first-author publications. It is structured into five short chapters summarising and discussing the published work (especially the full journal papers LEHMANN et al. (2022), LEHMANN et al. (2024) and LEHMANN et al. (2023d)) including an appendix containing all published papers related to this dissertation. The first chapter gives an introduction to the subject and research questions related to small-diameter tunnelling in hard rock, while the second chapter summarises the deployed methods. The third chapter summarises the published scientific articles, which are enclosed in the Appendix A.

Section 3.1 presents a detailed hard rock pipe jacking study in strong to very strong basement rocks in Brittany, France. The paper represents the first comprehensive study of a long-distance pipe jacking project in very strong metamorphic rocks. It illustrates that small-diameter pipe jacking in rock is slower than segment lining and underlines the importance of the concept of specific skin friction. It explains why penetration prediction is difficult with conventional models for such a small-diameter tunnelling project with heterogeneous ground conditions. The data analysis results suggest that the focus of pipe jacking projects is not the maximum advance speed but a safe tunnelling procedure.

The paper described in Section 3.2 compiles data from 37 small-diameter tunnelling projects all around the world. Diverse geotechnical information, including more than 1,300 samples, is included in the database, which covers most of the common TBM, lining and geology combinations in utility tunnelling. This data is crucial to understanding the status quo of recent small-diameter tunnelling job sites in terms of drive parameters and penetration prediction. It is also analysed to assess the accuracy of common penetration prediction models. Based on the poor performance of most of these models, a new small-diameter specific model is proposed and promises better penetration modelling results.

Section 3.3 comprises a study which demonstrates how granite and concrete react under microwave irradiation at 5 kW and 915 MHz. More than 700 samples consisting of granite and low, medium and high-strength concrete were prepared and irradiated with microwaves and tested for various properties. For the first time, a comprehensive geotechnical testing program on the influence of microwave irradiation on granite and concrete was conducted. Besides the P-wave velocity, porosity, specific heat capacity, density and temperature changes, the following geotechnical parameters were determined for heating intervals between 5 and 1200 s: (I) UCS, (II) BTS, (III) PLI (point load index), (IV) CAI (V) LAC (LCPC abrasivity coefficient), (VI) LBC (LCPC breakability coefficient). It was demonstrated that rock pre-conditioning works with microwave performances as low as 5 kW, with considerable reduction, especially in PLI, BTS and abrasivity, which would theoretically lead to a higher penetration rate and less wear.

The findings of the scientific papers are then discussed in Chapter 4, together with perspectives for further research. Chapter 5 provides a summary and conclusion, presenting the main findings from this dissertation and answering the presented research questions.

The appendix lists the published scientific articles that originated as part of this dissertation (Appendices A-1 – A-3, Table 1), including reviewed conference proceedings and conference abstracts as first and co-author (Appendices B-1 – B-5, Table 2).

Table 1. Peer-reviewed full journal articles of the cumulative dissertation thesis.

Appendix	Authors	Title	Year	Journal & DOI	Journal Impact Factor*	Status
A-1	Gabriel Lehmann, Heiko Käsling, Alexandre Cambier, Steffen Praetorius, Kurosch Thuro	Performance analysis of utility tunneling data: a case study of pipe jacking in hard rock in Brittany, France	2022	Tunnelling and Underground Space Technology *https://doi.org/10.1016/j.tust.2022.104574*	6.9 (2023)	Published in peer-reviewed journal
A-2	Gabriel Lehmann, Heiko Käsling, Sebastian Hoch, Kurosch Thuro	Analysis and prediction of small-diameter TBM performance in hard rock conditions	2024	Tunnelling and Underground Space Technology *https://doi.org/10.1016/j.tust.2022.104574*	6.9 (2023)	Published in peer-reviewed journal
A-3	Gabriel Lehmann, Martin Mayr, Heiko Käsling, Kurosch Thuro	Microwave pre-conditioning of granite and concrete and the implications on their geotechnical parameters	2023	International Journal of Rock Mechanics and Mining Sciences *https://doi.org/10.1016/j.ijrmms.2022.105294*	6.849 (2022)	Published in peer-reviewed journal

*Journal Citation Reports™ (JCR) (Clarivate Analytics, 2023)

Table 2. Additional articles published as part of the dissertation project, attached in the appendix.

Appendix	Authors	Title	Year	Journal & DOI	Status
B-1	Jürgen Schmitt, Ulrich Burbaum, Gabriel Lehmann, Heiko Käsling	Untersuchungen zum Einfluss der Mikrowellenbestrahlung auf die Änderung der Festigkeitseigenschaften von unterschiedlichen Gesteinsarten	2022	Conference proceedings of: 13. Kolloquium Bauen in Boden und Fels am 1. und 2. Februar 2022, Technische Akademie Esslingen	Published
B-2	Gerhard Lang, Gabriel Lehmann	Rock tunnelling in small diameters: latest trends and technologies	2023	Conference proceedings of: North American Society for Trenchless Technology (NASTT) NASTT 2022 No-Dig Show, Minneapolis, Minnesota, April 10-14, 2022	Published

B-3	Gabriel Lehmann, Heiko Käsling, Steffen Praetorius, Frederic Seng, Kurosch Thuro	Small-diameter tunneling in difficult ground – Analysis of TBM performance in hard rock	2023	Geomechanics and Tunnelling 16 (2023); TBM Digs 2022 *https://doi.org/10.1002/geot.202200061*	Published in peer-reviewed journal
B-4	Gabriel Lehmann, Heiko Käsling, Kurosch Thuro	On the way to a better performance prediction for small-diameter hard rock TBMs	2023	ITA-AITES World Tunnel Congress 2023, 12 – 18 May 2023, Athens, Greece *https://doi.org/10.1201/9781003348030-158*	Published
B-5	Gabriel Lehmann, Marcus Lübbers, Andrea Fluck	Pushing pipe jacking boundaries in hard rock	2023	Tunnelling Journal 12/2022-01/2023	Published

2 Methods

The basis of the work is a comprehensive literature review on the performance of small-diameter TBMs in general and pipe jacking TBMs in particular (LEHMANN et al. 2022; LEHMANN et al. 2023a; LEHMANN et al. 2024). Furthermore, existing penetration models are analysed and evaluated with a newly built database comprising small-diameter TBMs in hard rock (LEHMANN et al. 2024). Here, the machine data of 37 recently completed projects with mostly small outer diameters (OD < 5 m) and both segment lining and pipe jacking combined with different rock properties are evaluated with regard to their penetration rate and operating parameters (like torque, revolution speed & thrust force). The data are compared with data from larger projects in comparable ground. Important geotechnical parameters of the encountered rocks (especially UCS and BTS) are determined either directly by the construction companies or consultants on the job site or in the hard rock laboratory of the Chair of Engineering Geology at the Technical University of Munich. Then, the mechanical parameters are compared with the geological (preliminary) exploration data, and the actual driving speeds achieved, as well as the theoretical and actual operating points of the TBM projects, will be compared. Furthermore, penetration predictions are generated and compared with the actually achieved tunnelling speeds and correlated to the geotechnical parameters. Finally, the results are used to determine the model with the results that best match reality and to create our own approaches to penetration prediction modelling.

Following an extensive literature review, the current state of research on the development of hard rock cutting and the resulting possibilities for small-diameter TBMs is presented (SCHMITT et al. 2022; LEHMANN et al. 2023d). This review revealed that one of the most promising rock pre-conditioning techniques at present seems to be microwave irradiation. Current developments include transmitting microwave energy through openings in the cutting wheel to the rock of the working face, where the rock becomes damaged, and its strength is reduced, thus leading to higher advance rates (LU et al. 2021). Differential volumetric expansion coefficients of the individual minerals lead to the formation of (micro-)fractures in the rock, theoretically resulting in faster and less abrasive rock cutting. In addition to the literature research on the state-of-the-art, tests with a specifically designed microwave and different rock types (igneous and sedimentary rocks as well as concrete as an analogous material) were carried out on a laboratory scale. Here, not only the input variables of the microwave for efficient rock pre-conditioning were determined, but also the influence of the irradiation on the geotechnical parameters of the rock was characterised.

2.1 Data acquisition and pre-processing

TBM data processing is an important aspect of data analysis that affects several phases of the construction process of a tunnel excavated with a TBM (RISPOLI et al. 2019). It is of special importance for small-diameter projects, as for most past projects, only limited pre-processing has been undertaken. In total, data from 37 tunnelling projects have been gathered, pre-processed and analysed. Depending on the project size and location, different ways of data gathering were pursued:

- Projects with geotechnical and drive data from machine suppliers (including rental machines).
- Projects with geotechnical and drive data from construction companies.
- Projects with data directly gathered at the job sites with the permission of the owner, construction company or consultant.

In order to use the information for predictions in tunnel projects, all data must be in the same format. Before managing and filtering the raw data, verification of the geotechnical information is critical. In addition to geotechnical field and laboratory parameters, a detailed geotechnical cross-section provides the necessary information to combine engineering and geological information. Once it is ensured that sufficient high-quality geodata is available (CARTER & MARINOS 2020), the actual machine data processing can begin. Here, constant drilling progress must first be ensured. While new data acquisition systems can do this automatically, older data packages require standstill sections to be deleted manually (e.g. in the case of pipe change or revision). From the machine data obtained in this way, the penetration depth, cutting head contact force and torque can be calculated. Subsequently, the data is subjected to filtering. Useful values for filtering can be taken from the TBM specifications, are project and TBM dependent and require careful selection and interpretation. Filtering may include the removal of extreme values or apparently wrong values. Finally, the data are averaged at intervals such as 0.1 or 1 m because TBM operational data are uniformly distributed in time but not in space. If such averaging were not done, there would be many data points in areas of slow tunnelling and fewer data points in areas of fast tunnelling (ENTACHER & ROSTAMI 2019), especially with averages for the entire tunnel or homogeneous areas. As explained below, three database levels were used and adapted to the requirements of small-diameter projects, similar to the method deployed by FARROKH et al. (2012). Further information is also given in LEHMANN et al. (2024) and LEHMANN et al. (2023a).

2.1.1 Tunnel project

The tunnel project includes all available information on a specific construction project. In the best case, geotechnical, machine and project-specific information from the starting shaft to the target shaft is included. Average and mean values are calculated for all parameters, not taking into account potentially highly varying geotechnical conditions such as different lithologies or strength values.

2.1.2 Homogeneous geotechnical area

A homogeneous geotechnical area (HGA) is characterised by similar geotechnical conditions. Such an area usually consists of the same rock type, and the geotechnical parameters do not vary significantly. The machine parameters are averaged only for the corresponding area with homogeneous geotechnical conditions.

2.1.3 Detailed area

A detailed area (also called detailed borehole information – DBI) is based on “punctual” geotechnical information, mostly from exploratory boreholes or from boreholes drilled during tunnel construction and on mapping of the face or walls. After thorough analysis, this geotechnical information is then averaged for an interval of ± 25 m around the (vertical) projection of the borehole onto the tunnel alignment.

The 25 m interval is a necessary compromise due to the very heterogeneous data in the database. A very small averaging area around the geotechnical information would be beneficial to achieve high accuracy in the driving data. However, for some driving data, the resolution is even better than 1 m. In addition, the geotechnical data should be representative of the vicinity of the borehole in which it was recorded. Some utility projects are very short (e.g., the shortest distance in the database is 30 m), and very little geotechnical information is available. Often, and this is very typical for such short drives, only one borehole at the start shaft and one borehole at the target shaft were drilled to explore the ground conditions. Another aspect is the fact that the boreholes are typically not located directly on the tunnel route but a few meters (usually 5–20 m) beside it and/or at an angle. It should also be considered that the samples were taken a few meters above or below the tunnel alignment. A sensitivity analysis was performed for this averaging interval of machine data with respect to the geotechnical data. The results show that an interval of 1 m would produce exceptionally erratic results, while an interval of 100 m would show overly aligned results. Therefore, an interval of 25 m was used for this data analysis, which can be justified by the arguments mentioned above.

As described above, a comprehensive geological profile or geotechnical model is key in combining TBM and geotechnical data. While digital subsurface or BIM models are not yet state-of-the-art in small-diameter tunnelling, most profiles, when available, are hand-drawn or computer-drawn 2D representations. Indeed, some profiles lack information on the location of the boreholes, and in general, boreholes are projected onto the tunnel alignment, even though they may be located at considerable intervals. Furthermore, there are further inaccuracies connected with geological data:

- Frequency of geotechnical investigations: Lateral and vertical distance between individual points of geotechnical investigation and their distance to the tunnel alignment.
- The selection of samples for testing is highly dependent on laboratory or job site personnel.
- Quality of the test method: the values obtained in the laboratory can vary considerably depending on which laboratory performs the test and which tests are performed, even if the same standard method is used.
- The exact tunnel alignment of the TBM may differ from the route given in the geotechnical profile.

2.2 Data analysis and penetration prediction

The lack of quality and quantity of geotechnical information is a typical problem for small-diameter TBM projects. Previous experience from job sites has shown that common prediction models for such projects either require data that are not available or do not accurately predict the penetration and advance rate of TBMs in hard rock. This may be because these models were developed for larger projects with more well-known geotechnical parameters. There is currently no model that has been specifically developed for increasingly important pipe jacking projects. In these cases, due to the lack of designated models and research in that direction, it is common practice to use or adapt existing models even though experience shows that the results differ considerably from reality. To evaluate the accuracy of such models, eleven models that require minimal geotechnical input data were evaluated in LEHMANN et al. (2024) and compared for their ability to accurately predict penetration (see Table 3).

Both graphical representations and performance indices were used to evaluate the performance of the models under investigation and the newly proposed models. The accuracy of penetration prediction was quantified using the root mean square error (RMSE) and the mean-absolute-percentage error (MAPE) calculated in R®.

Table 3. TBM performance models with limited geotechnical input requirements. PR = penetration rate, F_n = cutter thrust force, F_r = cutter rolling force, D = cutterhead diameter, RTc = rock type code (FARROKH et al. 2012), RQDc = RQD class (FARROKH et al. 2012), UCS = uniaxial compressive strength, CAI = CERCHAR abrasivity index, k_i = correction factor, RQD = rock quality designation, RMCI = rock mass cuttability index, LBC = LCPC breakability coefficient (LEHMANN et al. 2024).

Author/Model	Reference	Comment	Model based on
Alpine Model	WILFING (2016)	Preliminary model based on Gehring's model and Koralm tunnel: $PR = \frac{F_n - b_{BTS/LBC}}{UCS} \cdot k_0 \cdot k_2 \cdot k_i + 3$	Data from Koralm tunnel penetration tests and the Gehring model.
CSM model	ROSTAMI (1997)	Updated CSM model: $PR = f(F_n, F_r)$	LCM tests with limestone (70 MPa), granite (140 MPa) and basalt (280 MPa); validation with 4 gripper TBM projects in massive rocks with UCS ranges from 20-45 MPa and 150-270 MPa.
Farrokh	FARROKH et al. (2012)	$PR = exp(0.41 + 0.404 \cdot D - 0.027 \cdot D^2 - 0.0691 \cdot RT_C - 0.00431 \cdot UCS + 0.0902 \cdot RQD_C + 0.000893 \cdot Fn)$	Large database with 17 hard rock TBM projects between 2.6 and 11.8 m, mostly in Iran and Italy, all terminated before 2010.
Farrokh modified	FARROKH (2012)	$FPI = \exp\,(1.97 + 0.0063 \cdot RQD + 0.103 \cdot CAI + 0.00685 \cdot UCS)$	Large database with 17 hard rock TBM projects between 2.6 and 11.8 m, mostly in Iran and Italy, all terminated before 2010.
Gehring	GEHRING (1995)	Commonly applied in the Alps: $PR = \frac{F_N}{UCS} \cdot k_i$	4 hard rock projects with UCS values mostly between 120 and 200 MPa.
Goodarzi	GOODARZI et al. (2021)	Soft rock model based on four projects: $PR = exp\,(0.006 \cdot Fn - 0.016 \cdot UCS + 1.833)$	4 projects in the Zagros mountains in Iran, mostly in soft sedimentary rocks (generally < 100 MPa).
Hassanpour HR	HASSANPOUR et al. (2009a)	Hard rock model based on Nowsood tunnel 2: $PR = \frac{F_N}{\exp\,(0.004 \cdot UCS + 0.008 \cdot RQD + 2.077)}$	49-km-long Nowsood water conveyance tunnel in Iran in sedimentary rocks with UCS values between 15 and 150 MPa.
Hassanpour RMCI	HASSANPOUR et al. (2009b)	Based on information from two projects: $FPI = 0.425 \cdot RMCI + 11.28$	16- + 8.7-km-long Karaj water conveyance tunnel in Iran in sedimentary and volcanic rocks with UCS values between 30 and 100 MPa.
Hassanpour all rocks	HASSANPOUR et al. (2011)	Based on four tunnels: $FPI = \exp\,(0.008 \cdot UCS + 0.015 \cdot RQD + 1.384)$	4 projects in Iran and New Zealand of approximately 75 km in length in total. UCS between 15 and 225 MPa.
Hughes	HUGHES (1986)	For sandstone and penetration rate of up to 10 mm/rev: $PR = 1.667 \cdot \left(\frac{F_n}{UCS}\right)^{1.2} \cdot (\frac{2}{D})^{0.6}$	TBM deployment in coal-bearing sedimentary rocks in England with UCS values generally < 100 MPa.
Xu Eq. 26	XU et al. (2021a)	Regression model based on 3 projects: $PR = 66.411 \cdot RMCI^{-0.482}$	3 projects (double shield and gripper) in China with large geotechnical variability. TBM diameter between 6 and 8 m.

For the evaluation, only projects equal or larger than 15 MPa were considered, as the cutting mechanism for rocks with lower strength is significantly more complex and involves a combination of disc cutting, scraping, and knife cutting. The homogeneous geotechnical areas (HGAs) in the database for this study were composed of marlstones and chalk. The projects were divided into two categories: pipe jacking and non-pipe jacking (primarily segment lining), as the machine diameter and, therefore, the available power is strongly linked with the lining type. Additionally, the projects were divided into two groups based on rock strength, with weaker rocks up to 50 MPa and harder rocks above 50 MPa, in line with ISRM standards (ISRM 1980). This division is based on practical experience and similar rock strength values used in other penetration prediction models, such as the one developed by ROSTAMI (1997).

Additionally, multivariate regression analyses were conducted using R® to predict the penetration rate, which then could be multiplied by the revolution speed to determine the advance rate. Thus, a sensitivity analysis was performed, and simple linear regression models were derived for five scenarios, which are the following: all data, pipe jacking and non-pipe jacking projects with UCS between 15 and 50 MPa, respectively, and pipe jacking and non-pipe jacking projects above 50 MPa, respectively. As described above, the goal was not to develop a model that is as accurate as possible but a model that achieves the best possible result with a low number of input parameters. For this purpose, the parameters uniaxial compressive strength (UCS), cutter thrust force (F_n), cutterhead diameter (D), revolution speed (Rev), torque (M) and Brazilian tensile strength (BTS) were selected on the basis of the sensitivity analysis, taking into account the availability of the individual values. These analyses allowed the penetration rate results to be extrapolated for different machine sizes.

Machine learning techniques have demonstrated impressive results in predicting the penetration of hard rock TBM projects (ZHOU et al. 2021b; ZHOU et al. 2021a; WANG et al. 2023). In this study, these techniques were applied to the generated dataset to predict the tunnelling speed of small-diameter hard rock projects using limited input parameters. Data from the detailed and homogenous areas were used to evaluate the results. Cross-validation was deployed to split the data from various tunnelling projects, aiming to realistically predict the performance of TBMs not included in the database. Several machine learning approaches were compared, including Support Vector Regression, GradientBoostingRegressor, RandomForestRegressor, and XGBRegressor, with classical methods (HASTIE et al. 2009). The GradientBoostingRegressor approach yielded the best results, with hyperparameters: learning_rate = 0.071, loss = "squared_error", n_estimators = 25, min_samples_split = 4, min_samples_leaf = 1, and max_depth = 3. The following TBM and geotechnical parameters were used as training data: lining type, cutting diameter, torque, revolution speed, thrust force per cutter ring, rock type code (FARROKH et al. 2012), UCS, BTS and RQD. The values were MinMax scaled or one-hot encoded.

2.3 Test materials

After an initial pre-testing program comprising sandstones and granites, a total of 546 concrete cylinders and 155 granite cylinders were drilled out of blocks of 20x20x40 cm for irradiation with a microwave (LEHMANN et al. 2023d). All concrete samples were left to harden for at least 28 days at room temperature before they were drilling and cutting into cylinders.

The specimens had cylindrical geometries with diameters of 5 cm and heights of 10 cm to ensure uniform microwave irradiation. The end faces were grinded planar before microwave irradiation on the specimen cylinders intended for UCS testing. The concrete and granite cylinders varied by ± 1 mm in diameter due to the abrasion of the drill bits. The location of the specimen ID ensured that the cylinders were placed uniformly in the microwave to exclude differences in the irradiation direction. Before irradiation, we determined the wet and dry weights, exact dimensions and densities of each sample. Porosity was calculated according to the specifications given in Section 2.4. Thin sections were prepared from all materials for microscopic and chemical analysis.

2.3.1 Granite

Granite is of magmatic origin and the most abundant rock type in the earth's upper crust (HALDAR & TIŠLJAR 2014). It typically occurs in the cores of many mountain ranges, covering large areas of batholiths and continental shields. Furthermore, many large ore deposits (for example, copper, gold, lead and zinc) are formed by hydrothermal fluids associated with the formation of granites and are, therefore, spatially embedded in granitic complexes. Hence, granite is an important rock type when it comes to mining and tunnelling environments. It is mostly composed of quartz (up to 60%), feldspar and mica. Granite is generally considered a comparably bad microwave irradiation absorber, as it contains large amounts of quartz and very little to no water (TEIMOORI & HASSANI 2020).

2.3.2 Concrete

Concrete is commonly used at test facilities as an analogue material for weak to strong rock types since large quantities of homogeneous material can be produced quickly and easily. Due to its low price, homogeneity and easy-to-pre-design geotechnical properties, various strengths from 5 to 120 MPa can be reproduced (LEE et al. 2021). Faults and discontinuities are less common in artificial materials like concrete. Important applications of microwave heating in concrete technology are curing, demolition, drilling and recycling (ONG & AKBARNEZHAD 2018). Microwave-based treatment systems are particularly important for the decommissioning of contaminated sites such as nuclear power plants. The application of these systems not only decontaminates concrete but also reduces the amount of radioactive material generated during the scabbling process and airborne contaminants released into the environment (BUTTRESS et al. 2015; ONG & AKBARNEZHAD 2018).

Three different concrete types were investigated: The greyish-beige concrete (B1) with the lowest concrete strength class C12/15 F3 has a target UCS of 20 MPa. The medium-strength grey concrete (B2) with concrete strength class C45/55 F3>4 has a target UCS of 65 MPa. The strong dark grey concrete (B3) has the concrete strength class C80/95 F4 and a target UCS of 105 MPa. The concrete strength class is reported according to DIN EN 206:2021-06 (2021).

2.4 Material properties and geotechnical testing

For the microwave trials, the surface temperature of each sample was measured with the FLIR ThermaCAM P640 thermal camera. The camera provided the minimum and maximum temperatures of the cylinder and a thermal image showing the temperature distribution on the surface of the sample. The temperatures were taken from the side facing towards the microwave path approximately 15 s after the end of irradiation (LEHMANN et al. 2023d).

The specific heat capacity C_p (kJ/(kg·K)) was determined by calculating the ratio between the thermal effusivity e_f (W·s$^{1/2}$/(m²·K)) and the thermal conductivity k (W/(m·K)) multiplied by the dry bulk density ρ_b (g/cm³) (Equation 1). Thermal effusivity and conductivity were measured using C-Therm's TCi Thermal Conductivity Analyzer.

$$C_p = \frac{e_f^2}{k \cdot \rho_b} \tag{1}$$

The usable pore space p_0, also called open porosity, describes the space that can be filled with water. This value excludes closed pore spaces and can be determined by water storage. The measurement of water storage was carried out according to DIN EN 13755:2008-08 (2008). The value was calculated from the ratio of dry bulk density and apparent bulk density. The dry bulk density ρ_b is the ratio of the dry mass to the raw volume, including all voids. The dimensions of the cylindrical specimen for the UCS tests were used to determine the volumes since their dimensions are well-defined. The determination of the primary (P-) wave velocities was carried out according to DIN EN 14579:2005-01 (2005). The P-wave velocity of the cylindrical specimens was measured in the axial direction from both directions before and after irradiation. From this, an average value was calculated for each sample. A maximum of 21 transversal measurements per core were performed parallel to the longitudinal axis perpendicular to the irradiation direction, lined up at a distance of 0.5 cm.

The UCS was determined according to Recommendation No. 1 of the Working Group on Rock Testing of the German Geotechnical Society (DGGT) (MUTSCHLER 2004), using the "Toni-NORM" testing equipment from Toni Technik Baustoffprüfsysteme GmbH. During the tests, the stress-strain curve and the deformation modulus were also recorded. The PLI was determined according to Recommendation No. 5 “Point Load Tests on Rock Specimens” of the Working Group on Rock Testing of the DGGT (THURO 2010), using a WILLE handheld device on “standing” cylinders. The BTS was determined according to Recommendation No. 10 of the Working Group on Rock Testing of the DGGT (LEPIQUE 2008), using the "ToniNORM" testing equipment. The loading direction was perpendicular to the irradiation direction for all subsamples, so any anisotropy would not affect the results.

The CAI was determined according to Recommendation No. 23 “Determination of the abrasivity of rocks with the CERCHAR test” of the Working Group on Rock Testing of the DGGT (KÄSLING & PLINNINGER 2016). The LCPC abrasivity coefficient (LAC) and LCPC breakability coefficient (LBC) were determined according to KÄSLING et al. (2022).

The specific performance (P_{sample} in W, heat flow) was calculated by using C_p (J/(kg·K)), mass m (kg), the temperature change of the samples while heating ΔT (K) in the irradiation time t (s):

$$P_{sample} = c_p \cdot m \cdot \Delta T \cdot \frac{1}{t} \quad (2)$$

Note that the highest temperature for a sample was always considered for the calculation, ignoring temperature differences towards the top, middle and bottom of the cylinder. However, the temperature measurement was conducted approximately 15 s after irradiation ended, and the entire cylinder started to heat by conduction. Furthermore, low efficiency proves that the vast majority of the irradiation was not absorbed by the sample, presumably because of the limited sample size.

This specific performance (Equation 2) can be divided by the incoming performance, resulting in the electrothermal efficiency e (%):

$$e = \frac{P_{sample}}{P_{microwave}} \quad (3)$$

Additionally, thin sections of both materials were prepared to assess their fracture characteristics. Those thin sections were analysed for structural characterisation with a polarised light microscope (Leica DM2500 P) and a scanning electron microscope (SEM Tescan Vega II). The SEM is equipped with an EDX (energy dispersive X-ray spectroscopy) from INCA x-act from Oxford Instruments, allowing for chemical characterisation. Furthermore, the mineralogy of the granites was revealed with X-ray powder diffraction (XRD, Bruker D8 Eco Bragg-Brentano diffractometer) using the quantitative phase analysis according to the Rietveld method (DOEBELIN & KLEEBERG 2015).

2.5 Microwave irradiation

Initial tests with a microwave are described partially in SCHMITT et al. (2022) and were conducted with sandstone and granite. Irradiation was carried out using a commercially available microwave with a frequency of 2450 MHz and a maximum power of 3.2 kW. The specimen was positioned on a glass plate so that it was in the centre of the microwave to ensure the most homogeneous irradiation of the specimen. However, irradiation in a microwave oven does not suitably represent real-world conditions of irradiating a working face due to the internal reflections inside the irradiation chamber. Therefore, a special test microwave oven was constructed in which the specimens can be placed directly in the irradiation pathway of the microwaves.

As detailed in LEHMANN et al. (2023d), a 5 kW single-mode microwave was subsequently developed for irradiating rock cylinders and deployed to pre-damage the rock samples. A frequency of 915 MHz was chosen to efficiently treat a larger surface area of the rock mass and to penetrate deeper into the rock compared to the higher available frequency of 2450 MHz, as recommended by (NEKOOVAGHT 2015). Furthermore, 915 MHz is more energy-efficient, commercially available, and space-saving, and its generation via magnetrons is considerably cheaper than 2450 MHz.

At least three experiments were performed for each parameter, treatment type and irradiation length. For the determination of UCS, sample cylinders with plane-parallel ground end faces were used. The cylindrical shape enables a simple evaluation of the specific heat capacity, usable pore space, dry bulk density, and P-wave velocity. For the PLI, the sample cylinders were split in half after irradiation. This provided at least six subsamples for the PLI. After testing, the residues were further used for the determination of the LCPC abrasivity coefficient and the LCPC breakability coefficient. For the BTS test, a sample cylinder was cut into three subsamples after irradiation. The residues from the BTS test were used to determine the CAI. Additional sample cylinders were available for each series in case the samples burst during irradiation. The heterogeneity of the results and the tested materials is represented by the standard deviations.

In total over 700 specimens consisting of granite and three different types of concrete (low, medium and high strength) were prepared, irradiated with microwaves and tested for various properties. In addition to ultrasonic wave velocity, porosity, specific heat capacity, density and temperature difference, the above-mentioned geotechnical parameters were determined for heating intervals between 5 and 1200 s. Furthermore, the internal structural changes of the materials were analysed by comparing thin sections of irradiated and non-irradiated rock and concrete samples. The electrothermal efficiency and total energy consumption of microwave preconditioning were calculated for the 5 kW, 915 MHz microwave system used.

3 Scientific papers

The following subsections briefly summarise the full paper journals which are listed in the appendix. In addition, the contributions of the authors to the paper are reported using the CRediT (Contributor Roles Taxonomy) author statement.

3.1 Paper 1: Hard rock pipe jacking data analysis

Even though pipe jacking in hard rock is becoming increasingly important, very little literature on such projects is available (STERLING 2020; SCHMÄH et al. 2021). Slurry TBMs have been deployed in combination with pipe jacking in hard rock for several decades (GRASSO et al. 1996; FRANK 1999; STEIN 2003); however, it is still a growing application in utility tunnelling. Few industry whitepapers on pipe jacking hard rock applications (e.g. BRADSHAW 2014) and only very limited case studies on actual pipe jacking projects have been published. SHEIL et al. (2016) presented a pipe jacking project in mostly weak limestone in Ireland. The latest research from DENG et al. (2021), TANG et al. (2021) and ZHONG et al. (2021) focuses on hard rock project-related issues like pipe strength and friction. This article represents the first comprehensive study of a long-distance pipe jacking project in very strong metamorphic rocks.

For the first time ever, geotechnical and TBM data from a 530-m-long hard rock pipe jacking project with an ID of 1.8 m in Brittany, France, was analysed. Thanks to an industry collaboration with SADE and Optimum, it was possible to gather detailed drive and geotechnical data for such a challenging project in hard rock. Special attention was paid to data interpretation techniques and the potential related pitfalls, which is especially important for small-diameter slurry TBMs, which are usually hydraulically driven (RISPOLI et al. 2019). Especially for these small-diameter TBMs, it is of utmost importance to process machine data through a thorough correction scheme. The paper presents data correction and analysis techniques for the cutterhead torque, cutterhead thrust force, disc cutter normal force, as well as drive parameter utilisation rates which can serve as a guide for further studies.

Heterogeneous Variscan gneiss and pre-Variscan schists with a UCS of up to 185 MPa and extremely high abrasivity were encountered and successfully excavated (CAGNARD 2008). Geotechnical samples were taken during the exploration program and tunnelling, leading to a variation of the actual rock strength values, especially in small-diameter projects. The Landivisiau pipe jacking project is outstanding regarding rock strength, drive length, overburden, friction analysis and alignment gradients, taking into account that hard rock pipe jacking is nowadays applied worldwide and gaining increasing importance. Data analysis of this project led to the implication that detailed construction site monitoring is critical as it can reveal significant deviations between the expected and actual geotechnical parameter values. Close monitoring of bentonite lubrication in hard rock is also key for a successful project with desirable specific skin friction values below 2 kN/m^2. The average penetration rate of the described project was 3.4 mm/rev, which is similar to or above that of other hard rock pipe jacking projects (SHEIL et al. 2016) but well below typical larger-diameter segment lining projects in hard rock (ROSTAMI 1997; HASSANPOUR et al. 2011; FARROKH 2020; CARDU et al. 2021). For this, the FARROKH et al. (2012) model was best suited to predicting the penetration rate with an average deviation of only 0.5 mm/rev.

This paper illustrates that small-diameter pipe jacking in rock is slower than segment lining and underlines the importance of the concept of specific skin friction. Typical drive parameters and values for skin friction are presented. It was found that penetration prediction using conventional models is difficult for such a small-diameter tunnelling project with heterogeneous ground conditions. The results suggest that the focus of pipe jacking projects is not the maximum advance speed but a safe tunnelling procedure.

The corresponding paper (LEHMANN et al. 2022) is fully enclosed in Appendix A-1.

CRediT authorship contribution statement

Gabriel Lehmann: Methodology, Writing – original draft, Writing – review & editing, Formal analysis, Investigation, Data curation, Visualisation, Project administration, Funding acquisition. **Heiko Käsling:** Conceptualisation, Writing – review & editing, Supervision. **Alexandre Cambier:** Resources, Writing – original draft. **Steffen Praetorius**: Investigation, Writing – review & editing. **Kurosch Thuro:** Supervision.

3.2 Paper 2: Small-diameter TBM data and performance prediction

Predicting the advance rate of a tunnel boring machine (TBM) in hard rock is an integral component in tunnelling project planning and execution. It has been applied in the industry for several decades with varying success. Most prediction models have been developed based on performance data from large-diameter TBMs, and a lot of research has been conducted on related tunnelling projects (GEHRING 1995; ROSTAMI 1997; HASSANPOUR et al. 2011; FARROKH et al. 2012; MACIAS 2016). However, only a few models incorporate information from projects with an outer diameter smaller than 5 m, and neither a comprehensive penetration analysis nor a prediction model for pipe jacking machines exists to date (GRASSO et al. 1996; HUNT & DEL NERO 2009; BRADSHAW 2014; SHEIL et al. 2016). In contrast to large TBMs, small-diameter TBMs and their projects are only little considered in research (STERLING 2020). In general, they are characterised by distinctive features, including insufficient geotechnical information, sometimes rather short drive lengths, special machine designs and partially concurring lining methods like pipe jacking and segment lining (LANG 2017; SCHMÄH et al. 2021).

In order to address this problem, a comprehensive database was created to examine the performance of small-diameter TBMs in hard rock conditions. The database consists of 37 projects with 70 geotechnically homogeneous areas to provide sufficient geological and technical variation. The results of the analysis indicate that small-diameter TBMs, in combination with segment lining, exhibit significantly higher penetration rates in similar geological and technical conditions. Various methodologies for predicting TBM penetration are discussed and deployed on projects in the database. However, most common penetration prediction models fail to accurately predict achievable penetration rates for small-diameter projects with a UCS range of 5 to 100 MPa. New application ranges for common penetration models for small-diameter TBMs are presented, and novel approaches are proposed for predicting the penetration rate of pipe jacking machines in hard rock.

For penetration prediction of small-diameter projects in hard rocks or pipe jacking projects, the model from FARROKH et al. (2012) shows the best results, similar to newly developed regression models. Additionally, it is concluded that a significant increase in the quality of preliminary exploration data is necessary for a wide range of small-diameter TBM projects to improve the prediction of the penetration rate. With the aid of a diverse and high-quality database, a more accurate prediction of the TBM penetration rate for small-diameter tunnels shall be feasible.

The corresponding paper (LEHMANN et al. 2024) is fully enclosed in Appendix A-2.

CRediT authorship contribution statement

Gabriel Lehmann: Conceptualisation, Methodology, Writing – original draft, Writing – review & editing, Formal analysis, Investigation, Software, Data curation, Visualisation, Project administration, Funding acquisition. **Heiko Käsling:** Conceptualisation, Writing – review & editing, Supervision. **Sebastian Hoch:** Software. **Steffen Praetorius**: Investigation, Writing – review & editing. **Kurosch Thuro:** Supervision.

3.3 Paper 3: Microwave pre-conditioning of concrete and granite

One of the major challenges for small-diameter TBMs, in particular, and all hard rock cutting methods in general, is the performance limitation in strong to very strong rocks (CIGLA et al. 2001). Numerous publications and experience from mining and tunnelling job sites all around the world show the dependency of hard rock cutting speed on the rock strength (ROSTAMI 1997; BRULAND 1998; THURO & PLINNINGER 1999; HASSANPOUR et al. 2011; BANERJEE 2019; ZHENG & HE 2021). Here, the advance speed is inversely proportional to the strength of the rock, i.e. the stronger the rock, the more difficult it is to cut. In contrast to conventional approaches which try to counteract increasing rock strength by increasing the power of the machine further and further, this work aims at artificially reducing the strength of the rocks and thus increasing the performance and the range of applications of existing machine technology (ALBER 2000;

GRAFE & DREBENSTEDT 2017; SIFFERLINGER et al. 2017; SIFFERLINGER et al. 2017; STOXREITER et al. 2018; ZHENG & HE 2021). Besides other alternative hard rock damaging technologies, microwave (MW) pre-conditioning is considered to be the most promising complementary hard rock cutting method, with a strong potential to improve the advance rate and profitability of future mechanised tunnel boring and mining equipment (HASSANI & NEKOOVAGHT 2011; HARTLIEB & GRAFE 2017; LU et al. 2019; TEIMOORI & HASSANI 2020). However, existing publications focus mostly on single or very few geotechnical parameters, and there is no comprehensive overview of the reaction of concrete to microwave irradiation (SHEPEL et al. 2018; BAI et al. 2022; GAO et al. 2020; LU et al. 2020a; MA et al. 2022; SCHMITT et al. 2022). In this context, concrete, in particular, could play an important role as an analogue material for various rocks in further, larger-scale tests (SOLDATOV et al. 2016; ONG & AKBARNEZHAD 2018; LEE et al. 2021; WEI et al. 2021).

For the first time, a comprehensive geotechnical testing program on the influence of microwave irradiation on granite and concrete was conducted. More than 700 concrete and granite samples were irradiated with a high-performance microwave (5 kW, 915 MHz) and a comprehensive testing program, including porosity, specific heat capacity, temperature difference, density, ultrasonic wave velocity, SEM, EDX, XRD, UCS, BTS, PLT, CAI and LCPC was conducted. Depending on the irradiation time and the mineralogical composition of the samples, they altered, cracked, spalled, burst, or melted. A major impact of MW pre-conditioning on most of the beforementioned parameters is presented, and also micro- and macro-photographs of the resulting cracks are given. Microwave irradiation heated concrete much faster than granite due to its chemical and mineralogical composition. The porosity of the samples (especially of the concrete samples) increased substantially, and the P-wave velocity was reduced in a range of 10 and 50% overall. While no clear trend was observed in UCS variation except for irradiation intervals above 400 s, the PLI and BTS were decreased significantly for all materials. The longer the irradiation takes, the higher the UCS/BTS and UCS/PLI ratios for all materials and the more brittle the behaviour of all four tested materials. Furthermore, electrothermal efficiencies and weakening ratios were calculated. Treatment of the rocks in terms of humidification or quenching before or after irradiation had no measurable effect on rock damage. The results indicate that a combination of mechanical equipment and MW preconditioning can cut hard rocks in a faster and economically more attractive manner.

The corresponding paper (LEHMANN et al. 2023d) is fully enclosed in Appendix A-3.

CRediT authorship contribution statement

Gabriel Lehmann: Conceptualisation, Methodology, Writing – Original Draft, Writing –Review & Editing, Formal Analysis, Investigation, Data curation, Validation, Resources, Investigation, Data curation, Visualisation, Project administration, Funding acquisition. **Martin Mayr:** Investigation, Data curation. **Heiko Käsling:** Conceptualisation, Data Curation, Writing – Review & Editing, Supervision. **Kurosch Thuro:** Supervision.

4 Discussion

As the need for new and longer utility tunnels increases, the utilisation of small-diameter TBMs in hard rock environments is becoming more widespread. The following sections discuss how fast such small-diameter TBMs are today, how their data can be analysed and how their advance rate could be potentially significantly increased. For more complete information and a more detailed discussion, the reader is encouraged to read the papers.

4.1 Hard rock pipe jacking

As safety regulations become stricter, the hard rock pipe jacking method is becoming increasingly important in the tunnelling industry for utility projects. To demonstrate this, LEHMANN et al. (2022) present the techniques and obstacles involved in analysing data for small-diameter pipe jacking projects using a specific example: the 530-m-long Landivisiau utility tunnel with a 2.2 m outer diameter in western Brittany, France, which serves as a casing tunnel for a gas pipeline diversifying France’s energy supply.

The rock strength of gneiss and schist at Landivisiau varies significantly, with values up to 185 MPa, and this variation is reflected in the TBM advance rate. The advance and penetration rates for small hard rock TBMs in this study are relatively low but similar to or even higher than those of comparable hard rock pipe jacking projects worldwide (FRANK 1999; HUNT & DEL NERO 2009; BRADSHAW 2014; SHEIL et al. 2016). In the specified project, it was observed that lower strength schist required greater thrust forces to achieve the same or even lower penetration rates compared to higher strength gneiss. This may be due to the highly heterogeneous and anisotropic nature of the schist, its partially very high rock strength, and potentially also more ductile and thus less chipping-friendly behaviour (WILFING et al. 2016). The high variance in horizontal and vertical deviation may be due to small adjustments made to the tunnel alignment during construction. The higher torque in the schist may be caused by the presence of weathered sections containing clay material, which increases the overall torque. The maximum jacking forces were far below the forecasted 9,000 kN. The use of an interjack station (IJS) reduced this force even more and prevented damage to the concrete pipes. The initial high forces at the IJS may be due to initial jamming. However, the use of an IJS was highly recommended due to the predictive friction model showing very high results (10,000 kN) and the design resistance of the concrete pipes (7,000 kN). Due to the much lower jacking forces in reality, the successful completion of the alignment may have been possible without an IJS. However, also the frequent disc replacement intervals and the relatively low overall advance rate reflect the safety philosophy of the TBM operator and contractor (LEHMANN et al. 2023a).

4.1.1 TBM parameter utilisation

Another important aspect of TBM performance is the overall utilisation of TBM parameters. In this study, we do not refer to the utilisation factor for meters per day commonly used in the literature, as it is another approach for determining TBM performance during the unsteady pipe jacking process (RISPOLI et al. 2019). Instead, we refer to the utilisation rate of the main drive parameters: revolution speed, torque, and thrust force. The machine was operated at an average of 43% of its total installed revolution speed, 45% of the total installed torque, and 52% of the total available power. However, the TBM can be operated at either high revolution speed or high torque, but not with high values of both at the same time. This may indicate that the machine is overpowered because only half of the TBM's installed power has been used on average. More likely, this may again reflect a philosophy of finishing the drive safely while accepting lower performance rates. The thrust utilisation rate varies between 40% and 110%, which indicates short-term exposure of the bearing above the long-term load case. For small-diameter TBMs, the impact of damage to the machines and excessive wear on overall construction times and project success is much greater than for large TBMs, where the repair and replacement of worn or damaged machine parts are much easier due to fewer space constraints. These findings are important for ongoing and future approaches to TBM automation. An adjusted definition of optimality (as in GARCIA et al. (2021)), requiring an intelligent operating system, may mimic this "philosophy" or define several operating modes (e.g. high speed, economical, low wear) through the drive utilisation parameters. In order to advance the automation of tunnelling, it is important to emphasise the need for the consistent collection of technical and geological data for autonomous systems (LI et al. 2023). This data should be collected consistently across projects, TBM types, operators, and geological conditions (GARCIA et al. 2021). Geotechnical project monitoring, which is becoming increasingly important in small-diameter pipe jacking projects, can also improve the accuracy of technical and geological data.

4.1.2 Cutting tool wear

All cutters were inspected and replaced at regular intervals of 50 m to prevent TBM damage, cutterhead wear, and the risk of TBM failure. This was due to the challenging geotechnical conditions and higher-than-expected abrasion index (CAI) values encountered in the gneissic zones. This proactive approach allowed the cutters on the cutterhead to be changed before they reached the tolerable wear limit, as measured with a wear gauge. Observed wear was mostly normal or abrasive wear (HAMZABAN et al. 2022). As a result, the tunnel alignment was successfully excavated without any unscheduled downtime.

4.1.3 Penetration rate modelling approach

The penetration rate for the Landivisiau pipe jacking project was exemplarily modelled using state-of-the-art models suitable for projects with limited geological information (see GEHRING (1995), ROSTAMI (1997), HASSANPOUR et al. (2011) and FARROKH et al. (2012) for more information on models). Four scenarios were considered based on different UCS and corresponding BTS ratios: 1) an average baseline rock strength (UCS) of 38 MPa, 2) the average rock strength encountered during project execution (120 MPa), 3) the maximum rock strength encountered (185 MPa), and 4) a theoretical rock strength, chosen to fit the above-mentioned models best. While the CSM model (ROSTAMI 1997) is highly dependent on UCS and BTS, the models from HASSANPOUR et al. (2011) and FARROKH et al. (2012) highlight technical aspects of the TBM and are less reliant on geotechnical input factors. At the Landivisiau project, the CSM model was not able to accurately predict the achieved penetration rates, while the FARROKH et al. (2012) and HASSANPOUR et al. (2011) models both had deviation in penetration rates of less than 1 mm/rev. The GEHRING (1995) model significantly underestimated the penetration, likely due to the lack of sufficient correction factors (e.g., rock mass information) and improper consideration of influencing quantities. The CSM model is not suitable for predicting the penetration rate of the utility TBM used at Landivisiau, possibly due to the empirical nature of the model, the lack of small-diameter pipe jacking TBMs in its database, and the low baseline UCS. Another possible explanation for the large deviations in the results is the accuracy of the UCS values from both the exploration and monitoring-while-tunnelling testing program. However, it is challenging to determine the accuracy of the UCS values for a single small project. LEHMANN et al. (2022) suggest that the model from FARROKH et al. (2012) is particularly tolerant of changes in rock strength and can accurately predict the penetration rate for this project.

4.1.4 Future work

The detailed evaluation and analysis of the Landivisiau project showed that, to further improve the automation of tunnelling, it is important to gather more consistent data on technical and geological aspects across different projects, TBM types, operators, and geological conditions, as recommended by Garcia et al. (2021). This will be especially important for small-diameter pipe jacking projects, where geotechnical project monitoring is becoming increasingly important. In order to better predict the performance of small-diameter utility projects, it will be necessary to compare multiple conventional models and projects of varying diameters, rock types, lining methods, TBM types, and cutterheads. Additionally, applying machine learning models to these projects could also help improve performance prediction.

4.2 Utility TBM performance analysis and prediction

A newly compiled database of small-diameter TBMs operating in hard rock formations was analysed, providing insights into the challenges encountered and the performance of small-diameter TBMs. The data shows a clear correlation between UCS and penetration rate, with high UCS values generally resulting in lower penetration rates. The contact force of the discs, TBM size, personnel qualification, and geological conditions also play major roles in the performance. Established models can provide acceptable penetration predictions, but uncertainties in geological conditions require much more reliable preliminary exploration data for a large variety of small-diameter TBM projects. Even with advanced methods and technologies, fully capturing the complexity of geological conditions in small-diameter tunnelling projects remains a challenge. Further information on utility TBM performance and analysis is given in LEHMANN et al. (2024), LEHMANN et al. (2023a) and LEHMANN et al. (2023b).

4.2.1 Data generation

Generating and processing TBM data and geotechnical data is a crucial aspect affecting various phases of the tunnel construction process (RISPOLI et al. 2019). However, comparing data from different TBM and lining types, diameters, utilisation, countries, and suppliers presents unique challenges to data processing (LEHMANN et al. 2023a). Obtaining accurate and complete TBM parameters from the acquisition system is difficult but essential for data analysis. Geotechnical information must also be available and evaluated before raw data management and filtering, and a detailed cross-section is required to combine technical and geological data. Once sufficient high-quality geodata is available, the data processing can commence by ensuring a constant drilling advance and filtering for reasonable values (LEHMANN et al. 2022; LEHMANN et al. 2024). The data is then averaged in length-dependent intervals, such as 0.1 or 1 m, to address the temporal variation. Additionally, three database levels similar to those from FARROKH et al. (2012) are adjusted to small diameter projects, introducing the homogeneous geotechnical area (HGA) and the detailed borehole information (DBI) besides a normal tunnel project (LEHMANN et al. 2024).

4.2.2 Performance analysis

The performance analysis revealed that, on average, the penetration rate of analysed segment lining projects is almost three times higher (4.5–10.8 mm/rev) than that of pipe jacking projects (2–4.4 mm/rev) in rocks with similar compressive strengths. Furthermore, a cutter thrust force of at least 100 kN per cutter ring is important to achieve efficient penetration rates. This fact was already previously known for large-diameter TBMs (WILFING 2016) but had not been extensively documented for small-diameter TBMs. Low thrust forces per ring, typically below 100 kN/ring, are used in pipe jacking projects, while non-pipe jacking projects (thus mostly segment lining projects) employ thrust forces per ring in the range of 150 kN/ring or higher. For efficient chipping in hard rock, at least 100–150 kN of thrust force per ring is necessary to achieve penetration rates above 3 mm/rev (FRENZEL et al. 2012; WILFING et al. 2016). Lower thrust forces and, therefore, lower penetration rates may result in crushing and deep grooves in the rock. Large-diameter TBMs have such high thrust forces per ring, which, combined with high revolution speeds, lead to higher advance rates compared to small-diameter TBMs (ROSTAMI 1997; THURO & BRODBECK 1998; PALTRINIERI et al. 2016; JING et al. 2019)

It's crucial to analyse the actual TBM drive parameters, as they often vary considerably from design values and must be included in penetration rate modelling (FARROKH et al. 2012). Utility TBM projects operate far from utilisation limits, particularly for small-diameter machines with limited mechanical capacities, resulting in lower contact force per disc and penetration rates (SHEIL et al. 2016; TANG et al. 2021). Parameters like outer diameter, torque, and contact force act as placeholders for TBM parameters which directly influence the rock cutting mechanism (e.g. cutter size, drive, power, and bearing load). Furthermore, the TBM's design type is indirectly related to penetration rate via diameter and other parameters.

Most utility tunnelling projects have rock strengths below 100 MPa, likely due to their proximity to the surface and related weathering effects. Previous research shows that the UCS is crucial in determining TBM performance (GONG & ZHAO 2009; FARROKH et al. 2012; YAGIZ 2017; SALIMI et al. 2019), while WILFING (2016) and this research indicate that the TBM penetration rate correlates well with the PLI.

4.2.3 Performance prediction

Using a small-diameter hard rock TBM database, models with little geotechnical input were compared for HGAs and DBIs. The root mean square error (RMSE) and mean absolute percentage error (MAPE) were used to quantify the accuracy of the performance prediction. The model from FARROKH et al. (2012) performs best for small-diameter segment lining and pipe jacking projects in hard rock. For non-pipe jacking projects with UCS > 50 MPa, the ROSTAMI (1997) model also shows good performance. However, all models have difficulty predicting the penetration rate in weak to medium strong rocks up to 50 MPa for non-pipe jacking projects.

Multivariable regression technique in R® was used to find a relationship among the penetration rate, the relevant TBM and geotechnical parameters. Simple linear regression models were created for five scenarios, selecting parameters based on sensitivity analysis and the availability of values. Results show low RMSE values for pipe jacking projects and higher values for non-pipe jacking projects, with overall low MAPE values. The models were developed for HGA and showed better results than when applying to DBI. Furthermore, a machine learning approach shows promising results for penetration prediction in hard rock TBM projects, making it suitable for the presented dataset. Data splitting was done via cross-validation for accurate performance prediction. The GradientBoostingRegressor approach yielded the best results, using parameters such as cutting diameter, torque, revolution speed and rock type.

Even though great emphasis was placed on the geotechnical data quality and variability, rock mass properties, which can be a crucial factor determining TBM penetration, were in most cases not available and, therefore, not taken into account (MACIAS et al. 2014). Furthermore, the approach using the punch penetration test was also not pursued as adequate data from enough tunnelling projects is missing (YAGIZ 2002; YAGIZ 2009; YAGIZ 2015; JEONG et al. 2016). Another important parameter for determining the strength of a rock is the tensile strength. As described by MENG et al. (2020), more than 80 different ways to determine the brittleness of a rock exist. However, WILFING (2016) has shown that the ratio between UCS and BTS has relatively little in common with brittleness, which is known from the tunnelling or cutting of rock (GONG & ZHAO 2007; YAGIZ 2009). Accordingly, the PLI or LCPC, in conjunction with the compressive strength, would be more suitable for determining the brittleness of a rock and could therefore lead to better penetration prediction results.

4.2.4 Future work

Performance analysis of small-diameter TBMs needs to be expanded for very small diameters (ID < 2 m) and for very strong rocks (UCS > 100 MPa), as still almost no information is available for such projects. Our proposed models for predicting TBM performance have limitations that should be considered before use. These models may not accurately reflect the performance of a TBM on a specific project if they do not include specific TBM and geotechnical parameters. While these models can provide preliminary estimates for TBM performance, using a combination of models or more sophisticated algorithms is recommended to ensure a higher degree of confidence in the results.

Small-diameter TBM research should not further rely on databases containing a limited number of projects to create sophisticated models, as these models may not be applicable to projects with slightly different geology or TBM types. Instead, efforts should focus on acquiring more reliable preliminary exploration and actual ground data to make accurate performance predictions (PARASKEVOPOULOU & BOUTSIS 2020). This requires the use of advanced data acquisition systems to collect high-quality data from more small-diameter projects in hard rock and a broader range of rock strengths and qualities. Digitalisation will play a crucial role in increasing the TBM's advance rate, improving economic efficiency, and helping to achieve broader overall knowledge and acceptance. However, accurate penetration prediction will remain a challenge for small-diameter hard rock TBMs.

4.3 Microwave pre-conditioning of rocks

Mechanised rock cutting has revolutionised hard rock tunnelling in terms of performance, safety and plannability (MAIDL et al. 2012; VOGT 2016). However, these inventions were made several decades ago, and little major developments have since been made in the field of mechanised rock cutting (SIFFERLINGER et al. 2017). According to TEIMOORI & HASSANI (2020) and ZHENG & HE (2021), one of the most promising alternative hard rock damaging technologies is microwave pre-conditioning due to its efficiency, effectiveness, rapidity, precise control, safety, and automation-readiness. Such a technology could significantly enhance the cutting speed of mechanised tunnelling and mining equipment, not only in small diameters.

Microwave irradiation causes the temperature of various materials to increase based on their dielectric properties (LEHMANN et al. 2023d). In order to investigate the effects of microwave irradiation on the geotechnical properties of rock material, different types of concrete and granite were irradiated with a 5 kW, 915 MHz microwave. The samples were irradiated dry, humidified or quenched in tap water after dry irradiation (LEHMANN et al. 2023d). It was observed that concrete heats up faster than granite due to its high water, cement, and water-bearing mineral content (Portlandite and Ettringite). The concrete with the highest UCS, which has the least water and most cement, is most prone to melting and spalling. Granite, which in this case contains more than 38% quartz, heats up more slowly due to the bad absorption properties of quartz. Samples that were humidified beforehand did not heat up significantly faster or slower. The specific heat capacity was measured for all materials and is similar to the values in DEYAB et al. (2020) for granite. The correlation between irradiation, heating of the samples, and the resulting weakening from the creation of cracks, as directly indicated by the significant reduction in P-wave velocity, is detailed in LEHMANN et al. (2023d). However, the visible cracks in granite may also be caused by larger-scale temperature differences between the heated and non-heated areas, resulting in macrocracks. The test setup allows for the cylindrical samples to expand and increase in volume while heating, which would not happen in a rock mass subjected to triaxial confinement. Therefore, it is likely that larger sample sizes would result in more macrocracks and spalling, as suggested by the tests in HARTLIEB & GRAFE (2017) and applied in FENG et al. (2021).

4.3.1 Geotechnical properties

Most geotechnical parameters of the irradiated materials decreased, but the strength decrease with the most pronounced reduction was in the BTS and PLI and less in the UCS. Although granite samples with apparent cracks after irradiation did not always exhibit a significant decrease in UCS, they did exhibit a clear decline in PLI and BTS, similar to the observations made by ZOU et al. (2023). One explanation might be that stress brought on by the force per unit area gives rise to various failure modes. A uniaxial compression test would compress a crack. In order for the crack to spread, it would encounter shear resistance and friction caused by the crack's frictional forces. No or very little shear forces are present in the point load or Brazilian tensile strength test. Furthermore, the crack areas do not add up to the total fracture area, which requires less force. The cracks' isotropic distribution offers yet another explanation. If the sample cylinder has cracks in all directions as a result of irradiation, this indicates that some angles are better suited for fracturing than others in the various strength tests. Visual examination and the notable decrease in P-wave velocity, which was also noted by MA et al. (2022) for diorite at a similar microwave power level, both attest to the creation of micro- and macrocracks. The large grain size of the concrete aggregates, which was required to achieve high UCS values, might be one cause for the variations in strength in concrete. It should be noted that the small sample size and large component size in concrete did not fulfil the requirements of the standard (MUTSCHLER 2004). Additionally, due to technical limitations of the microwave setup, the maximum size of the sample cylinders was limited. Therefore, the strength of the concrete cylinders, particularly for the highest-strength concrete, could have been reduced due to the large grain size of the components, which facilitates the creation of cracks. The reduction in rock strength, however, is consistent with observations made by NEKOOVAGHT (2015), and the reduction in P-wave velocity was tested for granite by HARTLIEB (2013) but not for concrete. The UCS test results are not entirely clear, especially for brief irradiation intervals. We were unable to reproduce the clearly decreasing UCS results from DEYAB et al. (2020) for granite with 5 kW irradiation, despite the fact that heating was even more efficient in some granite specimens in our tests. As suggested by additional experiments carried out by DEYAB et al. (2020), more research will be required to ascertain whether this trend becomes more pronounced with higher microwave power. Recent research with high-power microwaves has been undertaken on assisted comminution and ore sorting (FORSTER 2023).

Variability in the results of UCS testing may be attributed to various factors, such as the chemical composition of the tested materials and the frequency of the microwave system used. While our study employed a 915 MHz frequency, a 2450 MHz system with up to 15 kW power was used by DEYAB et al. (2020), which may have led to different irradiation results and, thus, varying results in rock strength. The lack of significant difference in geotechnical results among the three treatment types, dry irradiation, wet irradiation and quenching, suggests that the rock material properties play a more crucial role than water content for strength reduction with a microwave. When the samples were heated initially, UCS values tended to increase slightly before decreasing, particularly at low power rates. This behaviour, also observed in sedimentary rocks like sandstone (SCHMITT et al. 2019), could be attributed to a curing process that occurs in the rock at low and gradually increasing temperatures. Nonetheless, the precise mechanism underlying the strength increase with low microwave power remains unclear. Notably, sample damage was primarily induced during the initial heating stage and not significantly augmented by quenching. This finding supports the theory of rock damage utilised in ancient fire-setting methods commonly employed in ancient and medieval mining sites, as previously proposed by WEISGERBER & WILLIES (2000). The heating of minerals can alter their crystal structure and increase individual minerals' volume, creating tension between grains, which, in turn, can lead to cracks in grain boundaries and a reduction in rock strength. However, the EDX analysis revealed that there was no change measurable in the chemical composition of the individual mineral grains, probably because of insufficiently high temperatures.

The experimental results demonstrate that increasing temperatures lead to an increase in UCS/BTS and UCS/PLI ratios for all tested samples. While the term "brittleness" in rock engineering remains controversial (MENG et al. 2020), practical observations in tunnelling suggest that higher UCS/BTS and UCS/PLI ratios can increase rock cutting rates. Our irradiation experiments clearly indicate that UCS/BTS and UCS/PLI ratios are highly temperature dependent. Prolonged irradiation results in higher temperatures and higher UCS/BTS and UCS/PLI ratios in all four materials. Moreover, our findings suggest that the conversion factor used to derive a UCS value from a PLI can vary by up to 100% for both concrete and granite samples, depending on the irradiation time and heating conditions. Therefore, the application of a fixed conversion factor for PLI to UCS, as proposed in several approaches summarised by HUDSON & HARRISON (2005), seems even more unrealistic.

4.3.2 Electrical efficiency

The electrical efficiency of microwave heating is defined as the relationship between the input (in this case: 5 kW) and the power transmitted to the sample via temperature increase. In this study, we initially assumed a uniform temperature increase throughout the sample, but temperature measurements revealed that the highest temperature was reached in the middle of the sample, while the top and bottom remained cooler at the beginning. Although the temperature was measured 15 s after the irradiation ceased, resulting in a lower temperature reading, the error in the temperature decrease is believed to be relatively small. Nevertheless, more sophisticated techniques to obtain more accurate temperature readings were not implemented in this study. The overall heating efficiency depends on thermal and electromagnetic material properties, varies from 5 to 10% for granite and decreases with lower rock strength. For concrete, the efficiency is initially higher but then drops to a low level of 10 to 30%. In other words, the efficiency decreases as the sample temperature increases. This trend is consistent with the findings reported for the rock types kimberlite and basalt in HASSANI et al. (2020), who introduced the term HOME (Heat over Microwave Efficiency) to quantify the ratio between heat absorbed and microwave energy input. The low overall efficiencies observed in our study are likely due to the small sample size, which has a diameter more than six times smaller than the microwave wavelength (32.8 cm) and covers only 15% of the waveguide cross-section. Furthermore, strength reduction may increase with larger samples, leading to the creation of more macrocracks.

LEHMANN et al. (2023d) revealed that the relationship between temperature increase and strength reduction in granite is linear when using a 915 MHz microwave setup with an input power of 5 kW. Specifically, they found that the strength (PLI) decreases by 0.12% for every 1 Kelvin increase. The trend was not as linear for the two stronger concrete materials, with strength reduction ratios of 0.24 and 0.28% per Kelvin. A similar trend was also observed for the weak concrete, but the strength reduction was not necessarily linear. Furthermore, the specific energy required to achieve a certain reduction in strength (PLI) was calculated. For concrete materials B1 to B3, the required energy ranged from 200 to 500 MJ/m³, resulting in a 40 to 50% strength reduction. In the case of granite, we observed a clear linear trend, with a 50% reduction in strength achieved at around 700 MJ/m³. These values are significantly higher than the energy requirements of conventional mechanised hard rock cutting techniques, which typically range from 1 to 100 MJ/m³ for the overall cutting process in tunnelling and mining (ALTINDAG 2003). Nevertheless, LEHMANN et al. (2023d) report significant potential for optimising the energy efficiency of the microwave-assisted rock weakening method.

Previous research by HASSANI et al. (2020) introduced WOME (Weakening over Microwave Energy) as a measure of the percentage of strength reduction achieved per unit of energy input in kWh/t. Using PLI instead of UCS as the measure of strength reduction, LEHMANN et al. (2023d) found that the maximum WOME achieved for granite was 4.78% per kWh/t, which is slightly lower than the 5.35% per kWh/t for basalt and much higher than the 1.3% per kWh/t for kimberlite reported by HASSANI et al. (2020). However, the WOMEs achieved for concrete were much higher, with up to 8.99% per kWh/t for B2 and 11.08% per kWh/t for the high-strength concrete. Only the low-strength concrete exhibited a considerably lower WOME of 3.14% per kWh/t. The increased efficiency can be attributed to the lower frequency used, the design of our test set-up and the favourable microwave absorption behaviour, especially of concrete.

Experience shows that the presence of micro- and macrocracks can have a positive effect on the rock cutting process. Studies such as THURO & PLINNINGER (1999) have demonstrated that joint spacing in rock masses can greatly influence the speed of advancement of roadheaders. Thus, it is important to consider that the efficiency of microwave irradiation combined with cutting techniques may not be accurately reflected by calculations based on small-scale cylindrical samples and therefore offers possibilities for future research.

4.3.3 Future work

Further tests are recommended to investigate the potential of higher microwave power levels ranging from 80 to 100 kW or higher for more efficient energy transfer to rocks and to induce higher differential stresses leading to the creation of more pronounced micro- and macrocracks. The optimal frequency for damaging rock prior to cutting was explored, but further studies are required using high-performance microwaves. Additionally, simulations and real tests on various rock types should examine the influence of spot size and area. In order to obtain application-specific results, using an open-end microwave applicator instead of cavities or standing waves in waveguides that exhibit reflections is recommended. Larger sample sizes, such as full-face rocks that are naturally confined triaxially (except for the free rock face), should be irradiated, allowing for volumetric changes to occur only in one direction, towards the tunnel face, and thus, being more effective in rock destruction. Measuring changes in geotechnical parameters alone is insufficient in determining the potential increase in mining or tunnelling speed. Therefore, future tests should be extensive enough to consider variations in speed or penetration, wear, and electrical efficiency for full-scale hard rock cutting machines. Future work shall also include modelling and solving the electrothermal-mechanical problem in order to better understand and predict the processes depending on material properties.

5 Conclusion

This dissertation elucidates small-diameter TBMs with outer diameters below 5 m, which have always been and are still overshadowed by large TBMs but provide at least as much growth potential. Small-diameter TBMs nowadays offer mechanised solutions for projects in hard rock which were not considered to be feasible some years ago and are increasingly deployed in the construction of sewer, stormwater, freshwater and hydropower tunnels, as well as pipeline casing and cable tunnels for hydrocarbons, hydrogen, fibre optic and electricity lines. The following three main aspects could be elaborated:

Pipe jacking performance

The emphasis of small-diameter tunnelling projects, especially pipe jacking, is not primarily on achieving the highest possible advance rate but rather on ensuring safe excavation from the launch shaft to the reception shaft in order to minimise downtimes and avoid significant damage to the TBM. This approach is reflected in the overall medium levels of revolution speed, torque, thrust, and overall power utilisation rates, as well as in the frequent inspection of the cutterhead, proactive replacement of the cutting tools and the accurate deployment of key technologies like IJSs and bentonite lubrication. Given their limited scale, it is of utmost importance for such projects to prioritise the availability, precision and dependability of the data gathered, particularly with respect to penetration rate, the cutter thrust force, torque, and specific skin friction.

Utility TBM performance analysis and prediction

The analysed segment lining projects have, on average, a penetration rate almost three times higher (4.5–10.8 mm/rev) than the analysed pipe jacking projects (2–4.4 mm/rev) in rocks with the same compressive strengths. A clear correlation between the UCS and the penetration rate is observed: High UCS values generally result in lower penetration rates (< 5 mm/rev), while compressive strengths below 100 MPa result in a higher penetration rate. For the general penetration prediction of small-diameter projects in hard rocks or pipe jacking projects, the model from FARROKH et al. (2012) is most suitable. However, the model from GOODARZI et al. (2021) also leads to acceptable results. For segment lining projects in hard rock (> 50 MPa), the model from ROSTAMI (1997) and a model developed by the author are recommended. Performance prediction for segment lining in rocks with UCS < 50 MPa is not reasonably feasible with the studied models. Newly derived ML and regression models show partially promising results, especially for well-defined application areas, but so far, no significant improvement compared to conventional models has been achieved. For small-diameter projects, major discrepancies are commonly observed between the geotechnical exploration program and the actual geological conditions. Rather than developing new models, the emphasis should be on obtaining much more reliable and accurate preliminary geotechnical exploration data.

Microwave rock pre-conditioning

Microwave pre-conditioning of rocks could be a promising tool to increase the penetration rates of hard rock cutting machines. Microwave irradiation at 915 MHz and 5 kW heats concrete faster than granite and leads to the formation of inter- and intragranular cracks in both materials. The PLI and BTS decreased by up to 50% for all materials. The longer the irradiation takes, the higher the UCS/BTS and UCS/PLI ratios. Special treatment of the rocks in terms of humidification or quenching before or after irradiation did not benefit the rock damaging process. The specific energy needed to achieve a 50% reduction in PLI rock strength was roughly calculated at 200 to 700 MJ/m^3, which is, therefore, still higher compared to conventional hard rock cutting or mining technologies. However, especially for granite, the efficiency of the deployed microwave setup is low but can be increased by using much larger sample sizes and high-performance microwaves.

Having established the current status regarding performance and penetration of small-diameter TBMs, different models for predicting them were compared and promising approaches for new models were presented. The development of a large database incorporating 37 small-diameter TBM projects in hard rock has revealed the focus that needs to be placed on data quality, collection and processing, especially for geotechnical data. Finally, microwave pre-conditioning proves to be one of the most favourable artificial rock weakening technologies, which has the potential to facilitate faster, more cost-efficient, safer, and sustainable cutting of hard rock formations, extending beyond the scope of small-diameter TBMs.

6 References

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Appendix

Appendix A – Scientific articles

Appendix A-1

Title:	**Performance analysis of utility tunnelling data: A case study of pipe jacking in hard rock in Brittany, France**				
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Performance analysis of utility tunneling data: A case study of pipe jacking in hard rock in Brittany, France

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ABSTRACT

The increasing demand for renewable energy is accompanied with an urgent need for new and improved infrastructures worldwide, which in turn will require a greater number of utility tunneling projects in rock. Mainly due to tighter safety regulations, hard rock pipe jacking is getting increasingly important in the utility tunneling industry. Based on the example of the 530 m long Landivisiau utility tunnel case study, we present the first comprehensive pipe jacking study in high strength metamorphic rocks. The procedures and associated challenges of data analysis of a small-diameter pipe jacking project are presented and discussed. The tunnel has an outer diameter of 2.2 m and was excavated in Variscan basement rocks of Brittany. The geotechnical conditions at Landivisiau were very heterogeneous and stronger than expected, comprising fresh to highly weathered, weak to very strong gneiss, granite and schist with an UCS of up to 185 MPa. The TBM achieved an average advance rate of 17.3 mm/min and an average penetration rate of 3.4 mm/rev. The advance and penetration rates of the TBM are compared with results obtained by recent force estimation and penetration models. This study was conducted to raise awareness about the importance of using geological and technical data, to cope with increasingly strict controls by local authorities and to provide a foundation for further analysis and use of data, especially with respect to future automated tunneling.

1. Introduction

In the context of the accelerating global transition towards renewable energies, continuing urbanization, and the expansion of economically emerging regions, mechanized tunneling is increasingly being used for the modernization and expansion of underground infrastructures. Utility tunnels cover a broad application field comprising sewer, stormwater, freshwater or hydropower tunnels as well as pipeline casing and cable tunnels for hydrocarbons, hydrogen, fiber optic and electricity lines. Investment and implementation pressure is growing, particularly for the rehabilitation and modernization of drainage systems in industrialized countries. It results from the increasing supply needs of population and industry for data lines as well as for the expansion and conversion of energy networks (Valdenebro and Gimena, 2018; Luo et al., 2020). In contrast to traffic tunnels, the utility tunnel diameter range reaches up to around 5 m which is determined by common applications fields. However, some distinct large-diameter exceptions exist (e.g. large tunnels as deep sewer main collectors). Utility tunneling offers a high degree of reliability in terms of public safety, construction times and budget (Matthews et al., 2015). In addition, the pipe jacking method is significantly more environmentally friendly than conventional technologies like cut and cover (Tavakoli et al., 2017; Kaushal et al., 2020; Lu et al., 2020).

1.1. Utility tunneling methodology

Depending on the project-specific and geological conditions, utility tunnels can be constructed using a range of mechanized technologies such as Slurry Tunnel Boring Machines (TBMs), Earth Pressure Balance (EPB) TBMs, Single- and Double-Shield TBMs, Gripper TBMs or Partial Face TBMs. The main design differences between these machines and their main application areas are presented in Table 1. There are also significant variations in lining methods, which, strongly depending on the geotechnical conditions and the machine technology deployed, can

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Table 1
Main design features and application areas of the most common small diameter TBMs (partially after DAUB (2021)).

TBM type	Face support	Excavation type, cutting tools	Muck transport	Main application area
Slurry (AVN)	Slurry	Full face, design according to geology	Slurry circuit	Granular soil and weak rock
Slurry (AVND)	Slurry with D-Mode option	Full face, design according to geology	Slurry circuit	Granular soil and weak rock
EPB	Earth pressure	Full face, design according to geology	Screw conveyor, conveyor belt, muck skip	Cohesive soil and weak rock
Partial face	Soil angle support	Partial face excavator/ roadheader	Conveyor belt, muck skip	Dry soils and weak rock
Single & Double shield, Gripper TBM	mechanical/ by cutting wheel	Full face, rock cutting wheel	Conveyor belt, muck skip	Hard rock

range from no lining at all to rock anchors with wire mesh and shotcrete, rib and lagging, classic segment lining and pipe jacking. A comprehensive state-of-the-art overview of machine concepts and lining methods in small-diameter tunneling is given in Schmäh et al. (2021).

Even though Slurry TBMs have been deployed in combination with pipe jacking in hard rock for several decades (Grasso et al., 1996; Frank, 1999), it is still rather a minor application in utility tunneling. There exist some whitepapers from pipe jacking companies on hard rock applications (e.g. Bradshaw, 2014), and only very few case studies on actual pipe jacking projects are published. Sheil et al. (2016) presented a pipe jacking project in mostly weak limestone in Ireland. Latest research from Deng et al. (2021), Tang et al. (2021) and Zhong et al. (2021) focuses on hard rock project-related issues like pipe strength and friction. Especially with the progressing energy transition, pipe jacking is gaining importance in hard rock tunneling with small diameter and the performance of these drives is coming into focus. Furthermore, tightened safety regulations for segment lining tunnels with an inner diameter of less than 3000 mm will lead to a further gain in importance of pipe jacking in both soil and hard rock (Schmäh et al., 2021). Probably due to the relatively small technical and financial project sizes compared to large tunneling projects, very little has been published on such hard rock pipe jacking projects (Sterling, 2020). However, these projects are highly interesting, as small TBMs in hard rock quickly reach their technical limits and very little project data is available regarding advance and prediction of performance and wear. To date, no comprehensive study of a pipe jacking project in very strong metamorphic basement rocks has been published. The aim of this paper is to fill this gap and to present new insights from the planning and construction of a casing tunnel for a gas pipeline in hard rock in Landivisiau in north-western Brittany, France. For this purpose, geotechnical information is combined with project-specific information and machine data, including predictions of pipe friction and modelling of TBM performance. Furthermore, an approach for the evaluation of Slurry TBM machine data and the necessary data corrections will be presented.

1.2. Pipe jacking principles

The pipe jacking method is mostly used for tunnels with inner diameters smaller than 3 m and drive lengths of up to 1000 m and more, to construct underground tunnels and pipelines with a tunneling machine (Stein, 2003). As shown in Fig. 1, the TBM and pipes are jacked by hydraulic cylinders from a launch shaft into the ground to a reception shaft with a TBM excavating the ground in front. Interjack stations (IJS) can be used to provide sufficient jacking force even at long drives and in hard rock, to overcome the frictional resistance to pipe motion along the respective tunnel sections (Sterling, 2020).

The Slurry TBM is by far the most common utility tunneling machine type (Schmäh et al., 2021). The concept of slurry-supported excavation allows the deployment of these machines in almost all geological conditions, from silt and clay to granular soils, gravel and hard rock. Slurry TBMs belong to the category of closed, full-face excavation machines with a hydraulic slurry circuit. The small slurry machines, which are especially in Germany also called AVNs, are available between 0.25 and 4 m inner diameter (Schmäh et al., 2021). Above this diameter, Slurry TBMs are operated differently, use a jaw crusher and are generally called Mixshield machines. The soil to be excavated, is removed using a cutterhead specifically designed for the respective geotechnical conditions. A cone-shaped crusher inside the excavation chamber in the suction box crumbles stones and other obstacles to a conveyable grain size during the advance. The conveyance of the excavated material is undertaken with a slurry, that holds the material in suspension. The slurry is pumped into the excavation chamber via the feed pump, where it is mixed with the excavated material, and pumped back to the surface separation plant via the slurry pump.

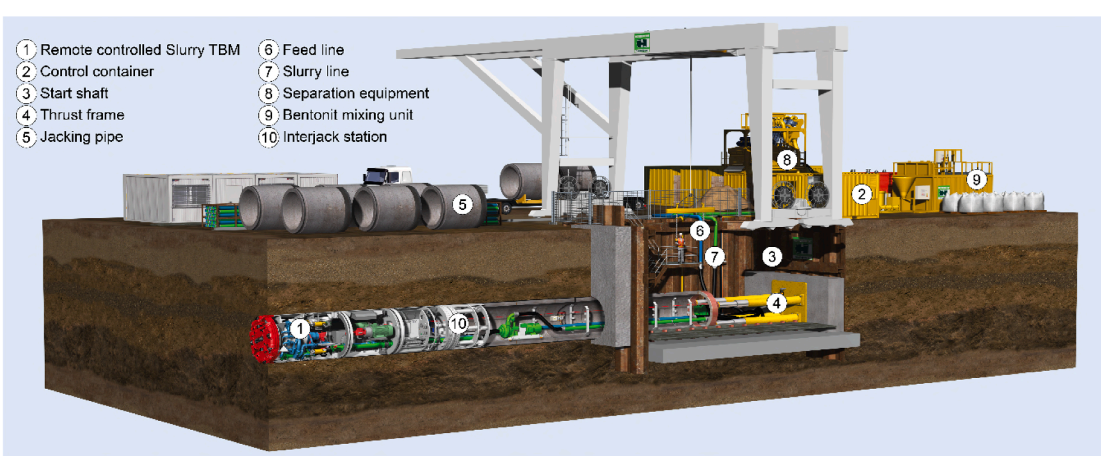

Fig. 1. Pipe jacking jobsite set-up including the Slurry TBM and a separation plant. It also features a telescopic station to provide additional thrust force directly behind the machine. Interjack stations are installed at regular intervals on long or specifically challenging (e.g. hard rock) drives, to reduce the thrust force required to push the pipes and TBM, thus reducing the likelihood of blockages to a minimum (modified after Herrenknecht AG).

2. Project information

GRTgaz, one of France's two natural gas transmission and storage companies, was commissioned by Total Energies to supply its new combined cycle power plant in Landivisiau, Brittany. To ensure energy independence for this remote area, the power plant requires a constant flow of gas through a DN400 (16″) pipeline.

The 22 km route included two areas where conventional trenching work could not be carried out, both for environmental reasons and due to heavy impact on existing strategic infrastructures. After an unsuccessful preliminary attempt using Horizontal Directional Drilling (HDD), the crossing of the Paris-Brest railway line, the Elorn river and a cliff was redesigned, finally tendered and carried out by pipe jacking (Fig. 2).

The complex geological conditions as well as the topographical constraints (26 m altitude difference between entry and exit point, 40 m altitude difference between entry point and deepest point of tunnel route) were the determining factors which led to the technical decision in favor of pipe jacking rather than HDD. With its 530 m long and 2.22 m wide tunnel, these conditions made Landivisiau one of the most complex trenchless projects carried out in Europe in recent years. The tunnel was driven from an 8 m deep launch shaft (Fig. 2a). Along the tunnel route, the TBM handled a downward gradient of up to 17%, a curve radius of 700 m, and a groundwater pressure of up to 3 bar. The successful breakthrough was celebrated on October 27, 2020 (Fig. 2b). Commissioning of the power plant was scheduled for December 2021.

A Herrenknecht AVN1800 with an outer diameter of 2225 mm was deployed for the project. The TBM had a maximal revolution of 11.7 rev/min and a nominal torque of 424 kNm. As typical for such small-diameter hard rock projects, the hard rock cutterhead was equipped with five monoblock single-ring center cutters and eight monoblock double-ring face and caliber cutters, resulting in a total of 21 cutting rings. The cutterhead is partially visible in Fig. 2b. The most important TBM specifications are summarized in Table 2.

Table 2
Technical specifications of the deployed Slurry TBM.

TBM Type	AVN1800T
Cutting head type	Rock
Lining method	Pipe jacking
Cutting diameter (mm)	2225
Inner diameter (mm)	1800
Load main bearing (kN)	2600
Nominal torque (kNm)	424
Max. revolution (1/min)	11.7
Quantity of cutters	13
Cutters without center (2-Ring)	8
Center cutters (1-Ring)	5
Total number of cutting rings	21
Cutter size (in)	12
Max. Load per cutter (kN)	218
Average spacing (mm)	80
Ring width (mm)	13
Total disc load (kN)	2599

2.1. Geological conditions at the study site

According to Cagnard (2008), the Pays the Léon, where the Landivisiau jobsite is located, is dominated by metamorphic rocks that were exposed to local anatexis. These Variscan rocks were intruded by granites of Carboniferous age (300 Ma) and were subjected to the development of ductile shear zones (Ballèvre et al., 2013). The tunnel alignment is characterized by Variscan Gneiss of Brest to the northwest and early-Cambrian schists and phyllites to the southeast. These basement rocks are covered by a layer of Holocene lacustrine and fluvial formations up to 10 m thick, consisting mainly of clay, sand, gravel and stones. Fig. 3 shows a geotechnical profile summarizing the predominant lithological units as described in the six exploration boreholes and the tunnel alignment.

The majority of the alignment was expected to be in highly weathered to fresh gneiss (Fig. 4a). As shown in Table 3, the gneiss was initially described as medium strong to strong and not extremely abrasive. The average unconfined compressive strength (UCS) was given with 41 MPa. Below the Elorn river valley, the gneiss was found to be very fractured and weathered. The last third of the alignment was expected to be in moderately weathered schist (Fig. 4b). The schist was initially described as weak to medium strong and moderately to very abrasive (Table 3). Due to the partially thick overburden, a groundwater pressure of up to 3 bar was anticipated.

2.2. Predicted and actually encountered conditions

The baseline geotechnical conditions are described in Table 3. However, comprehensive geological construction site monitoring revealed that the geotechnical conditions deviate considerably from the initial description. Several geotechnical investigations on samples taken at interventions during tunneling revealed a significantly higher rock strength especially at the gneissic/granitic portion with an average of 120 MPa and a maximum of 185 MPa. The great majority of the samples showed an isotropic, granitic texture (Fig. 4a) which could be caused by anatectic processes that are common in this region. Another possibility could be a local granitic intrusion, which was not covered by the exploration drilling program. This could also explain the significantly higher rock strength. Between chainage 284 and 290 m, just below the Elorn river, a fault with cataclastic material was encountered during tunneling, which had not been previously described. Due to the high

Fig. 2. Impressions of the pipe jacking jobsite in Landivisiau: a) Launch shaft in the middle of the jobsite with minimal environmental footprint. View towards the Elorn valley in tunneling direction. b) Breakthrough of the TBM in the reception pit. The monoblock double-ring face and caliber cutters are clearly visible.

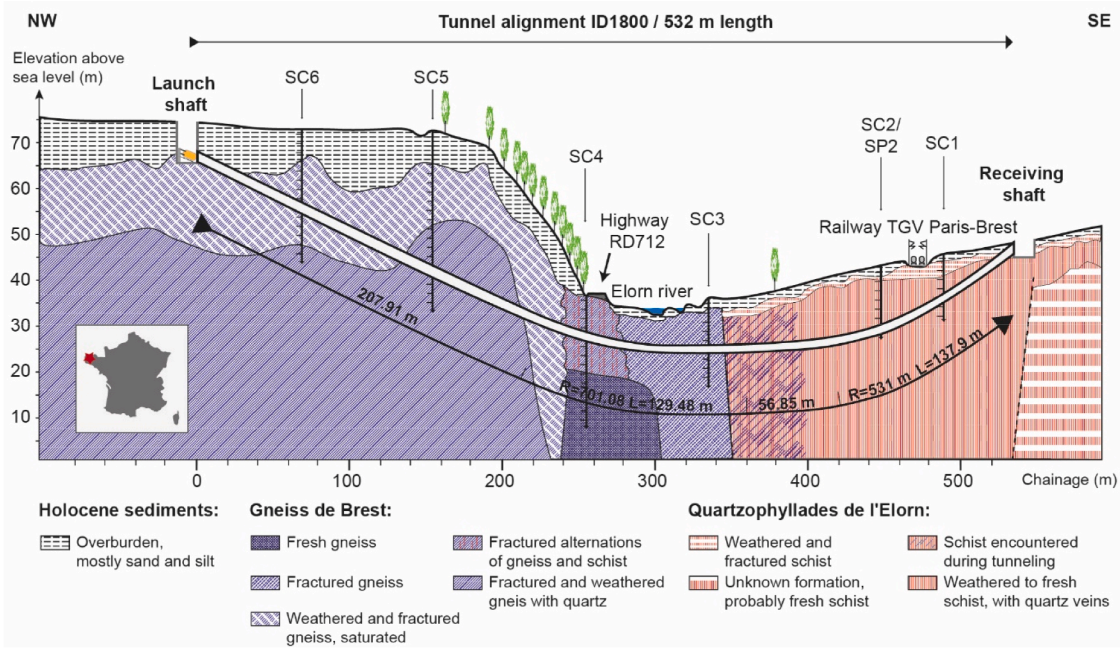

Fig. 3. Synthesis of the geotechnical and geophysical exploration program. The nomenclature shown is the same as presented in the geotechnical data report. Please note that the contact between gneiss and schist was indicated from geophysical and geotechnical data at chainage 350 m, but during tunneling it was encountered about 40 m later.

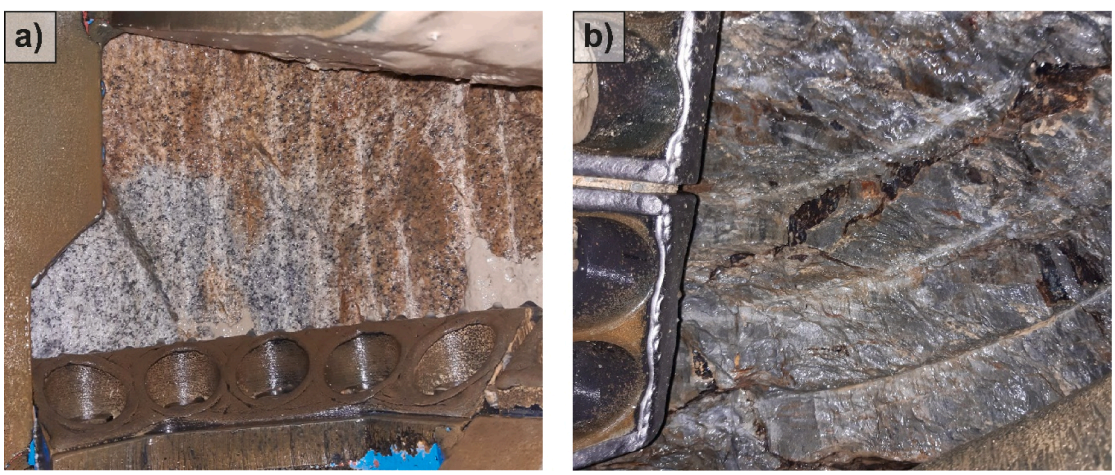

Fig. 4. The two main lithologies as seen through a cutterhead intervention: a) Fresh to moderately weathered gneiss with an almost granitic texture from chainage 225 m. b) Dark-grey to brown, fine-grained schist from chainage 492 m. Note the different appearance of the cutter tracks in both lithologies.

permeability of the mostly silty to sandy material and the low overburden, seepage in the Elorn river occurred, which was stopped immediately after detection. The contact between gneiss and schist was encountered at chainage 400 m about 50 m later than expected based on the geotechnical and geophysical exploration data (Fig. 3). The Cerchar Abrasivity Index (CAI) of the rock during tunneling ranged from 3.8 (altered schist) to 5.1 (max. value for schist), characterizing the rock on average as very abrasive to extremely abrasive. The petrographic analysis revealed a proportion of quartz higher than 50% locally, underlining the high CAI values.

3. Machine drive data processing

As already described in Rispoli et al. (2019), TBM data processing is an important aspect that affects several phases of the construction process of a tunnel excavated by a TBM. Especially small-diameter TBMs, such as the one used at the Landivisiau project, are hydraulically driven. Therefore, direct measurement of torque is difficult. However, parameters like torque are highly valuable for the determination of the overall machine performance and especially for the comparison of the driving data of those of larger machines. Furthermore, unlike a few large TBMs, so far small-diameter TBMs do not have direct load measurement at the discs (Barwart and Edelmann, 2015). Hence, it is necessary to calculate the effective forces at the cutterhead, in order to determine the actual force acting on the rock. A detailed data analysis procedure for performance comparison of small-diameter TBMs will be published in a separate manuscript (Lehmann et al., 2022).

3.1. *Cutterhead torque correction*

A correction or calculation of the cutterhead torque is necessary for all TBMs with hydraulic drives. Especially for pipe jacking TBMs, the

Table 3
Geotechnical parameters of the alignment as presented in the Geotechnical Baseline Report.

Parameter (number of tests, n)	Gneiss	Schist	Sand
Percentage of the alignment	58%	36%	6%
Unconfined Compressive Strength (MPa) (n = 9)	7.5–99.5 (ø 41.0) (Max value during tunneling: 185 MPa)	12.1–43.9 (ø 32.0) (Max value during tunneling: 67 MPa)	Not applicable
Point Load Index (IS_{50} – MPa) (n = 9)	0.2–9.2 (ø 3.6)	1.6–2.8 (ø 2.1)	
Cerchar Abrasivity Index (CAI) (n = 7)	2.1–4.3	0.7–5.1	
Rock Quality Designation (RQD - %)	Extremely low	Extremely low	
Permeability	$7 * 10^{-7}$–$1.7 * 10^{-6}$	low	
Water pressure	Up to 3 bar		

torque is mostly not calculated automatically. Instead, the working pressure of the cutterhead drive (W_p in bar) is regulated by the operator and available for analysis. If the TBM is equipped with a non-adjustable drive, the torque (τ in kNm) can be calculated using the working pressure and the torque constant (k_t in kNm/bar):

$$\tau = W_p * k_t \quad (1)$$

In case the TBM is equipped with an adjustable hydraulic drive, the torque below the nominal speed limit (ϑ_{nom}) can be calculated using equation (1). Above the nominal speed limit and below the maximum speed limit (which is the range in which most Utility TBMs are operated), τ can be approximated using the following equation, where ϑ_{nom} is the nominal speed limit and ϑ_x is the actual rotational speed:

$$\tau = \frac{\vartheta_{nom}}{\vartheta_x} * W_p * k_t \quad (2)$$

3.2. Cutterhead thrust force correction

For most TBM performance analysis, comparison and prediction models, the normal cutter force (F_n) is the most important technical parameter (Gehring, 1995; Rostami, 1997). However, determining F_n during tunneling was for a long time only possible with elaborate tests due to the lack of direct measurements. A comprehensive study on determining the correct F_n at a real project is presented in Frenzel et al. (2012). Since a few years, some large-diameter TBMs are equipped with systems that are able to conduct direct measurements of the disc cutter rotation and load (Barwart and Edelmann, 2015). These systems are not yet designed and available for the calculation of F_n at small-diameter TBMs. Therefore, a correction of the available thrust force at the TBM has to be carried out to estimate the force acting on the cutting wheel (F_{CW}) and on all disc cutters. This correction is required for all machine types except Gripper TBMs, as here the advance force of the gripping cylinders should theoretically act directly on the cutterhead. For all other machine types, at least the friction (F_{Fr}) between the thrust (F_{AC}) or steering (F_{SC}) cylinders and the cutterhead and, if applicable, the counterforce (F_E, F_W) resulting from earth (P_E) or groundwater (P_W) pressure must be considered (Fig. 5).

$$F_{CW} = F_{SC,AC} - F_{E,W} - F_{Fr} \quad (3)$$

With.

$$F_{E,W} = \frac{P_{E,W}}{A} \quad (4)$$

$$F_{Fr,Rock} = \mu_G * F_{N,TBM} \quad (5)$$

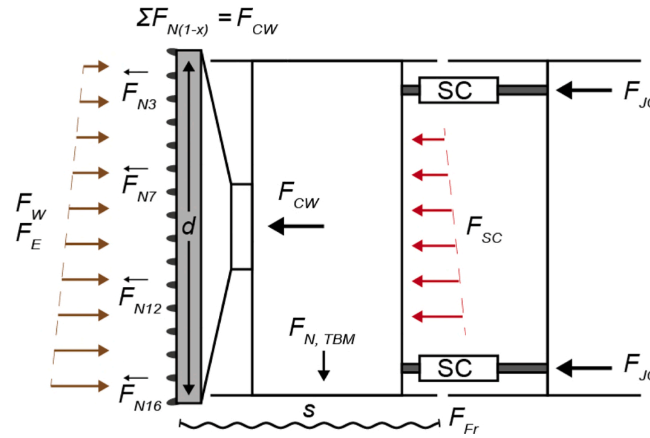

Fig. 5. Forces acting on a small diameter Slurry TBM in hard rock (with F_{CW} = Force applied on the cutting wheel; F_{NX} = Normal force per disc cutter; F_E = Counterforce from earth pressure, F_W = Counterforce from groundwater pressure; F_{SC} = Force steering cylinders; F_{JC} = Force jacking cylinders; F_{Fr} = Friction force; $F_{N,\ TBM}$ = Weight force of the TBM; d = cutting diameter; s = length of the shield; SC = Steering cylinders). Note that the sum of all disc cutter normal forces equals the total force applied on the cutting wheel.

$$F_{Fr,Soil} = d * \pi * s * \varphi \quad (6)$$

φ is the specific skin friction and can be conservatively considered to be 3 kN/m^2 at the shield of the TBM (Stein, 2003). A is the area of the cutting wheel, μ_G is the coefficient of friction and can be estimated as 0.4 (Stein, 2003), $F_{N,TBM}$ is the weight force of the TBM between the location of the thrust or steering cylinders (generally at the end of the shield) and the cutting wheel. Usually $F_{N,TBM}$ includes the weight of the shield and the cutting wheel. d is the diameter of the cutting wheel and s is the length of the shield.

3.3. Drive parameter utilization rate

In order to get a better understanding of the driving procedure, the main driving parameters revolution, torque and thrust force were compared to the maximum installed capacity, with the ratio defining the parameter utilization rate. The actual power (P) was compared to the total available power of the machine. P was calculated using torque (τ) and the actual rotational speed (ϑ_x):

$$P = \tau * 2\pi * \vartheta_x \quad (7)$$

4. Measurements

Between chainage 155 and 325 m, the average machine parameters were recorded every 20 cm. For the rest of the drive, data was recorded every minute, resulting in almost 28,000 individual data sets each comprising 437 sensor values and parameters. However, only a few of them are of interest for performance analysis and are presented in the following section. For better representation in the graphics, the data was averaged for each 5 m of advance.

4.1. Machine parameters and performance

The average TBM advance rate is shown in Fig. 6a. The advance rate was highest in the sand/fill at the beginning of the drive with 29.8 mm/min, decreasing in the gneiss with an average of 16.9 mm/min and was constant in the schist with an average of 15.3 mm/min. The total average advance rate was 17.2 mm/min. With a generally constant revolution of 5 rpm, the average penetration rate was 3.4 mm/rev. The maximum advance per day was 15.8 m, while the average advance per day was 6.5 m, for a total of 79 working days. Fig. 6b shows the

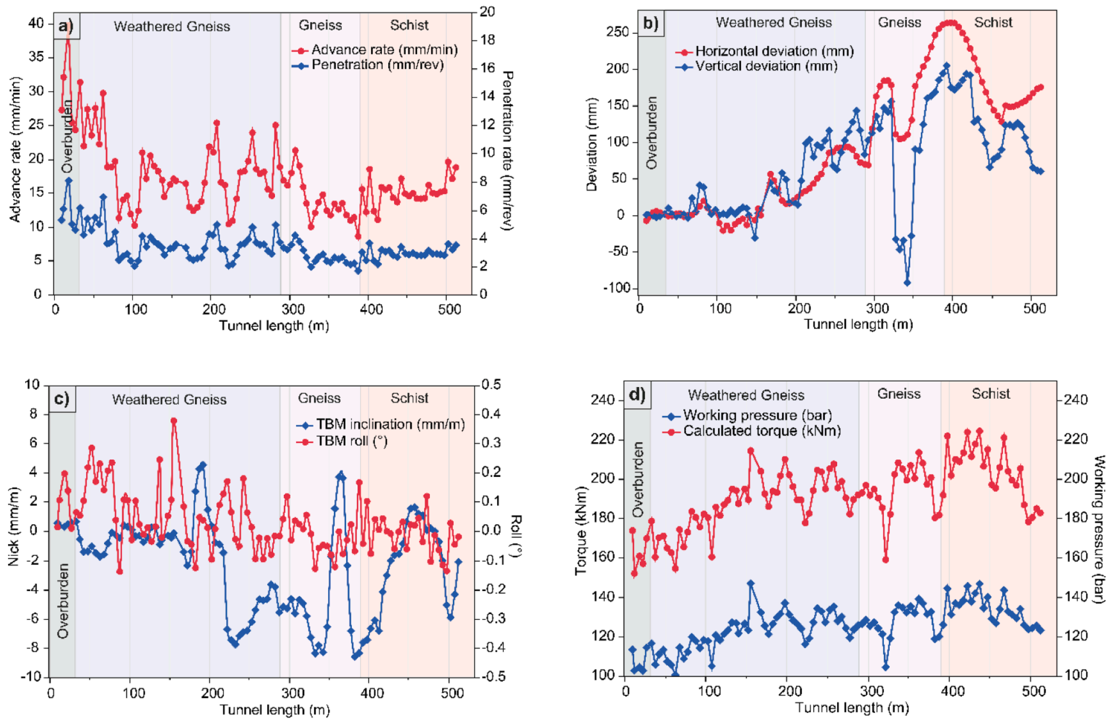

Fig. 6. Machine parameters: a) Advance rate and penetration rate; b) Horizontal and vertical deviation; c) Inclination and roll of the TBM; d) Working pressure of the cutterhead and calculated torque.

evolution of the horizontal and vertical deviation, both increase with drive length. Fig. 6c shows the TBM inclination and roll of the shield. The shield roll reflects well the capability of turning the cutting wheel in two directions. The torque is calculated as described in Section 3.1 and its evolution is shown in Fig. 6d. The average torque is 192.3 kNm, while the average working pressure of the cutting wheel drive is 125.9 bar. The average thrust force recorded at the steering cylinder was 2092.5 kN. As described in Section 3.2, this force also requires an adjustment considering the earth counterpressure of up to 3.1 bar (or counterforce of 1200 kN) and the friction of the TBM's shield of 35 kN, resulting in an average thrust force at the cutting wheel of 1231.7 kN respectively an average normal cutter force of 58.3 kN which results from the number of cutters. The evolution of these parameters and the resulting thrust force at the cutting wheel is shown in Fig. 7a. The thrust force of the main jack increased from 1000 kN at the beginning of the tunnel drive to almost 5000 kN at chainage 390 m, as shown in Fig. 7b. The advance of the TBM was supported by the first IJS installed some 35 m behind the TBM which was first used at chainage 320 m. This IJS experienced highest thrust force at the beginning of its deployment with almost 3500 kN, which then steadily decreased to less than 1500 kN. The most likely explanation for this observation could be improved lubrication, however, also changes in geology or alignment gradient can lead to more favorable friction conditions.

4.2. *Lubrication and skin friction*

Skin friction is an important parameter for any pipe jacking jobsite. The right amount of bentonite lubrication fluid has to be pumped to the annulus. If the amount of bentonite pumped into the annulus is too small, an incomplete lubrication film is created, which can cause partial contact between the pipe and the ground and thus extremely high friction. Overlubrication might also lead to disadvantages, such as blockage due to the high annular pressure or a washout of the annulus and potential bentonite blowout at the surface. Lubrication at the Landivisiau project was executed with an automated volume-controlled bentonite-system, which injects bentonite into the annulus according to the prevailing grain size and permeability of the surrounding geological units. Fig. 8a shows the evolution of the overall friction forces. For the

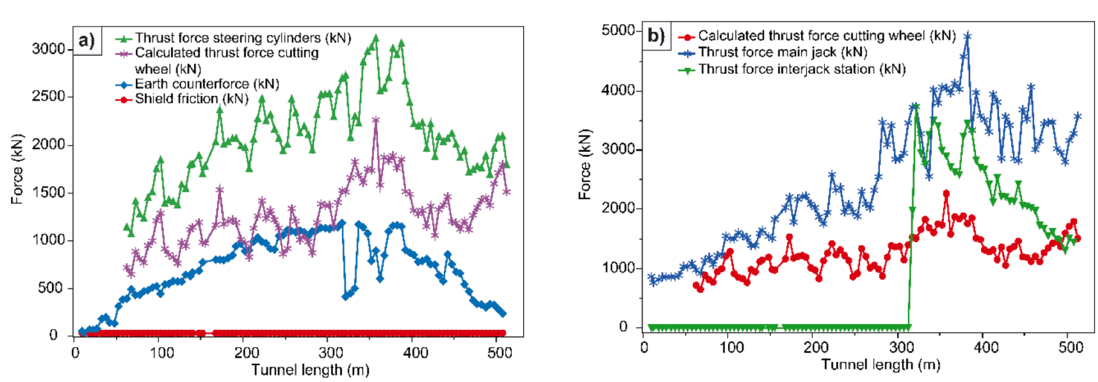

Fig. 7. a) Evolution of the parameters required to calculate the thrust force on the cutting wheel. b) Evolution of the main forces in the pipe jacking procedure: Main jack, interjack and cutting wheel.

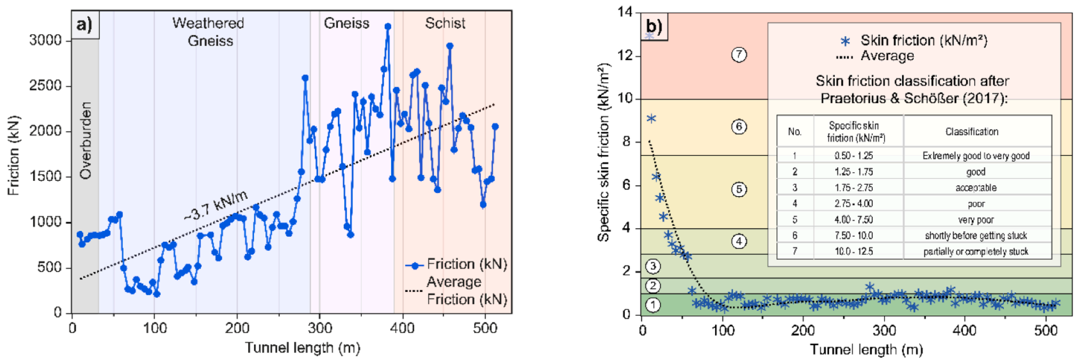

Fig. 8. Friction evolution: a) Total friction increases up to 390 m and then decreases slightly; b) Classification of the specific skin friction after Praetorius and Schößer (2017) and the corresponding values from the Landivisiau project.

Landivisiau jobsite, an increase in friction of 3.7 kN/m has been achieved during tunneling. A sharp increase in total jacking forces appeared after 290 m, coinciding with a change in geology (weathered to more competent rock). Even though it is impossible to accurately determine the reason for this increase, it is known form other jobsites that a transition from soft or weathered to more competent material can cause an accumulation of fine-grained material below the machine which leads to increase friction. Other possible explanation could be grinding of concrete pipes in (horizontal and vertical) curve section, rock wedges and a deficit in lubrication. It should be noted, that due to the deployment of an IJS from chainage 320 m, the friction calculation is only valid from the main jack to the IJS, placed some 30 m behind the TBM. The specific skin friction is more significant, as it gives a direct indication of the quality of the overall lubrication efficiency per square meter. Praetorius and Schößer (2017) state that values below 1.75 kN/m^2 can be considered as "good". At the Landivisiau project, the average skin friction was 1.2 kN/m^2. Fig. 8b shows a typical evolution of a well-lubricated pipe jacking operation. It starts with a high specific skin friction, resulting from the combination of the relatively high friction around the non-lubricated TBM shield and the still relatively small tunnel length. Hence, the lubricated area at the beginning of a pipe jacking drive is generally very small. However, with increasing drive length, these effects get less important and the specific skin friction decreases significantly. A low constant specific skin friction, as presented in Fig. 8b, indicates a successful lubrication regarding injected volume and the right properties of the lubrication bentonite.

5. Discussion

Given that at Landivisiau the rock strength of gneiss and schist varies considerably and reaches up to 185 MPa, the TBM advance rate also shows a high variance. Compared to larger hard rock TBMs, both the advance and penetration rates are relatively low but similar or even higher than comparable hard rock pipe jacking projects worldwide (Sheil et al., 2016). Fig. 9 shows that the schist requires higher thrust forces than the gneiss for the same or even lower penetration rates. This could be caused by the highly heterogeneous nature of the schists, its partially very high rock strength and potentially also a more ductile and thus less chipping-friendly behavior (Wilfing, 2016). The high variance in horizontal and vertical deviation could be explained by a small adjustment of the tunnel alignment during execution. The higher torque in the schist could be due to some weathered sections including clay material, causing a higher overall torque. The jacking forces are in line with or slightly below the forecasted 9000 kN. With the aid of an IJS, this force is reduced, saving thrust force and preventing any damage to the concrete pipes. The initial high forces at the IJS could be explained by initial jamming. Fig. 7a also shows the theoretical thrust force calculated prior to the project, which was higher than the values actually encountered. However, an IJS was highly recommended due to very

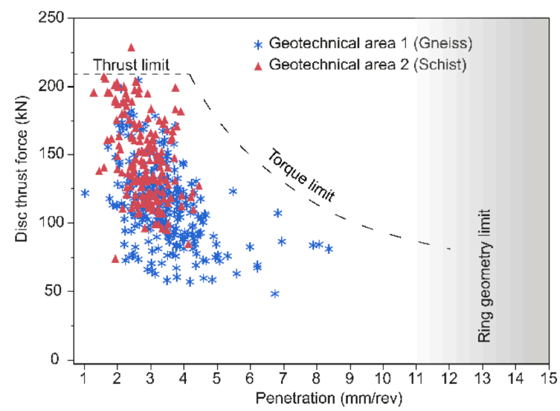

Fig. 9. TBM operating parameters in gneiss and schist.

high friction modelling results (10,000 kN) and the maximum load capacity of the concrete pipes of 7000 kN. In other words, the alignment could probably have been realized without IJS. However, the frequent disc replacement intervals and the rather low overall speed show the safety philosophy of the TBM operator and the contractor.

5.1. TBM parameter utilization

Another important aspect of TBM performance is the overall TBM parameter utilization. In this context there is no reference to the utilization factor for meters pers day commonly used in the literature, as it is not really suitable for determining the performance of the TBM during the unsteady pipe jacking process (Rispoli et al., 2019). Instead, refer to the utilization rate of the main drive parameters revolution, torque and thrust force (see Section 3.3). Note that the maximum technical specifications are given in Table 2. While the machine was operated at an average of 43% of its total installed revolution speed, 45% of the total installed torque was used, resulting in an overall used electrical performance of 52% of the total available power (Fig. 10a). However, the TBM can be operated at either high revolution or high torque, but not both at the same time (Fig. 10b). It either indicates that the machine is over-powered, or that less than half of the TBM's installed power has been used. This could again reflect a philosophy of finishing the drive safely, while accepting lower performance rates. This "philosophy" could be also seen at the thrust utilization rate, which varies between 40 and 110% (Fig. 10a). Considering the small diameter of the machine, possible damages to the machines and excessive wear have a much larger impact on the overall construction times and project success compared to large TBMs, where the repair and replacement of worn or damaged machine parts is much easier in comparison. These findings are important regarding ongoing and future approaches to TBM

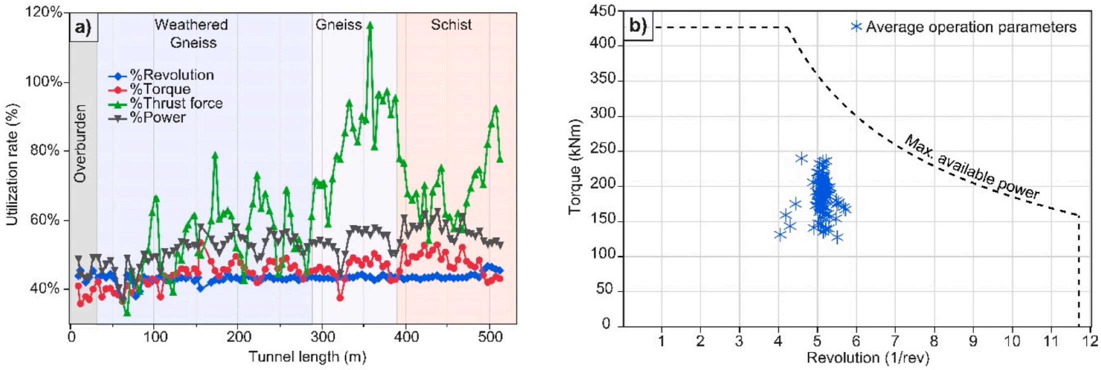

Fig. 10. Utilization of TBM parameters: a) Utilization rate for revolution, torque, thrust force, and electrical power. Please note that a higher torque means a lower revolution. Therefore, 100% is not achievable at both parameters. b) Drive parameters at Landivisiau.

automatization. An adjusted optimality definition (as e.g. in Garcia et al., 2021), required for an intelligent operating system, could mimic this "philosophy" or even several operation modes (e.g. high speed, economic, low wear) could be defined via the drive utilization parameters.

In order to push progress of automation in tunneling, there is also a need to draw attention to the importance of further use of data with respect to autonomous systems. For this purpose, technical and geological data needs to be collected more consistently across projects, TBM types, operators and geological conditions, as recommended by Garcia et al. (2021). Geotechnical project monitoring, which is also gaining importance in small-diameter pipe jacking projects, could further enhance the accuracy of technical and geological data.

5.2. *Wear of cutting tools*

In order to minimize damage to the TBM, its cutterhead and to prevent the machine getting stuck, all cutters were inspected and changed at every intervention, which was executed at regular intervals of 50 m due to the complex geotechnical conditions. This was also in response to the much higher CAI values encountered during tunneling in the gneissic zones. After 50 m, especially the caliber cutters were at the tolerable wear limit, which was measured with a wear gauge. Therefore, the early and pro-active change of the cutting tools prevented any significant damage to the cutters and the cutterhead. As a result, the entire alignment could be excavated safely and without unscheduled downtime.

5.3. *Penetration rate modelling*

The penetration rate was modelled with state-of-the-art penetration models suitable for projects with little available geological information. For a detailed description of the models see Gehring (1995), Rostami (1997), Hassanpour et al. (2011) and Farrokh et al. (2012). The modelling results are presented in Fig. 11. The Figure also shows the minimum, average and maximum advance rate as well as the 25th and 75th quartiles. Four scenarios with different rock strength (UCS) and corresponding tensile strength (with ratio 1/10) were calculated: 1) Average baseline rock strength of 38 MPa, 2) Average rock strength encountered during project execution (120 MPa), 3) Maximum rock strength encountered while tunneling (185 MPa), 4) Theoretical rock strength best fitting the CSM, Farrokh and Hassanpour models. While the CSM model is highly dependent on the UCS and tensile strength (TS), the Farrokh and the Hassanpour models highlight technical aspects of the TBM and are less dependent on geotechnical input factors. At the Landivisiau project, the CSM model is not suitable to adequately predict the archived penetration rates, while the Farrokh and Hassanpour models both achieve deviation rates of less than 1 mm/rev. The Gehring model underestimates the penetration considerably, probably caused by the lack of sufficient correction factors (i.e. rock mass information). The CSM models do not seem to be able to correctly predict the penetration rate of the Utility TBM used at Landivisiau, which could be caused by the semi-empirical nature, the lack of small-diameter pipe jacking TBMs in its database and by the low baseline UCS. Another explanation for the highly deviating results could be inaccurate UCS values from both, the exploration and monitoring-while-tunneling testing program. However, the accuracy of the UCS values is difficult to determine for a single small

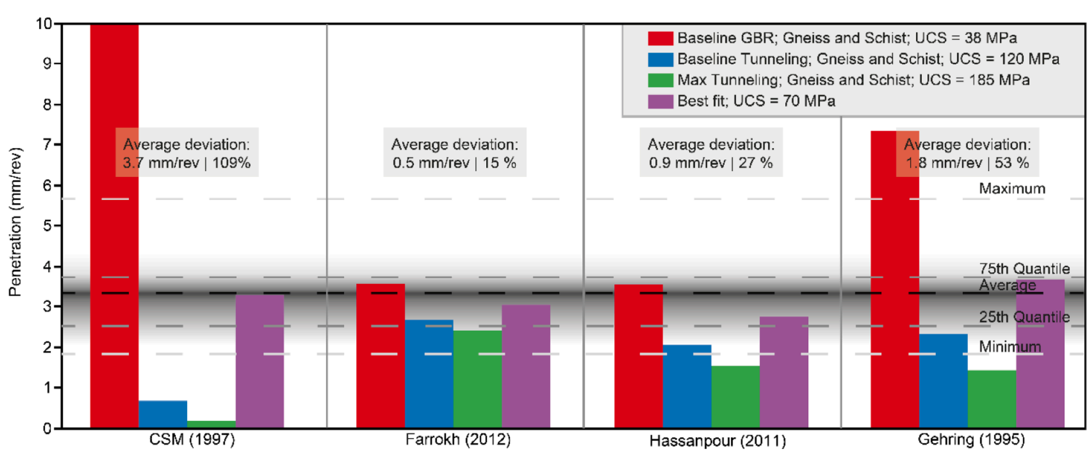

Fig. 11. Comparison of different penetration prediction models for the Landivisiau project. The black and grey dashed lines show the actual penetration rates achieved at the jobsite.

project. This study shows that especially the Farrokh model is very tolerant to changes in rock strength and can predict the penetration rate with sufficient accuracy for this project.

6. Conclusion and implications for practical engineering

This article presents the first comprehensive study of a long-distance pipe jacking project in very strong metamorphic rocks, as to date no such data has been published, analyzed and discussed in the literature. Accordingly, a hard rock pipe jacking project with over 530 m length in Landivisiau in Brittany, France is described. Heterogeneous Variscan gneiss and pre-Variscan schists with an UCS of up to 185 MPa and extremely high abrasivity were encountered and successfully excavated. The Landivisiau pipe jacking project is outstanding regarding rock strength, drive length, overburden, friction analysis and alignment gradients, considering that hard rock pipe jacking is nowadays applied worldwide and gains increasingly importance. Data analysis of this project leads to the following implications for practical engineering:

- Detailed construction site monitoring is critical as it can reveal significant differences in both the lithological description and geotechnical parameters, especially UCS and CAI.
- Close monitoring of bentonite lubrication, even in hard rock, significantly decreases the probability of getting stuck. This project shows that also in hard rock desirable specific skin friction values below 2 kN/m^2 can be reached after an initial ramp-up phase.
- The average penetration rate was 3.4 mm/rev, while the advance rate was 17.3 mm/min. The advance speed of this hard rock pipe jacking project is well below that of comparable segment lining projects, but similar to or above that of other hard rock pipe jacking projects (Sheil et al., 2016) and very good taking into account the TBM type, machine diameter, alignment length, steep gradients, partially low overburden, low friction, high rock strength and abrasivity.
- However, the focus of the presented and many other pipe jacking projects is not maximum advance speed, but on safe excavation from the launch shaft to the reception shaft as it prevents longer downtimes and severe damages to the TBM. This philosophy is evident in low revolution, torque, thrust and overall power utilization rates as well as in regular cutterhead inspection and cutter replacement intervals.
- The Farrokh et al. (2012) model was best suited to predict the performance of the Landivisiau utility tunneling project with an average deviation of only 0.5 mm/rev.

Further research is required to analyze the performance data of multiple small-diameter utility projects. For these projects, due to their small size, special emphasis must be placed on the data quality and correctness as shown in an initial approach in this paper. For performance prediction, several conventional models and projects varying in diameter, rock, lining, TBM type and cutterhead need to be compared. Furthermore, future work needs to focus on an improved performance prediction and the application of machine learning models to small-diameter utility projects for both, pipe jacking and segment lining TBMs.

CRediT authorship contribution statement

Gabriel Lehmann: Methodology, Writing – original draft, Writing – review & editing, Formal analysis, Investigation, Data curation, Visualization, Project administration, Funding acquisition. **Heiko Käsling:** Conceptualization, Writing – review & editing, Supervision. **Alexandre Cambier:** Resources, Writing – original draft. **Steffen Praetorius:** Investigation, Writing – review & editing. **Kurosch Thuro:** Supervision.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Gabriel Lehmann reports financial support was provided by Herrenknecht AG.

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Appendix A-2

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Analysis and prediction of small-diameter TBM performance in hard rock conditions

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ABSTRACT

Analysing and predicting the advance rate of a tunnel boring machine (TBM) in hard rock is integral to tunnelling project planning and execution. It has been applied in the industry for several decades with varying success. Most prediction models are based on or designed for large-diameter TBMs, and much research has been conducted on related tunnelling projects. However, only a few models incorporate information from projects with an outer diameter smaller than 5 m and no penetration prediction model for pipe jacking machines exists to date. In contrast to large TBMs, small-diameter TBMs and their projects have been considered little in research. In general, they are characterised by distinctive features, including insufficient geotechnical information, sometimes rather short drive lengths, special machine designs and partially concurring lining methods like pipe jacking and segment lining. A database which covers most of the parameters mentioned above has been compiled to investigate the performance of small-diameter TBMs in hard rock. In order to provide sufficient geological and technical variance, this database contains 37 projects with 70 geotechnically homogeneous areas. Besides the technical parameters, important geotechnical data like lithological information, unconfined compressive strength, tensile strength and point load index is included and evaluated. The analysis shows that segment lining TBMs have considerably higher penetration rates in similar geological and technical settings mostly due to their design parameters. Different methodologies for predicting TBM penetration, including state-of-the-art models from the literature as well as newly derived regression and machine learning models, are discussed and deployed for backward modelling of the projects contained in the database. New ranges of application for small-diameter tunnelling in several industry-standard penetration models are presented, and new approaches for the penetration prediction of pipe jacking machines in hard rock are proposed.

1. Introduction

Due to the ongoing trend of placing and expanding infrastructure underground, small-diameter tunnelling is gaining importance all over the world (Sterling, 2020; Ong et al., 2022). This trend is driven by major global developments like the accelerating worldwide energy transition, continuing urbanisation, and the expansion of economically emerging regions. As a result, small-diameter tunnelling is being used more frequently in the modernisation and expansion of underground infrastructures (Stein, 2003; Schmäh and Peters, 2018; Schmäh et al., 2021). These utility tunnels cover a broad application field, including wastewater, stormwater, freshwater, optical fibre, hydropower, pipeline casing and cable tunnels. In contrast to traffic tunnels, they are typically characterised by an outer diameter range between 1 and 5 m, even though some distinct exceptions exist, especially in the broad hydropower application field. Utility tunnelling generally means pipe jacking or segment lining in combination with small-diameter TBMs and offers a high degree of reliability in terms of safety for people, construction times and budget (Matthews et al., 2015). Besides the advantage of a reduced surface space requirement, the method is significantly more environmentally friendly than conventional technology (e.g. cut and cover) (Najafi and Kim, 2004; Hunt et al., 2014; Lu et al., 2020; Ong et al., 2022). A comparison of the conventional cut-and-cover method and utility tunnelling technology revealed a six times smaller CO_2 footprint for the mechanised technology (Tavakoli et al., 2017).

From a technical point of view, utility tunnelling can be described as

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highly heterogeneous and variable (Girmscheid, 2008; Maidl et al., 2012; Schmäh et al., 2021; Lang and Lehmann, 2022). Depending on the project-specific and geological conditions, utility tunnels can be constructed with different mechanised technologies such as slurry TBMs, earth pressure balance (EPB) TBMs, single and double shield TBMs, gripper TBMs or partial-face TBMs (Girmscheid, 2008; Maidl et al., 2012; Girmscheid, 2013). There are also significant variations in lining possibilities, which, strongly depending on the geotechnical conditions and the machine technology deployed, can range from no lining at all to rib and lagging, classic segment lining and pipe jacking. Pipe jacking is probably the most widely used method in utility tunnelling (Stein, 2003; Lang, 2017). Furthermore, it can be combined with various machine types, whereby combination with a slurry TBM is probably the most commonly deployed and versatile combination in utility tunnelling, especially in microtunnelling (Stein, 2003; Sterling, 2020). Fig. 1 summarises the application ranges of the most common lining and TBM types and their recommended geotechnical application fields.

The demand for small-diameter hard rock tunnelling using pipe jacking has been growing, particularly as the energy transition progresses. Additionally, there is growing emphasis on improving the performance and efficiency of these drives. However, because of rather small technical and financial project sizes compared to large tunnelling project schemes, very little has been published about such hard rock pipe jacking projects (Sterling, 2020). Even though slurry TBMs, in combination with pipe jacking, have been deployed in hard rock for several decades, their application in hard rock is still a growing application in utility tunnelling (Grasso et al., 1996; Frank, 1999; Sofianos et al., 2004; Hunt and Del Nero, 2009; Bradshaw, 2014; Sheil et al., 2016). In general, such smaller-size projects are characterised by very limited geotechnical information due to a limited budget for exploration and onsite geotechnical campaigns. However, such projects are highly interesting because small TBMs reach their technical limits more quickly in hard rock, but as indicated above, very few project data are available regarding the advance rates and prediction of performance and wear (Rostami, 1997; Hassanpour et al., 2011; Farrokh et al., 2012; Xu et al., 2021). To address this lack of knowledge, a comprehensive database with 37 small-diameter projects, including all relevant TBM types, lining types and various geological units, was established. Subsequently, this data was analysed in detail to understand better the interaction between small-diameter TBMs and their deployment in hard rock. Finally, an approach for the improved penetration prediction of utility tunnelling TBMs is presented.

For the estimation of the economic efficiency of any tunnel construction jobsite, the construction duration, which in turn depends on the advance and penetration rate, is crucial (Cardu et al., 2021). Therefore, numerous prediction models have been developed to estimate the advance rate. In particular, a large number of models have been developed for penetration rate estimation in hard rock, which is probably the most important driving parameter for performance modelling (Büchi, 1984; Rostami and Ozdemir, 1993; Gehring, 1995; Yagiz, 2006; Alber, 2008; Hassanpour et al., 2011; Farrokh, 2012; Rostami et al., 2014; Brino and Peila, 2015; Macias, 2016; Wilfing, 2016; Entacher and Rostami, 2019; Wang et al., 2020; Jing et al., 2021). However, most of these models are limited to evaluating tunnelling in the same rock types and do not represent a reliable prediction in other geologies. Examples for studies on site-specific hard rock TBM performance analysis and prediction are the Lötschberg (Delisio et al., 2013), Brenner (Rispoli et al., 2020) and the La Maddalena tunnel in the Alps (Armetti et al., 2018) as well as the Songhua River water supply project in limestone strata in Jilin, China (Jing et al., 2019). Such highly specific models are often closely associated with the use of artificial intelligence models (Armaghani et al., 2019; Salimi et al., 2019; Gao et al., 2020; Li et al., 2020; Afradi and Ebrahimabadi, 2021; Zhou et al., 2021a). In particular, research into small-diameter tunnelling performance in soil and loose rock has been largely neglected, and predictions are based on the experience of TBM manufacturers and contractors (Geng et al., 2016; Macias et al., 2020; Goodarzi et al., 2021; Lehmann et al., 2022). More strikingly, the projects in the databases used for the TBM prediction can be quite old (going back to the 1960 s) and thus neglect advancements in machines technology. Furthermore, the actual drive parameters, like operating thrust, are often unavailable. Thus, it was assumed that the TBMs operated close to the design values, which, as this work demonstrates, is commonly incorrect.

Experience shows that most common prediction models either require input data unavailable for small-diameter projects or fail to accurately predict the penetration and advance rate of small TBMs in hard rock. This observation is also closely linked to the fact that these models were developed for larger-diameter projects with well-known geotechnical parameters (Rostami, 1997; Macias and Barton, 2022). To the knowledge of the authors, there is no explicit penetration prediction model for the increasingly important pipe jacking projects, and here too, the use or adaptation of existing models is commonly applied in the industry. In order to quantify the accuracy of existing models, eleven models which require very limited geotechnical input data have been considered for comparison of the penetration prediction accuracy (Table 1).

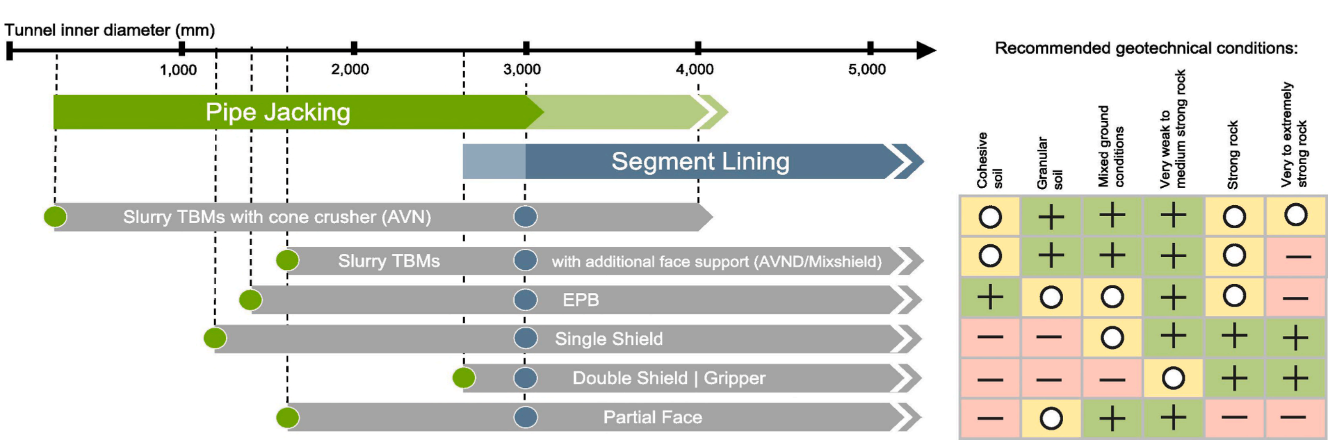

Fig. 1. Application range of the most important lining and TBM types within the utility tunnelling field and its application in different geotechnical conditions (according to DAUB (Deutscher Ausschuss für unterirdisches Bauen e.V., 2021), ISRM (ISRM, 1980) and Herrenknecht AG). (+) means recommended application range, (o) means feasible, but the application needs to be verified, and (-) means the application is not recommended or not feasible.

Table 1
TBM performance models with limited geotechnical input requirements.

Reference:	Comment:	Model based on:
Rostami (1997)	Updated CSM model: $PR = f(F_N, F_r)$	Linear cutting machine tests with limestone (70 MPa), granite (140 MPa) and basalt (280 MPa); validation with 4 gripper TBM projects in massive rocks with UCS ranges from 20 to 45 MPa and 150–270 MPa.
Farrokh et al. (2012)	$PR = \exp(0.41 + 0.404*D - 0.027*D^2 - 0.0691*RT_C - 0.00431*UCS + 0.0902*RQD_C + 0.000893*F_N)$	Large database with 17 hard rock TBM projects between 2.6 and 11.8 m, mostly in Iran and Italy, all terminated before 2010.
Farrokh (2012)	Empirical model based on CAI: $FPI = \exp(1.97 + 0.0063*RQD + 0.103*CAI + 0.00685*UCS)$	Large database with 17 hard rock TBM projects between 2.6 and 11.8 m, mostly in Iran and Italy, all terminated before 2010.
Gehring (1995)	Commonly applied in the Alps: $PR = F_N/UCS*k_i$	4 hard rock projects with UCS values mostly between 120 and 200 MPa.
Hassanpour et al. (2009a)	Hard rock model based on Nowsood tunnel 2: $PR = F_N/(\exp(0.004*UCS + 0.008*RQD + 2.077))$	49-km-long Nowsood water conveyance tunnel in Iran in sedimentary rocks with UCS values between 15 and 150 MPa.
Hassanpour et al. (2009b)	Based on information from two projects: $FPI = 0.425*RMCI + 11.28$	16 + 8.7-km-long Karaj water conveyance tunnel in Iran in sedimentary and volcanic rocks with UCS values between 30 and 100 MPa.
Hassanpour et al. (2011)	Based on four tunnels: $FPI = \exp(0.008*UCS + 0.015*RQD + 1.384)$	4 projects in Iran and New Zealand of approximately 75 km in length in total. UCS between 15 and 225 MPa.
Goodarzi et al. (2021)	Soft rock model based on four projects: $PR = \exp(0.006*F_N - 0.016*UCS + 1.833)$	4 projects in the Zagros mountains in Iran, mostly in soft sedimentary rocks (generally $\ll$ 100 MPa).
Hughes (1986)	For sandstone and penetration rate of up to 10 mm/rev: $PR = 1.667*(F_N/UCS)^{1.2}*(2/D)^{0.6}$	TBM deployment in coal-bearing sedimentary rocks in England with UCS values generally < 100 MPa.
Wilfing (2016)	Preliminary model based on Gehring's model and Koralm tunnel: $PR = (F_N - b_{BTS/LBC})/UCS*k_0*k_2*k_i + 3$	Data from Koralm tunnel penetration tests and the Gehring model.
Xu et al. (2021)	Regression model based on 3 projects: $PR = 66.411*RMCI^{-0.482}$	3 projects (double shield and gripper) in China with large geotechnical variability. TBM diameter between 6 and 8 m.

PR = penetration rate, F_N = cutter thrust force, F_r = cutter rolling force, D = cutterhead diameter, RTc = rock type code (Farrokh et al., 2012), RQDc = RQD class (Farrokh et al., 2012), FPI = field penetration index, UCS = unconfined compressive strength, CAI = CERCHAR abrasivity index, ki = correction factor, RQD = rock quality designation, RMCI = rock mass cuttability index, LBC = LCPC breakability coefficient.

2. Material and methods

Geological and machine drive data processing is an important aspect of data analysis that affects several phases of the construction process of a tunnel excavated with a TBM (Rispoli et al., 2019). It is of special importance for small-diameter projects, as no data pre-processing was undertaken for most past research projects. In total, in this work, data from 37 tunnelling projects has been gathered, pre-processed and analysed. Depending on the project size and location, different ways of data gathering were pursued:

- Projects with geotechnical and drive data from TBM suppliers.
- Projects with data directly gathered at the job sites with the permission of the owner, construction company and/or consultant.
- Projects lacking geodata. Here additional samples were gathered during tunnelling and analysed.

However, comparing data with different machine and lining types, diameters, utilisation types, countries, and suppliers poses special challenges to data processing. As stated in Rispoli et al. (2019), the exact nature of some TBM parameters provided by the data acquisition system is sometimes difficult to obtain but extremely important for the correct analysis of the data. Lehmann et al. (2022) pointed out that some small-diameter TBMs have a hydraulic main drive which makes a correction to the torque calculation necessary. Furthermore, Lehmann et al. (2022) described a procedure for correctly calculating the thrust force at the cutterhead and drive parameter utilisation factors, which are also deployed for dataset creation.

2.1. Creation of the dataset

As stated in Lehmann et al. (2023), all information needs to be submitted in the same format to be able to use it for predictions in tunnel projects. Therefore, verifying the geotechnical information before organising and filtering raw data is crucial. In addition to geotechnical field and lab parameters, a detailed geotechnical cross-section provides the necessary information for combining technical and geological data. Once it has been confirmed that there is sufficient high-quality geodata available, the processing of machine data can begin. The first step is to ensure that tunnelling progresses continuously. While newer data acquisition systems may do this automatically, older data packages may require manual removal of downtime sections (e.g. during pipe changes, revisions or holidays). The machine data obtained in this way can be used to calculate the penetration rate, the thrust force per cutter and the torque. Finally, the data is filtered using reasonable values from the TBM specifications, which must be carefully selected and interpreted based on the specific project and TBM. The data is then averaged at intervals like 0.1 or 1 m to evenly distribute the TBM operational data over time rather than along the length of the alignment. If this averaging is not performed, there will be many data points in areas of slow progress and fewer in areas of fast progress, especially when averaging for the entire tunnel or homogeneous areas (Entacher and Rostami, 2019).

The information included in the database can be clustered into TBM parameters, cutterhead design parameters, geotechnical parameters, machine drive parameters and project parameters. Table 2 gives further details on the information contained in the database. In contrast to the technical data, data on geomechanical parameters beyond strength are often unavailable, inadequate or of poor quality for small-diameter projects. Such projects often face limited financial resources leading to constraints in acquiring a comprehensive geotechnical dataset. The restricted budget may hinder conducting extensive site investigations, resulting in a limited quantity and quality of geotechnical data. This limitation can lead to uncertainties, potential risks, and challenges during the planning, design, and construction phases of the project.

Table 2
Summary of the parameters included in the database.

TBM parameters	Cutterhead design	Geotechnical parameters	Machine drive parameters	Project parameters
• Machine designation • Manufacturer • Machine type • Cutting head type • Lining type • Cutting diameter • Main bearing load • Power • Max. torque • Max. revolution speed • Drive efficiency	• Quantity of cutters • Number of cutters without centre • 2-ring cutters • 3-ring cutters • Centre cutters • Cutter type • Cutter size • Max. load per cutter • Sum track radii • Number of cutter rings • Average face spacing • Cutter ring width • Total disc load	• Dominant lithology • Mean, min. and max. unconfined compressive strength (UCS) • Mean, min. and max. tensile strength (TS/BTS) • Mean, min. and max. point load index (PLI) • Mean, min. and max. CERCHAR abrasivity index (CAI) • Mean, min. and max. rock quality designation (RQD) • Rock mass rating (RMR) • Q-value • Alteration (estimation) • Fracture density (estimation)	• Advance rate • Penetration rate • Torque • Working pressure • Revolution speed • Thrust force • Supporting pressure	• Name • Country • Alignment length

2.2. Level of detail

As shown in Fig. 2 and similar to the procedure proposed by Farrokh et al. (2012), three database levels were used and adapted to the requirements of small-diameter projects. The first level of detail is the tunnel project (TP) itself, containing all accessible data. From the launch to the exit point, geotechnical, machine-related, and project-specific information is ideally incorporated. All parameters are given mean and median values, with potentially highly changeable geotechnical factors like differing lithologies or strength values being ignored.

The second level of detail is the homogeneous geotechnical area (HGA), which is defined by similar geotechnical conditions. An HGA is generally characterised by only one lithology, with minimal variation within the geotechnical properties. Therefore, only the corresponding area with uniform geotechnical conditions is used to determine the average machine parameters.

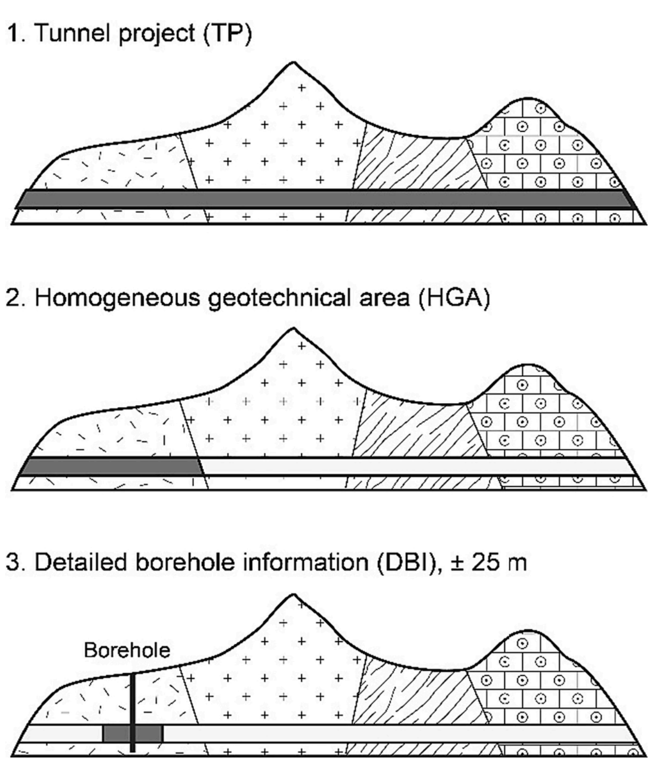

Fig. 2. Detail levels included in the small-diameter hard rock tunnelling database (modified after Farrokh et al. (2012)).

The third level of detail is the detailed borehole information (DBI). It is based on "point-like" geotechnical data, primarily from exploratory drilling or drilling done during tunnel construction. Then, this geotechnical data is averaged for the respective DBI for a distance of about 25 m around the (vertical) projection of the borehole on the tunnel alignment.

As also stated in Lehmann et al. (2023), the 25 m interval for averaging machine data with geotechnical data is necessary due to the highly diverse nature of the data in the database. In order to achieve high accuracy with the drive data, it would be ideal to have an even more narrow averaging region around the geotechnical information. However, some drive datasets have a resolution > 1 m. It is important for the geotechnical data to be representative of the area surrounding the borehole where it was collected, even if the distances to the tunnel axis may differ. A comparative analysis was conducted on all projects to determine the appropriate interval for averaging machine data with geotechnical data. It was noted that the geological conditions might vary considerably over a few metres, and the boreholes are sometimes several tens of metres away from the tunnel route. The results showed that an interval of 1 m would lead to extremely fluctuating results as it would barely cover the diameter of the smallest machine in the database (1001 mm), while an interval of 100 m would result in excessively aligned and over-averaged results. Therefore, an interval of 25 m was chosen for this data analysis, which can be justified by the arguments provided.

2.3. Data quality

When comparing tunnelling data from different sources with different machines, geological conditions, contractors, TBM suppliers etc., several aspects of data quality and quantity need to be taken into account. Additionally, project-specific and machine-specific parameters must be obtained from the construction company and TBM manufacturer. There is a significant amount of variability in TBM drive data. Some of the key differences to consider include the technical variance (such as TBM type, cutterhead type and geometry, excavation tools, and support method), data collection variance (including frequency, parameter and sensor labelling, units, sensor reliability and accuracy, data format, and the availability of sensors), and short-term changes (like technical parameters that may be changed shortly before the project begins). A comprehensive geological profile or subsurface model is crucial for combining TBM and geotechnical data. While digital underground or construction models are not yet common in small-diameter tunnelling, most profiles (if available) are either hand-drawn or computer-drawn 2D representations with varying quality. Geological data is often inconsistent, with known issues such as the varying resolution of geotechnical data (which may depend on the country and size of the tunnel), selection of samples being highly dependent on job site personnel, variability in testing results even when the same standard method is used, and discrepancies between the actual tunnel course of the TBM and the information given in the geotechnical profile.

2.4. Database structure

The database includes utility tunnelling projects with cutting diameters mostly below 5 m. It includes technical and geological information from projects executed in their majority in the last 10 years. They are distributed over 18 different countries on five continents, as illustrated in Fig. 3. The database is structured in 37 projects with > 73 km total tunnel length, 58 km with segment lining projects, 8.3 km with pipe jacking projects and the rest with gripper or rib and lagging projects, making it one of the largest and most up to date TBM databases. In total, it includes almost 635,000 data points distributed within 70 homogeneous areas or 1286 detailed borehole information data points.

The average length of a previously described homogenous area is around 1000 m. It includes hard rock projects executed with slurry shield, double shield, EPB and gripper TBMs. However, it has to be stated that most slurry shield TBMs are indeed AVN machines (small-diameter slurry TBMs with a cone crusher – Automatische Vortriebsmaschine Nass) and deployed with the pipe jacking principle. This combination represents most of the projects smaller than 3 m outer diameter. Different to other databases, a wide lithological variety is given with projects in sedimentary rocks (26 km), metamorphic rocks (32 km) and magmatic rocks (15 km) (Table 3).

Fig. 4a shows the distribution of the TBM types in the database, while Fig. 4b compiles the lining types and Fig. 4c the TBM diameter distribution. The most important geotechnical parameters are given in Fig. 4d–i. Fig. 4d–f show the frequency of unconfined compressive strength (UCS) values, tensile strength (TS) values and point load index (PLI) values, respectively. Fig. 4g shows the rock quality designation (RQD), and Fig. 4h the rock mass rating (RMR). Fig. 4i shows the frequency of the rock mass quality index Q (Barton et al., 1974). Fig. 4j and 4 k show the frequency of the penetration rate and the revolution speed for all types of TBMs and linings. Finally, the cutter thrust force in Fig. 4l is given per ring for 2- or 3-ring cutters.

From the distribution of the UCS values, it can be inferred that the majority of the utility tunnelling projects are executed in rock strengths well below 100 MPa. On average, information (as defined above) exists for one borehole every 55 m. The distribution of the drive parameters is illustrated in Fig. 4j–l. Clear differences can also be seen in the length of the projects (Fig. 3). While segment lining projects in the database have an average length of 4463 m, the length of an average pipe jacking project is considerably lower, at 415 m.

3. Results

This section presents the current state of the art of small-diameter TBM performance in hard rock, including performance parameters from worldwide projects. Within this section, individual parameters and not parameter combinations are compared.

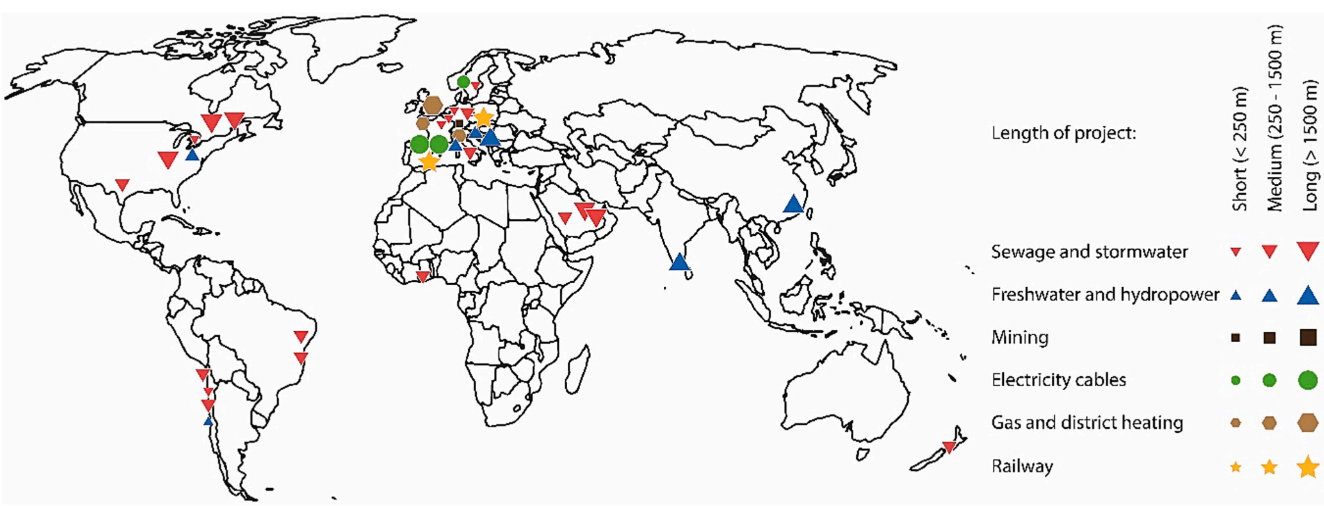

Fig. 3. Spatial distribution of the 37 utility tunnelling projects included in the small-diameter hard rock tunnelling database and their respective project length. Please note that the drive length might have been longer, but only the length of the usable data is represented.

Table 3
Distribution of summarised drive lengths in different lithological units.

Magmatic rock type	Drive length (m)	UCS (min. - avg. - max.) (MPa)	Metamorphic rock type	Drive length (m)	UCS (min. - avg. - max.) (MPa)	Sedimentary rock type	Drive length (m)	UCS (min. - avg. - max.) (MPa)
Granite	8881	3 - 88 - 291	Gneiss	7506	5 - 205 - 42	Chalk	4866	3 - 16 - 9
Granodiorite	1581	3 - 223 - 67	Granulite	856	69 - 156 - 111	Limestone	14,887	8 - 196 - 37
Diorite	1846	19 - 370 - 99	Schist	21,223	32 - 200 - 99	Sandstone	2783	1 - 238 - 68
Gabbro	1081	1 - 199 - 49	Weathered schist	2918	7 - 197 - 45	Shale	3537	1 - 64 - 33
Basalt	1274	18 - 132 - 50						

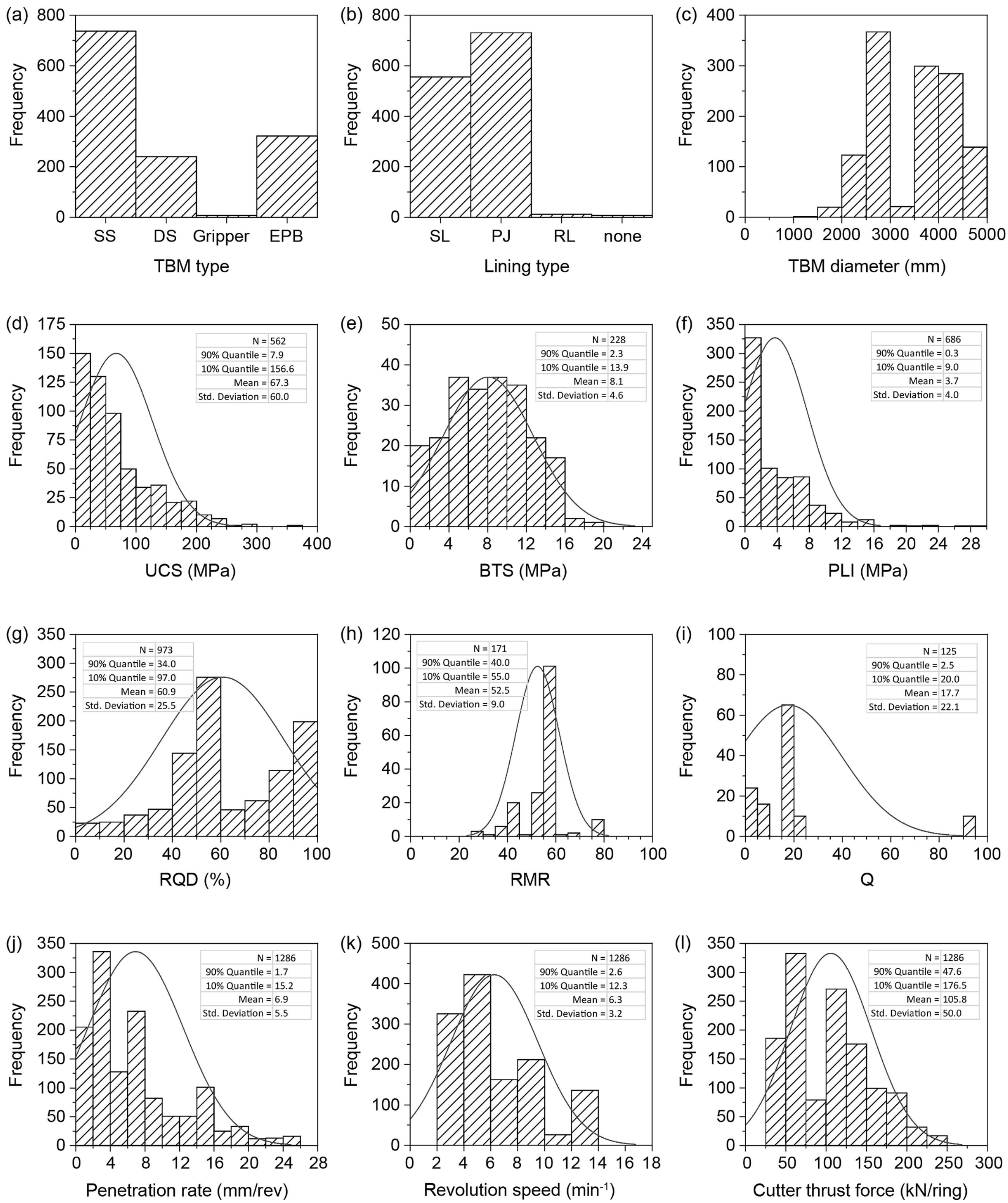

Fig. 4. Variability of the utility TBM database comprising project data (a-c), geotechnical data (d-i), and machine drive (j-l) data. Please note that the frequency (amount of data points per parameter) of the values shown refers to individual values, the detailed borehole information (DBI). SS = slurry shield (mostly AVN(D) machines), DS = double shield, EPB = earth pressure balance, SL = segment lining, PJ = pipe jacking, RL = rib and lagging. Note that not all geotechnical values are available for all projects.

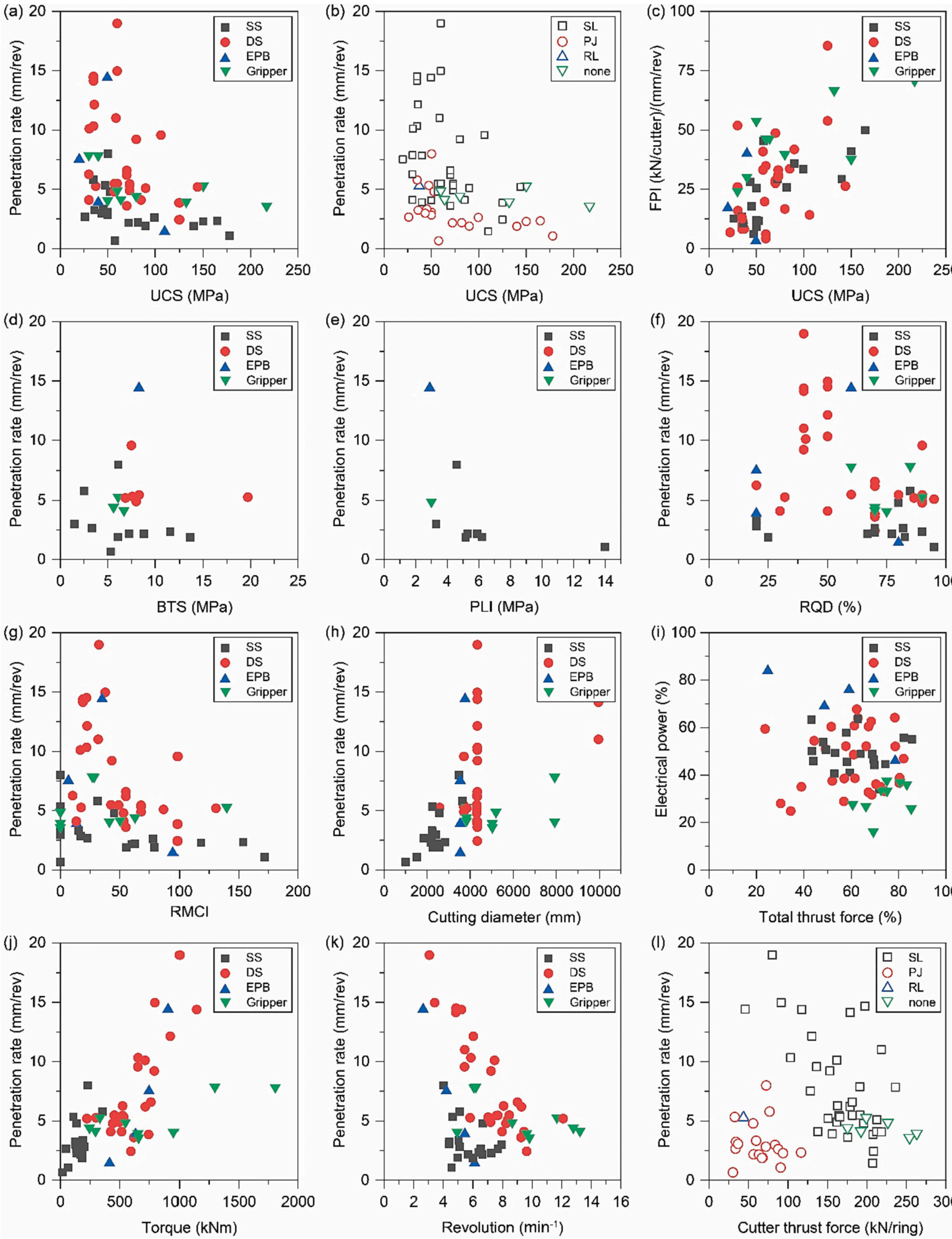

Fig. 5. TBM penetration and performance analysis for small-diameter projects in rock for homogeneous geotechnical areas (HGAs), partly based on Lehmann et al. (2023). Please note that most pipe jacking TBMs are equipped with 2- or 3-ring cutters. UCS = unconfined compressive strength, FPI = field penetration index, TS = tensile strength, PLI = point load index, RQD = rock quality designation, RMCI = rock mass cuttability index, SS = slurry shield (mostly AVN(D) machines), DS = double shield, EPB = earth pressure balance, SL = segment lining, PJ = pipe jacking, RL = rib and lagging.

3.1. Utility TBM performance analysis

The homogeneous geotechnical areas (HGA) for the performance analysis are presented in Fig. 5. The detailed borehole information (DBI) with over 1200 individual points shows a much wider scattering. The first seven subfigures (Fig. 5a to 5g) show the relationship between penetration rates or field penetration index (FPI) and various geotechnical parameters commonly available in utility tunnelling projects. The FPI is defined as the ratio between the cutter thrust force and the penetration rate, which is equal to the inverse specific penetration rate. The remaining five subfigures show the relationship between the penetration rate and machine engineering parameters as well as the overall utilisation of utility TBMs.

There is a clear link between the UCS and the penetration rate. High UCS values result in a low penetration rate, while compressive strengths below 100 MPa may or may not result in a high penetration rate (Fig. 5a). However, most small-diameter projects in hard rock obtain a penetration rate between 3.3 and 8.4 mm/rev (lower and upper

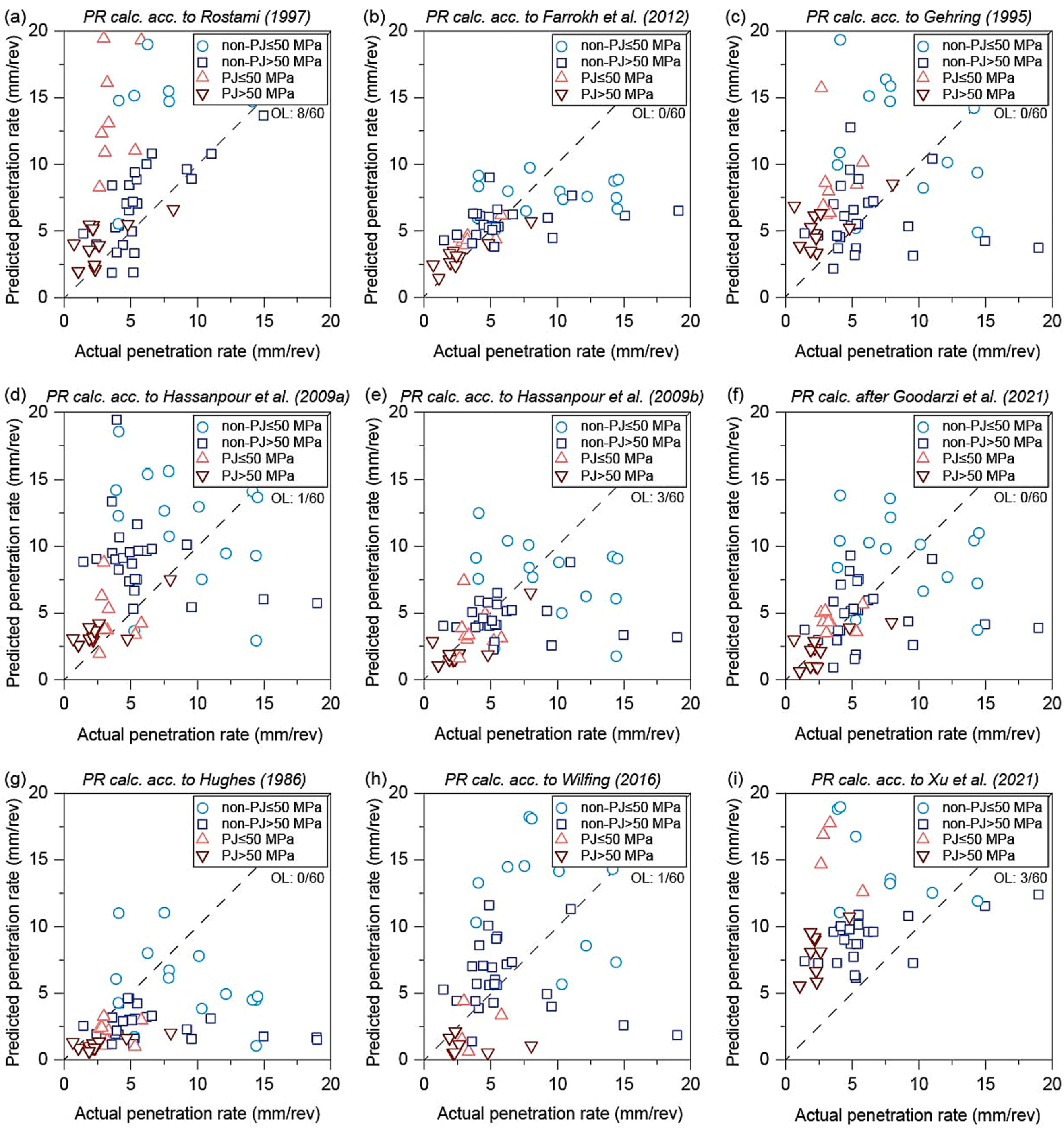

Fig. 6. Comparison of selected penetration prediction models for homogenous geotechnical areas (HGA) with different strength (UCS) parameters. PJ = pipe jacking, non-PJ = segment lining, rib and lagging or no lining. Strength values are given as unconfined compressive strength (UCS). OL = outliers (values not depicted in the plots).

quartile). Despite low strengths, there are some projects with lower penetration rates. These are typically the projects excavated by small-diameter slurry TBMs (more correctly designated AVN machines because of the small diameter and the cone crusher). Fig. 5b also shows that these projects are pipe jacking projects with average penetration rates between 2 and 4.4 mm/rev. Overall, there is a clear distinction here: segment lining projects have, on average, a penetration rate almost 3 times higher (4.5–10.8 mm/rev) than pipe jacking projects in rocks with the same compressive strengths. For the FPI index, a quasi-linear trend is evident in conjunction with increasing UCS. The FPI was chosen to normalise the influence of different disc sizes and contact forces (Fig. 5c). The advantage of FPI is that it eliminates the influence of two important TBM operating parameters: thrust force and revolution speed of the TBM. However, the use of FPI suggests a linear relationship between thrust and penetration rate, which is not true, as a non-linear relationship between the two parameters has been demonstrated both in the laboratory and in the field (Wilfing, 2016; Yagiz, 2017).

Fig. 5d shows the relationship between tensile strength and penetration rate. No distinctive trend can be seen here. The number of points is limited, as is the point load index (Fig. 5e) since these parameters have not been determined for many projects. However, despite its low number of values, the point load index shows a good correlation with the penetration rate, as stated in Wilfing (2016).This is also evident in the DBIs. No clear trend can be seen between the RQD and the penetration rate (Fig. 5f). The rock mass cuttability index (RMCI), on the other hand, behaves similarly to the UCS (Fig. 5g), from which it is calculated

Table 4
Ranking of the accuracy of selected penetration prediction models for homogeneous geotechnical areas (HGA).

	First	RMSE (mm/rev)	MAPE (%)	Second	RMSE (mm/rev)	MAPE (%)	Third	RMSE (mm/rev)	MAPE (%)
All (n = 61)	Farrokh et al. (2012)	3.65	39.64	Goodarzi et al. (2021)	4.29	63.96	Gehring (1995)	5.30	54.68
PJ ≤ 50 MPa (n = 8)	Farrokh et al. (2012)	1.26	26.75	Goodarzi et al. (2021)	1.50	41.09	Hassanpour et al. (2009b)	2.09	41.32
PJ > 50 MPa (n = 11)	Farrokh et al. (2012)	1.18	31.55	Rostami (1997)	1.12	52.01	Hassanpour et al. (2009b)	1.27	50.35
Non-PJ ≤ 50 MPa (n = 16)	Farrokh et al. (2012)	5.27	52.49	Goodarzi et al. (2021)	6.01	65.34	Hassanpour et al. (2009b)	6.26	61.72
Non-PJ > 50 MPa (n = 26)	Rostami (1997)	2.37	32.40	Farrokh et al. (2012)	3.61	39.11	Xu et al. (2021)	4.44	88.82

PJ = pipe jacking, non-PJ = segment lining, rib and lagging or no lining. Strength values are given as unconfined compressive strength (UCS), RMSE = root-mean-square error, MAPE = mean average percentage error.

Table 5
Ranking of the accuracy of selected penetration prediction models for detailed borehole information (DBI).

	First	RMSE (mm/rev)	MAPE (%)	Second	RMSE (mm/rev)	MAPE (%)	Third	RMSE (mm/rev)	MAPE (%)
All (n = 466)	Farrokh et al. (2012)	4.20	45.17	Goodarzi et al. (2021)	5.14	75.52	Hassanpour et al. (2009a)	6.04	99.14
PJ ≤ 50 MPa (n = 79)	Farrokh et al. (2012)	2.45	41.96	Goodarzi et al. (2021)	3.20	105.11	Gehring (1995)	3.45	56.22
PJ > 50 MPa (n = 121)	Farrokh et al. (2012)	1.75	38.65	Goodarzi et al. (2021)	2.25	60.46	Hassanpour et al. (2009a)	2.40	79.77
Non-PJ ≤ 50 MPa (n = 107)	Farrokh et al. (2012)	6.80	71.79	Goodarzi et al. (2021)	7.59	70.29	Rostami (1997)	7.73	78.39
Non-PJ > 50 MPa (n = 159)	Farrokh et al. (2012)	3.91	60.21	Rostami (1997)	5.28	79.30	Xu et al. (2021)	5.32	85.18

PJ = pipe jacking, non-PJ = segment lining, rib and lagging or no lining. Strength values are given as unconfined compressive strength (UCS), RMSE = root-mean-square error, MAPE = mean average percentage error.

Table 6
Simple linear regression models for penetration prediction of small-diameter TBMs in hard rock.

			Homogenous geotechnical areas > 15 MPa		Detailed borehole information > 15 MPa	
Mode	**Regression**	**Formula**	**RMSE (mm/rev)**	**MAPE (%)**	**RMSE (mm/rev)**	**MAPE (%)**
All	Equation 1	$PR = 7.731 - 0.01086*UCS - 0.009367*F_N - 0.00007563*D - 0.1947*Rev + 0.004349*M - 0.09088*TS$	**2.78**	**35.03**	6.02	96.02
PJ ≤ 50 MPa	Equation 2	$PR = -7.337083 + 0.080050*UCS-0.098196*F_N + 0.001679*D + 1.093971*Rev + 0.016773*M + 0.077934 * TS$	**0.54**	**8.18**	2.77	54.72
PJ > 50 MPa	Equation 3	$PR = -5.9033–0.041611*UCS-0.01038*F_N + 0.005656*D + 0.053293*Rev-0.030636*M + 0.460223*TS$	**0.75**	**22.01**	2.53	97.71
Non-PJ ≤ 50 MPa	Equation 4	$PR = 12.6003473 + 0.0552407*UCS - 0.0929049*F_N + 0.0003493*D + 0.7747064*Rev + 0.0047568*M - 0.6102484*TS$	**1.59**	**15.76**	7.49	85.17
Non-PJ > 50 MPa	Equation 5	$PR = 13.595387 + 0.034204*UCS - 0.069404*F_N + 0.002078*D - 0.481460*Rev - 0.001404*M - 0.252044*TS$	**1.77**	**29.24**	4.99	88.57

PR = penetration rate (mm/rev), UCS = unconfined compressive strength (MPa), F_N = cutter thrust force (kN/ring), D = cutterhead diameter (mm), Rev = revolution speed (rev/min), M = torque (kNm), TS = tensile strength (MPa). PJ = pipe jacking, non-PJ = segment lining, rib and lagging or no lining. Strength values are given as unconfined compressive strength (UCS).

together with the RQD (Bilgin et al., 1996). At high RMCI, the penetration rate achieved is consistently low (< 5 mm/rev), whereas, at lower RCMI values, the penetration rate can be significantly higher but also shows a higher range of variation.

Fig. 5h shows the clear dependency of the penetration rate and the TBM diameter. The larger the TBM, the higher the penetration rate. It is clearly visible that the small-diameter slurry TBMs (AVNs) mainly achieve penetration rates < 5 mm/rev, while larger-diameter double shield TBMs, EPB, or gripper TBMs are able to achieve penetration rates mostly between 5 and 15 mm/rev. Fig. 5i shows the utilisation rates of the installed electrical power and the available thrust force. It is well visible that most TBMs, regardless of type, are between 35 and 55% utilisation of electrical power. The same applies to the thrust force. Usually, between 55 and 75% of the available capacity is utilised.

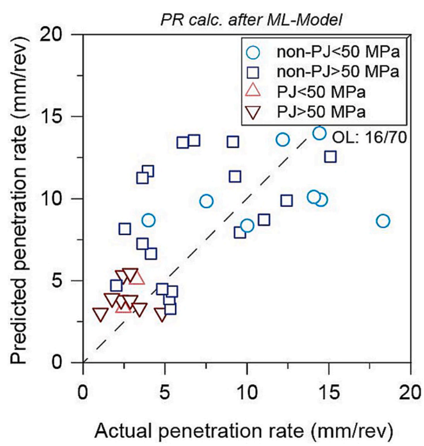

Fig. 7. Comparison of the results derived by the ML Model with the actual penetration rate for the HGA. PJ = pipe jacking, non-PJ = segment lining, rib and lagging or no lining. Strength values are given as unconfined compressive strength (UCS).

However, it should also be noted that these are average quartile values, and individual load peaks can be significantly higher.

Furthermore, a clear correlation between the penetration rate and used torque can be recognised (Fig. 5j), similar to Fig. 5h. The larger and more powerful the machine, the more torque is available and the higher the penetration rate. Fig. 5k shows the relationship between the revolution speed and the penetration rate. Low-revolution machines, such as double shield TBMs or EPB machines, typically exhibit higher penetration rates than high-revolution machines like gripper TBMs. Most small-diameter slurry TBMs have a unique position, with lower penetration rates at lower revolution speeds than other TBM types.

It is well known that a certain cutter thrust force is essential to achieving an efficient penetration rate (Wilfing, 2016). Fig. 5l proves that higher thrust forces lead to higher penetration rates. Pipe jacking projects generally show low thrust forces per ring in the 40 to 80 kN/ring range. Non-pipe jacking projects are characterised by much higher thrust forces per ring, which range from 144 to 205 kN/ring. However, it must be stated that most pipe jacking TBMs are equipped with cutters with two or even three rings due to space constraints. Although there are a few exceptions, the graph clearly shows that, as a rule, at least 100 to 150 kN should be applied per cutter in hard rock to achieve penetration rates above 3 mm/rev, which can be classified as efficient chipping. Penetration rates below this value are more likely to be generated by crushing and creating deep grooves in the rock. Finally, it must be emphasised once again that an overview of the individual parameters is shown here, but ultimately the combination of technical and geological parameters is responsible for the penetration of a TBM.

3.2. *Utility TBM performance prediction*

Dozens of models for TBM performance prediction exist. In the mechanised tunnelling industry, the CSM and NTNU models are mainly utilised for TBM penetration and advance rate prediction. However, for international small-diameter projects, the quantity and quality of the geotechnical data are relatively poor, as explained above. That limitation can be due to low testing standards in the respective country, little funds for a comprehensive exploration program, or the small project size, which is especially true for most pipe jacking projects. It is commonly observed that budget planning is undertaken prior to

Table 7
Accuracy of the newly developed ML model for penetration prediction in hard rocks.

		Homogenous geotechnical areas > 15 MPa		Detailed borehole information > 15 MPa	
		RMSE (mm/rev)	**MAPE (%)**	**RMSE (mm/rev)**	**MAPE (%)**
All	ML model	3.87	65.81	3.10	54.61
PJ ≤ 50 MPa	ML model	1.02	29.92	3.23	75.75
PJ > 50 MPa	ML model	1.23	41.06	1.98	51.08
Non-PJ ≤ 50 MPa	ML model	5.10	46.09	3.92	37.01
Non-PJ > 50 MPa	ML model	4.20	79.42	3.14	57.63

PJ = pipe jacking, non-PJ = segment lining, rib and lagging or no lining. Strength values are given as unconfined compressive strength (UCS).

Table 8
Selected results for penetration prediction for the Hong Kong reference project.

Model	**Actual penetration rate (mm/rev)**	**Predicted penetration rate with original UCS** from tender documents (144 MPa) (mm/rev) and deviation from the actual penetration rate	**Predicted penetration rate with verified UCS** from tunnel drive (78.9 MPa) (mm/rev) and deviation to the actual penetration rate
Farrokh et al. (2012)	5.19	3.77 (−27%)	5.02 (−3%)
Rostami (1997)	5.19	1.76 (−66%)	2.89 (−44%)
Equation 1 (All)	5.19	2.33 (−55%)	3.01 (−42%)
Equation 5 (Non-PJ > 50 MPa)	5.19	7.81 (+50%)	5.53 (+7%)

PJ = pipe jacking, non-PJ = segment lining, rib and lagging or no lining. Strength values are given as unconfined compressive strength (UCS).

executing a comprehensive geotechnical exploration and testing program, which presents the challenge of making informed decisions with limited information. However, the task of a reasonably accurate performance prediction remains. For the presented performance prediction analysis, nine HGAs with UCS values below or equal to 15 MPa were excluded. Experience from job sites shows that the cutting mechanism, especially for such projects, is highly complex and comprises a mixture of disc cutting and cutting with scrapers and knives not representable with common models. The concerned HGAs in the database are characterised by marlstones and chalk.

3.2.1. State of the art

With the aid of the small-diameter hard rock TBM database described above, a comparison of models with few geotechnical input parameters was performed for the homogenous geotechnical areas (HGA) and detailed borehole information (DBI). Besides the graphical representation of the results (Fig. 6), performance indices were calculated to evaluate the performance prediction of the investigated models and the proposed new models. The root-mean-square error (RMSE) and the mean absolute percentage error (MAPE) are calculated to quantify the accuracy of the penetration prediction. The results of the penetration modelling with the models mentioned above are presented in Fig. 6. The projects are subdivided into pipe jacking and non-pipe jacking (mostly segment lining) projects, as the lining type reflects the machine diameter (Fig. 1). Furthermore, the projects were divided into weaker rocks up to 50 MPa and stronger rocks above 50 MPa, corresponding to the limits of the ISRM (ISRM, 1980). Practical experience and many penetration prediction models like the one from Rostami (1997) draw a boundary line for a substantial change in the cutting tool-rock interaction at similar rock strength values.

Table 4 ranks the accuracy of conventional penetration prediction models for the homogeneous geotechnical areas (HGAs). If little geotechnical information is available and the average accuracy for both small-diameter segment lining and pipe jacking projects in hard rock is of importance, the model from Farrokh et al. (2012) shows the best performance. This model shows the lowest error values for all except one scenario for homogeneous geotechnical areas and detailed borehole information. Of all models, it has the least variation in all scenarios (RMSE = 3.65 mm/rev), except for HGA non-pipe jacking (mostly segment lining) projects with average UCS values above 50 MPa (Table 4). It should also be noted that the data points with an actual penetration rate of around 15 mm/rev or higher all belong to one single project. Excluding that project would increase the accuracy of the model even further (Fig. 6b). The model from Goodarzi et al. (2021) shows the best performance for all scenarios with a UCS $\leq$ 50 MPa. For non-pipe jacking projects (mostly segment lining projects) with a UCS $>$ 50 MPa, the model from Rostami (1997) shows very good accuracy with an RMSE of 2.37 mm/rev, followed again by the model from Farrokh et al. (2012) with an RMSE of 3.61 mm/rev. However, all models have difficulty accurately predicting the penetration rate in weak to medium strong rocks up to 50 MPa for non-pipe jacking projects. In such ground conditions, the best-performing model is from Farrokh et al. (2012), with an RMSE of 5.27 mm/rev. The best penetration predictions are achieved with the model from Farrokh et al. (2012) for pipe jacking projects with UCS $\leq$ 50 MPa (RMSE = 1.26 mm/rev) and UCS $>$ 50 MPa (RMSE = 1.18 mm/rev).

Table 5 shows the RMSE and MAPE for the detailed borehole information. Even though the general trend remains with moderate results for all datasets—better results (lower RMSE) for pipe jacking projects and worse results (higher RMSE) for non-pipe jacking (which means mostly segment lining) projects—the absolute error values are approximately 50% higher than for the HGA. For DBI, the best model for all project types is from Farrokh et al. (2012), with an RMSE of 4.20 mm/rev, 18% higher than the HGA error value. The best model for pipe jacking drives in weak and strong rocks is available from Farrokh et al. (2012), with an RMSE of 2.45 mm/rev and 1.75 mm/rev, respectively. The average best penetration prediction model for all projects in the database for non-pipe jacking projects is from Farrokh et al. (2012), with RMSE 6.80 and 3.91 mm/rev.

3.2.2. Empirical modelling

The multivariable regression technique was used to find a correlation between the penetration rate and the most relevant TBM or geotechnical parameters. For the database, a sensitivity analysis was performed (with UCS, cutter thrust force, torque and diameter being some of the most important parameters), and simple linear regression models were derived for all five scenarios. As described above, the goal was not to create a model that is as accurate as possible but a model that achieves the best possible result with the fewest possible input parameters. For this purpose, the parameters unconfined compressive strength (UCS), cutter thrust force (F_N), cutterhead diameter (D), revolution speed (Rev), torque (M) and tensile strength (TS) were selected on the basis of the sensitivity analysis, taking into account the availability of the individual values. The formulas and the corresponding RMSE and MAPE are presented in Table 6 for HGA and DBI. It is important to note that the models were developed for the HGA, which leads to very good results (overall low RMSE of 2.78 mm/rev) for the HGA and much higher RMSE for the DBI.

Furthermore, a similar pattern to conventional models is observed. In analogy to the prediction models from literature, the lowest RMSE values are achieved for the pipe jacking projects (RMSE of 0.54 and 0.75 mm/rev) and higher for the non-pipe jacking projects (RMSE of 1.59 and 1.77 mm/rev). Also, the MAPE is very low, with values between 8 and 35%. Finally, it should be noted that the presented formulas are empirically derived, and that they can only be used within certain "normal" application limits (e.g. thrust force, torque).

3.2.3. Machine learning model

Machine learning approaches show highly promising results for the penetration prediction of hard rock TBM projects (Zhou et al., 2021a; Zhou et al., 2021b; Wang et al., 2023) and justify their application on the presented dataset. However, as a sufficient amount of data is required for machine learning (ML) models and data for the HGA (homogeneous geotechnical area) is baselined data, the DBI (detailed borehole information) data is particularly suitable for building ML models. The goal of our ML model is the prediction of the tunnelling speed for small-diameter projects in hard rock before the start of the project, with limited input parameters, especially because the extraction of geotechnical parameters is expensive in small projects, as described above.

In order to achieve an evaluation of the approaches that is as close to reality as possible, data splitting is performed by cross-validation over the tunnelling projects. In particular, this achieves accurate performance prediction for new projects (and new TBMs). For each project, the data from the DBI and the HGA are used to evaluate the results. Different approaches, such as Support Vector Regression, GradientBoostingRegressor, RandomForestRegressor and XGBRegressor (https://arxiv.org/abs/1603.02754), were tried with the DBI and then compared with classical methods as mentioned above (Hastie et al., 2009). The best results were obtained by the GradientBoostingRegressor approach with the hyperparameters: learning_rate = 0.071, loss = "squared_error", n_estimators = 25, min_samples_split = 4, min_samples_leaf = 1 and max_depth = 3. The following TBM and geotechnical parameters were used as training data: lining type, cutting diameter, torque, revolution speed, thrust force per cutter ring, and rock type code following Farrokh et al. (2012) and Hoek and Brown (1980), UCS, TS and RQD. Values were MinMax scaled or one-hot encoded. The calculated results for the ML model are presented in Fig. 7, while the model's accuracy is given in Table 7. On both the DBI (RMSE = 3.10 mm/rev) and the HGA (RMSE = 3.87 mm/rev), the ML model gives acceptable results when incorporating all projects compared with conventional models.

3.2.4. Model validation with reference project

A reference project in Hong Kong was used to verify the findings of the abovementioned analysis. A 2.8-km-long water transfer tunnel was built with a 3.8 m double shield TBM. The ground was described as fine- to coarse-grained and occasionally chloritised granite. A total of 109 UCS tests were performed during the exploration program, with most results ranging between 140 and 180 MPa. During tunnel excavation, a comprehensive geotechnical testing program was conducted, and cores were drilled through an opening in the lower part of the TBM shield. A total of 60 cores were drilled with a diameter of 72 mm and a length of 500 mm to compare the values given along with the tender document with the actual parameters encountered during tunnelling. Geotechnical testing was undertaken in accordance with international recommendations and guidelines on rock testing. The testing revealed that the average UCS was 78.9 MPa (with quartiles between 45 and 105 MPa), the average PLI 5.1 MPa and the average TS 7.6 MPa, all indicating a much weaker rock than initially expected. The penetration values shown in Table 8 could be determined based on the data obtained. The comparison with the best-performing penetration prediction models above clearly shows that, obviously, the actual penetration rate achieved can be predicted much more accurately with the newly derived geotechnical values (especially due to the significantly lower UCS of 78.9 MPa). The closest to the real penetration of 5.19 mm/rev are the models of Farrokh et al. (2012) with 5.02 mm/rev (-3.3%) and the regression equation 5 for non-PJ projects > 50 MPa (+6.5%), both showing a very good correlation (Table 8), highlighting the importance of a representative and carefully undertaken geotechnical exploration campaign.

4. Discussion

The performance of a small-diameter TBM depends on multiple variables, including technical and geological factors. The performance analysis revealed that a certain cutter thrust force is essential to achieving efficient penetration rates. This fact was previously known for large-diameter TBMs (e.g. Wilfing, 2016) but had not been extensively documented for small-diameter TBMs. The results of the analysis, as depicted in Fig. 5l, demonstrate a correlation between higher thrust forces and increased penetration rates. While pipe jacking projects tend to utilise low thrust forces per ring, typically below 100 kN/ring, non-pipe jacking projects employ significantly higher thrust forces per ring, typically 150 kN/ring or higher resulting in higher penetration rates. While pipe-jacking TBMs often have two or even three rings per cutter, non-pipe jacking TBMs usually have a larger cutterhead diameter and therefore enough space available for 1-ring cutters, which allow to deploy the full cutter thrust force on only one ring, instead of dividing it on two or three rings. The data suggests that, generally, at least 100 to 150 kN of thrust force per ring is necessary for efficient chipping in hard rock with penetration rates above 3 mm/rev. Practical experience proves that lower penetration rates are indicative of crushing and the creation of deep grooves in the rock. Another important piece of information gained by the performance analysis is the information on the revolution speed. Larger TBMs tend to have higher revolution speeds than small TBMs. This fact, combined with similar or higher penetration rates due to more available thrust force per ring, stronger bearings and more overall power, leads to much higher advance speeds of large-diameter TBMs in hard rocks than small-diameter TBMs.

From the distribution of the UCS values, it can be inferred that the majority of the utility tunnelling projects are executed in rock strengths well below 100 MPa. This fact is not surprising as infrastructure tunnels, for example, for cable casings, sewage or freshwater, are built relatively close to the surface, especially when compared to larger traffic tunnels (e.g. deep alpine railway tunnels with respective geotechnical parameters). In turn, proximity to the surface means the more or less strong influence of weathering and, thus, lower compressive strength. It is well known through previous research that the UCS (unconfined compressive strength) is a significant factor in determining the performance of TBMs and it has been demonstrated as the most crucial single geotechnical parameter in hard rock (Gong and Zhao, 2009; Farrokh et al., 2012; Yagiz, 2017; Salimi et al., 2019). Additionally, our analysis indicates that the PLI (point load index) exhibits a strong correlation with the penetration rate of TBMs, assuming that the PLI data is available (Wilfing, 2016). Since it is quite easy to obtain PLT data accompanying UCS tests due to the availability of sample material, we suggest further extending this database in the future.

However, the analysis also shows that some projects should theoretically show higher penetration rates due to their TBM and geotechnical parameters, but for special projects, there are isolated cases of significant deviation from the correlations shown above. This is especially true for some projects with particularly low UCS values. In the absence of other geotechnical parameters, such projects can end up with severe estimation errors in penetration prediction. Such special projects are believed to be particularly associated with low-strength and rather ductile rock. From several projects, it is known how difficult it is to produce chipping with disc cutters under such conditions, and higher penetration rates would be possible with other technically much better-suited tools (e.g. knives, ripper tools etc., Lang and Lehmann (2022)). Another reason for low penetration rates in low-strength homogeneous areas could be that the TBMs were not run in the optimum application area. Other reasons for low penetration rates might be the operator's driving style and design compromises made at the TBM to accommodate tunnelling through multiple HGAs areas with differing geotechnical characteristics within a single tunnel drive.

It is of utmost importance to gather and analyse the actual drive parameters of the machine. As Farrokh et al. (2012) described, it is often assumed that the TBMs operate close to the design (thrust) values. However, as demonstrated in Chapter 3, the drive parameters vary considerably from the TBM design values and need to be incorporated in any modelling approach to the penetration rate. Fig. 5i clearly shows that utility TBMs are generally operated far from the utilisation limits (not including peak values). This has technical and probably also practical construction site reasons (e.g. reduction of wear). However, especially for machines with small diameters, which due to their size, have only limited mechanical capacities in terms of contact force, revolution speed, torque and power, the contact force per disc is simply no longer sufficient to achieve high penetration rates. The parameters presented in Chapter 3, such as outer diameter, torque, or contact force, are placeholders for TBM parameters such as cutter size, drive, power, and bearing load. Of course, the design type of the TBM has no direct influence on the penetration rate, but it is related to the diameter and, thus, to the above parameters.

Our analysis highlights the challenge of accurately predicting the penetration rate of a TBM based solely on a few geotechnical parameters. Despite this, there is a well-established correlation between the penetration rate and the UCS, as demonstrated by Rostami (1997). Our findings also suggest that PLI has promising potential in this regard. However, further research is still needed in this field. Furthermore, it has to be stated that one single borehole (e.g. DBI) is not enough and not characteristic for the prediction of the performance of a whole tunnel drive. This is reflected by the partially lower correlation factors for the DBI compared with the HGAs and might be explained by the short averaging areas of DBI. However, when baseline data is available, several models are able to predict the performance of a small-diameter hard rock TBM.

The most accurate baseline model comes from Farrokh et al. (2012), with an average RMSE of 3.65 mm/rev. It shows a very good, low RMSE for pipe jacking machines, so its application is recommended for such projects. The model from Farrokh et al. (2012) was developed with 17 tunnel projects and therefore covers a large variability, which could be a reason for the good performance since the number of projects or rock types used is limited to 1–3 in most other models. Furthermore, the low influence of the UCS limits potential errors related to geological variance and sampling or testing inaccuracies. However, it is also important to note that the dataset used in Farrokh et al. (2012) is mainly taken from the literature with unclear data quality and origin.

For non-pipe jacking projects with a UCS above 50 MPa, the CSM model from Rostami (1997) shows the best performance with a RMSE of 2.37 mm/rev, followed by the model from Farrokh (RMSE = 3.61 mm/rev). Therefore, we recommend the application of both models for such projects. For non-pipe jacking (mostly segment lining) projects below with a UCS below 50 MPa, the model from Farrokh et al. (2012) shows the best performance but, with a much higher RMSE of 5.27 mm/rev, is inadequate for such project planning. Even though research in the direction of penetration prediction in weak rocks has gained more attention in the last years (Goodarzi et al., 2021), more work is required to increase the accuracy of such models. Nevertheless, the model from Goodarzi et al. (2021) shows acceptable performance for projects with weak to medium strong rocks and can be therefore recommended as well. The results are in good agreement with findings from other authors for larger-diameter TBMs (Brino and Peila, 2015; Millan and Lorenzana, 2022). The research by Millan and Lorenzana (2022) shows that, generally, large deviations are quite common, even for penetration prediction of large-diameter TBM projects. They studied the Guadarrama (Spain), As Maceiras (Spain) and Follo Line (Norway) projects and found deviations between the predicted and actually achieved penetration rate of up to 72%, especially for the two models of Rostami (1997) and Gehring (1995) also studied here because of their few input parameters. In their research, the NTNU model shows the highest accuracy in performance prediction. However, as mentioned above, the application of the NTNU model is currently not realistic for most small-diameter projects due to the large number of necessary geological parameters and limited possibilities to perform the specific laboratory tests.

Our analysis also shows that the errors for the DBI are higher than for the HGA. This might be explained by the large geological variability and uncertainty. Therefore, we conclude that relying on one or two single geotechnical samples to conduct a robust penetration prediction may not be sufficient. Rather, using characteristic and precise geotechnical parameters for a respective HGA for such modelling is recommended. Furthermore, as shown in Fig. 5, parameters such as torque, revolution speed or diameter correlate much more strongly with the penetration rate achieved and might vary considerably when not using average values.

There are nine outliers for the HGA with a rock strength between 1 and 15 MPa, which consist of chalk or limestone. They increase the RMSE of the model from Farrokh et al. (2012) by 30.13% from 3.65 to 4.75 mm/rev when included. The fact that projects with a UCS $<$ 15 MPa are very scattered shows the problem that there is no generally accepted model for these projects due to their geological and technical complexity (mining principle). Very small TBMs with 2 or 3 rings or even other cutter geometries are also problematic, which cannot be represented with conventional models.

Similarly to the approach from Xu et al. (2021), simple linear regression formulas were derived. The very low RMSE values (2.78–0.54 mm/rev) are achieved within the HGA data. The results are promising for future regression approaches, as the corresponding database presented in this paper is much larger and more variable. The so-derived equations perform well in homogenous areas and for the first time provide specific calculation approaches for special application areas such as pipe jacking, but more advanced regression techniques and more data are necessary to obtain the universally applicable formula. In this context, a machine-learning approach has been developed with an RMSE of 3.87 mm/rev and 3.10 mm/rev for the HGA and DBI, respectively. The machine learning model already shows a similar quality of correlation to the best conventional models and, thus, a promising path for future research. Recent examples of machine learning models (e.g. a PSO-XGB hybrid model from Zhou et al. (2021a) or a PSO-ANN hybrid model from Armaghani et al. (2019)) have very low RMSE values, which are likely to be explained by the low variability in the dataset due to the limitation to one single project. Gao et al. (2020) developed a real-time PR prediction model based on an LSTM neuron network, resulting in similar RMSE values slightly higher than the ML model presented in this paper. Even though the DBI contains 1300 data points, only 550 could be correlated with a UCS. None of the rest was available for training the ML model. At this point, it is again important to note that the results of any model can only be as good as the input data (Erharter and Marcher, 2021). Furthermore, even the most sophisticated mathematical model can only predict what its input data implies. Short-term changes, which can be of geological nature and are often not trained, cannot be foreseen by such a model.

An important explanation for the overall heterogeneous results of the regression and ML penetration prediction and the conventional models is the deviation of the geotechnical parameters. They are generally derived from the preliminary exploration phase, and there is usually no verification of the geotechnical parameters during the tunnel drive, as there is often no pressing reason for this. Furthermore, it is often technically not possible due to the small diameters. Experience and the project in Hong Kong presented above show that even if a detailed preliminary investigation has been conducted, the in-situ conditions during tunnelling might often be very different. The evaluated project in Hong Kong not only shows significantly different (in this case lower) rock strength, but also the difficulties associated with the penetration prediction. Furthermore, the robustness of the model from Farrokh et al. (2012) leads to very good results as well as the equation no. 5, which was developed exactly for such application areas.

The geological conditions encountered often differ from what was specified in the preliminary exploration, and many parameters are only estimated. Furthermore, there is a lack of consideration for rock quality or strength in small projects, which is another reason for the large scatter in the data. Another factor leading to variability in the results might be the influence of anisotropy on penetration in anisotropic rocks, such as schist. However, the influence of rock's anisotropy on TBM penetration is poorly understood (Dammyr, 2016). We assume that in our study with 37 projects (mostly in non-anisotropic geological units) the influence is likely to be minimal due to the large amount of data available, contrasting a single case study.

However, a detailed and accurate picture of the geological conditions is important not only for the design and layout of the machine but also for an accurate penetration prediction during the project planning stage. It is not useful to have a few projects with a good database and create a model out of it because the so-established model no longer fits with a slightly different geology or TBM type. Therefore, the focus should not necessarily be on developing new models but on much more reliable preliminary exploration data. To accurately predict performance, it is necessary to use state-of-the-art data acquisition systems to collect more high-quality data from more small-diameter projects in hard rock and to consider a wider range of rock strengths and qualities. Therefore, digitalisation and more high-quality exploration data will play a key role in increasing the advance rate of the TBM and, ultimately, higher economic efficiency and acceptance in general.

5. Conclusion

With the support of a recently compiled database consisting of small-diameter tunnel boring machines (TBM) operating in various hard rock formations, a thorough analysis of their performance has been presented for the first time. Despite the prevalence of literature on the performance of large-diameter TBMs, research on the performance of small-diameter TBMs in hard rock has been very scarce. The presented database, which includes data from 37 utility tunnelling projects, offers a comprehensive examination of the challenges encountered in creating it and provides insights into the performance of small-diameter TBMs in hard rock, including pipe jacking and segment lining projects.

The analysed segment lining projects have an average penetration rate almost 3 times higher (4.5–10.8 mm/rev) than pipe jacking projects

(2–4.4 mm/rev) in rocks with the same compressive strengths. A clear correlation between the UCS and the penetration rate is observed: high UCS values generally result in lower penetration rates (< 5 mm/rev), while compressive strengths below 100 MPa may result in a higher penetration rate. A similar trend can be observed for the PLI, while the BTS shows a less clear trend. It has been shown that the penetration rate of small-diameter hard rock TBMs depends on the contact force of the discs, which in turn depends on the size of the TBM and thus on the installed components such as drive, bearings, cutter type and number of rings per cutter, etc. Furthermore, the qualification of the TBM personnel and the geological conditions also play a major role. These factors make penetration prediction with established models challenging. However, the recommended procedure for penetration prediction would be to use the project data, geotechnical data and machine parameters to select the appropriate model. Based on the findings mentioned above, the following can be concluded and generalised for the practical application of conventional penetration prediction models:

- For penetration prediction of small-diameter projects in hard rocks or pipe jacking projects, the model from Farrokh et al. (2012) is most suitable. However, the model from Goodarzi et al. (2021) also leads to acceptable results.
- For segment lining projects in hard rock (> 50 MPa), the model from Rostami (1997) an the newly derived equation 5 is recommended. The equations 2 and 3 are recommended for specific pipe-jacking applications.
- The penetration prediction for UCS > 50 MPa is better by a factor of 1.5 to 2 than for UCS < 50 MPa. The RMSE for pipe jacking projects are smaller than for segment lining projects, especially because the achievable penetration rates are generally lower.
- It is slightly better to work with baseline values (HGAs) than with individual values (DBI), especially in the case of PJ, there is between 50 and 72% less error.
- Performance prediction for non-pipe jacking application (mostly segment lining) in rocks with UCS < 50 MPa is not reasonably feasible with the studied models.
- ML and regression models show partially promising results, especially for well-defined application areas, but so far, no significant improvement compared to conventional models has been achieved.
- Even though existing models do not (always) predict achievable penetration rates precisely, there is currently no better approach for the performance prediction. Hence, these models can be employed as a rough estimate. However, the results have to be considered with care. Adjustment to the actual geotechnical conditions is recommended.

Despite the most meticulous and thorough exploration, it is not uncommon to detect discrepancies between the exploration program and the actual geological reality found during tunnelling. These deviations can stem from a variety of sources, including a limited understanding of the geotechnical conditions, geological heterogeneity, unforeseen events, and inaccuracies in data collection, testing and analysis. As long as these uncertainties exist, there is no point in creating new models, especially not for a single project due to the high risk of overfitting. Rather, much more reliable preliminary exploration data is required for a large variety of small-diameter TBM projects. With such a high-quality, diverse database, a new attempt could be ventured to improve TBM penetration prediction. However, even with the most advanced methods and technologies, it remains a challenge to fully capture the complexity and nuances of the geological conditions and their practical implications on (small-diameter) tunnelling projects.

CRediT authorship contribution statement

Gabriel Lehmann: Methodology, Writing – original draft, Writing – review & editing, Formal analysis, Investigation, Data curation, Visualization, Project administration, Funding acquisition. **Heiko Käsling:** Conceptualization, Writing – review & editing, Supervision. **Sebastian Hoch:** Formal analysis, Investigation. **Kurosch Thuro:** Supervision.

Declaration of Competing Interest

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Data availability

The data that has been used is confidential.

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Appendix A-3

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Microwave pre-conditioning of granite and concrete and the implications on their geotechnical parameters

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ABSTRACT

Microwave pre-conditioning is considered to be the most promising complementary hard rock cutting method, with a strong potential to improve the advance rate and profitability of future mechanized tunnel boring and mining equipment. This technique is based on selective heating and differential volumetric expansion of minerals causing micro- and macrofracturing in rock. Over 700 samples consisting of granite and three different strength grades of concrete were irradiated and underwent a comprehensive geotechnical testing program. Besides longitudinal wave velocity, porosity, specific heat capacity, density, and temperature difference, additional geotechnical parameters are influenced by material-specific heating intervals: Unconfined compressive strength (UCS), Brazilian tensile strength (BTS), Point load index (PLI), CERCHAR abrasivity index (CAI), the LCPC abrasivity coefficient (LAK) and its breakability coefficient (LBK). Comparisons of thin sections of irradiated and non-irradiated materials show microscopic structural changes. A slight reduction of the UCS was observed after longer irradiation intervals for granite and concrete, while the weakening effect on the BTS and PLI is more pronounced. Rock strength was reduced by up to 48% for granite and 40–48% for concrete, which potentially leads to a substantial increase in penetration rate of a tunnel boring machine and reduced wear. Furthermore, we found a linear correlation between granite strength, sample temperature, and specific energy, resulting in a reduction of the PLI by 0.12% K^{-1}. The tested concrete types showed strength reduction ratios between 0.21 and 0.28% K^{-1}. By calculating efficiencies of the deployed energy, we showed that pre-conditioning with microwaves can be an effective and efficient tool to artificially reduce the strength of rocks in order to increase the advance rate of tunnel boring and mining machines.

1. Introduction

The cutting performance of hard rock excavation machines is a key factor of their success and their application in tunneling and mining projects. Low advance rates are commonly accompanied with high wear, long project durations and low economic success while high advance rates are associated with comparably low wear, short project durations and high economic success.[1]

Fig. 1 illustrates the performance of hard rock excavation machines in direct correlation with rock strength – the higher the rock strength the lower the advance rate and vice versa.[2–9] Furthermore, high rock strength is generally linked to high abrasivity which can cause excessive tool wear. Therefore, high strength rocks often cause delay during tunneling and mining projects or prevent the deployment of mechanized rock cutting technology.[10–12] Hence, it seems reasonable to not only increase the efficiency and power of the machines, but also to artificially reduce the strength of the rock to be mined by adding micro- and macrocracks. In theory, a machine able to artificially reduce the strength of the rock would be able to achieve higher advance rates and unlock the huge potential of mechanical excavation technologies in hard rock mining and tunneling environments.[7,13,14]

1.1. Alternative hard rock cutting methods

Mechanized rock cutting has revolutionized hard rock tunneling in terms of performance, safety and plannability.[17,18] However, these inventions were made several decades ago and little major development has since been made in the field of mechanized rock cutting.[19] Therefore, alternative rock cutting methods have been studied and tested for the past several decades, but so far none have been shown to be

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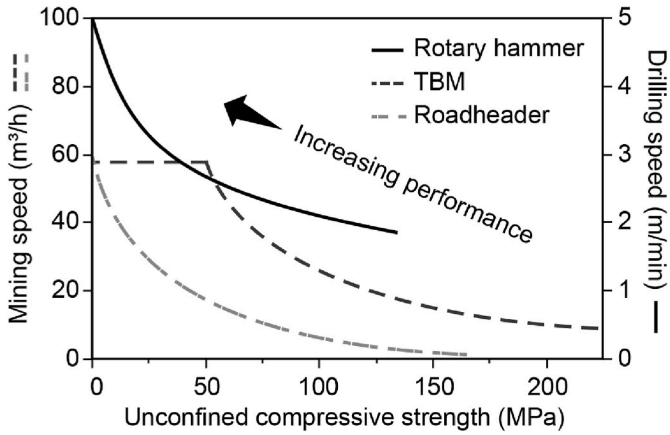

Fig. 1. Correlation of mining, tunneling and drilling speed with rock strength (UCS). Note the performance increase with decreasing UCS. The Tunnel Boring Machine (TBM) advance rate was calculated with a modified Colorado School of Mines (CSM) model for a TBM 3000 with 800 kW.[2,15] The rotary hammer speed comes from a 20 kW device further explained in Ref. 16. The roadheader performance was taken from a partial face machine with 130 kW described in Ref. 8.

practicably applicable.[7] Alternative rock cutting methods can be summarized in four different groups (Fig. 2):

1. Alternative mechanical cutting: Oscillating disc cutter, undercutting, projectiles
2. Assisted cutting: Laser, waterjet
3. Thermal methodologies: Flamethrower, microwave, hot gas
4. Others: Chemical, electrical, nuclear etc.

A brief overview of alternative hard rock cutting methodologies is given in Ref. 7 and 20. According to the authors, one of the most promising alternative hard rock damaging technologies is microwave pre-damaging due to its efficiency, effectiveness, rapidity, precise control, safety, and automation-readiness.

1.2. Microwave principle

Microwave irradiation heats up rocks selectively based on the dielectrical properties of their individual minerals. Microwaves are electromagnetic waves with frequencies between 300 MHz and 300 GHz. For industrial applications only frequencies of 915 and 2450 MHz are available. The dielectric properties define the microwave absorption behavior, which affects the heating behavior.[21] Due to the variety of chemical compositions of the individual rock-forming minerals and their different absorption behaviors, microwave irradiation induces temperature gradients and differential volumetric expansions. For example, some of the most common rock forming minerals, quartz and feldspar, increase in volume between 1.0 and 4.5% at 600 °C, which leads to various rock damaging mechanisms such as stress peaks due to differential expansion of minerals, expansion across temperature gradients, fluid inclusion rupture or decrepitation, vaporization of water, thermal shock or a chemical breakdown of minerals.[22] Hence, microwave rock pre-conditioning is considered to be a highly promising rock damaging technique, especially in combination with existing mechanized rock cutting methods.[23,24] Further information about the history and recent advances in rock pre-conditioning with microwave irradiation is available in Ref. 25-28 and 20.

1.3. Existing studies on microwave rock pre-conditioning

Early successful trials of microwaves for rock (pre-) destruction date back to the 1970s, 80s and 90s.[29–32] In addition to the previously mentioned review articles, numerous other articles on the influence of microwave irradiation of rocks have been published, especially during the past 10–15 years. Ref. 33 provides a comprehensive overview on how microwaves interact with rocks. However, he initially used low performance microwave and energies between 0.6 and 3 kW. Further research in North America subsequently focused on multiple rock types and higher microwave powers.[34–38] At the same time, considerable research was conducted in Europe in order to better understand the interaction of microwave irradiation with different rock types and their potential application with mechanized rock cutting machines.[9,39–46] Over the past decade, a considerable amount of research on the pre-conditioning effect of microwave irradiation has also been conducted in Asia.[47–55] Most of the research to date has not tested the effect of microwave irradiation on multiple geotechnical parameters or on the use of only low performance microwaves, however Ref. 56 proved that microwave pre-conditioning is very efficient in a full-scale linear cutting test with basalt.

Tests were also conducted on concrete, both with the use of models and in practical experiments focusing on sintering effects.[57–61] To date, no comprehensive study has been published characterizing the change in geotechnical parameters of concrete after irradiation with microwaves. Besides rock pre-conditioning for an increase of the performance of tunneling and mining machines, other possible application fields of microwave irradiation in combination with rocks are mineral liberation and ore processing methodologies as well as deep drilling,[62–68] while Ref. 69 discussed a potential application of microwave irradiation in space mining.

2. Methodology and materials

Over 700 specimens consisting of granite and three different types of concrete (low, medium, and high strength) were prepared, irradiated with microwaves and tested for various properties. Besides ultrasonic wave velocity, porosity, specific heat capacity, density and temperature

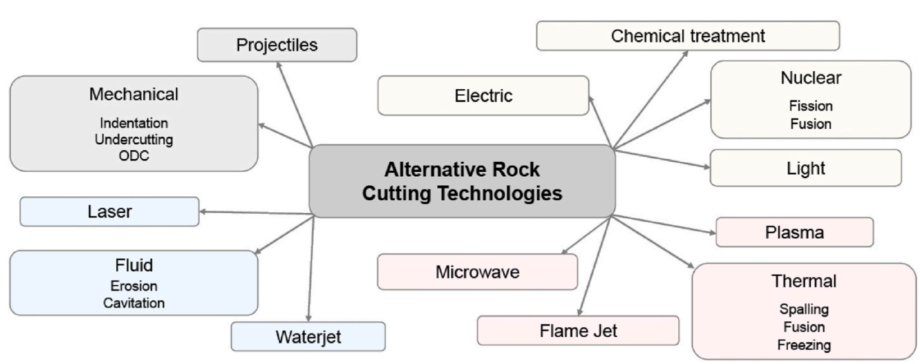

Fig. 2. Overview of alternative rock cutting technologies besides conventional drill & blast and mechanized cutting.

difference, the following geotechnical parameters were determined for heating intervals between 5 and 1200 s: Unconfined compressive strength (UCS), tensile strength (TS), point load index (PLI), CERCHAR abrasivity index (CAI), the LCPC abrasivity coefficient (LAK) and the LCPC breakability coefficient (LBK). Furthermore, the internal structural changes of the materials were analyzed comparing thin sections of irradiated and non-irradiated material. The electrical efficiency and the overall energy consumption of pre-conditioning with microwaves were calculated for the deployed 5 kW 915 MHz microwave setup.

2.1. Irradiated materials and background information

To investigate the influence of microwave irradiation on geotechnical properties of rock and concrete, four different materials were irradiated and tested: A granite was selected as a reference for a rock material that is often encountered in geotechnical concerns and also a bad microwave absorber. Furthermore, three types of concrete serve as analog material for weak to strong rocks, since the geotechnical properties can be controlled very well (Table 1). The direct comparison with granite is interesting, as granite is generally considered to be a poor absorber and its damage by microwave irradiation has been well investigated in contrast to concrete. Microwave cracking of granite is caused mostly at grain boundaries by different expansion coefficients, while concrete fissures within the fine-grained, water-rich cement matrix. This study therefore might serve as the starting point for a series of tests with different materials at different scales.

2.1.1. Granite

Granite is of magmatic origin and has been chosen for the tests as it is considered to be the most abundant rock type in the earth's upper crust.[70] It typically occurs in the cores of many mountain ranges, covering large areas of batholiths and continental shields. Furthermore, many large ore deposits (for example copper, gold, lead, zinc) are formed by hydrothermal fluids associated with the formation of granites and are therefore spatially embedded in granitic complexes. Hence, granite is an important rock type when it comes to mining and tunneling environments. The granite described in this paper is from Striegau, Poland, with an average UCS of 183 MPa. XRD analysis revealed a mean volumetric content of 38% quartz, 20% alkali feldspar, 34.5% plagioclase and 5.5% biotite. Therefore it can be lithologically described as a monzogranite (Table 2). Granite is generally considered a comparably bad microwave irradiation absorber, as it contains large amounts of quartz and very little to no water.[20]

2.1.2. Concrete

Concrete is commonly used at test facilities as an analogy for weak to strong rock types since large quantities and comparable material can be produced quickly and easily. Due to its low price, homogeneity and easy pre-design geotechnical properties, various strengths from 5 to 120 MPa can be easily reproduced.[71] Faults and discontinuities are also less likely in those artificial materials. Important applications of microwave heating in concrete technology are curing, demolition, drilling and recycling.[58] Microwave-based treatment systems are particularly important for the decommissioning of contaminated sites such as nuclear power plants. Application of these systems not only decontaminates concrete, but also reduces both the amount of radioactive material generated during the scabbling process, as well as airborne contaminants released into the environment.[58,72]

Table 1
Overview of the tested materials and their nominal UCS.

Material name and class	Abbreviation	Nominal UCS (MPa)	Porosity (%)	Density (g/cm^3)
Concrete C12/15 F3	B1	20	8.8	2.28
Concrete C45/55 F3>4	B2	65	11.2	2.25
Concrete C80/95 F4	B3	105	8.7	2.28
Striegau Granite	G	183	0.77	2.62

Table 2
Mineralogical composition of two tested granite samples from Striegau, Poland, derived by XRD analysis.

All values in %	GO-02-01	GO-02-02	Average
Quartz	37	39	38
Alkali feldspar (microcline and orthoclase)	20	20	20
Plagioclase (oligoclase, albite)	35	34	34.5
Biotite	6	5	5.5
Chlorite, amphibole and accessory content	<3	<3	<3

For the test series described in this paper, three different concrete types were investigated: The grayish-beige concrete (B1) with the lowest concrete strength class C12/15 F3 had a target UCS of 20 MPa. The medium-strength gray concrete (B2) with concrete strength class C45/55 F3>4 had a target UCS of 65 MPa. The strong dark gray concrete (B3) has the concrete strength class C80/95 F4 and a target UCS of 105 MPa. The concrete strength class is given in according to DIN EN 206–1/DIN 1045–2.

The grain size range and share of aggregates were the same for all types of concrete and were in the 00/02 sand range (33–38%) and the 08/16 round gravel range (42–44%). Marginally, 02/08 round gravel had a share of only 18–25%. The cement contents of B1, B2 and B3 were 10.2%, 15.7% and 22.8%, respectively. The amounts of sand and gravel were required to achieve the desired specifications of the concrete. The sand and gravel components are sediments from the Rhine river, mostly representing hard and abrasive minerals like quartz. Depending on the strength class, certain additives and admixtures were added.

2.2. Sample preparation

A total of 546 concrete cylinders and 155 granite cylinders were drilled out of blocks of 20 × 20 × 40 cm for the tests. All concrete samples were left to harden for at least 28 days at room temperature before they were drilled and cut into cylinders.

To ensure uniform microwave irradiation, the specimens had all the same cylindrical geometry with a diameter of 5 cm and height of 10 cm. On the specimen cylinders intended for UCS testing, the end faces were grinded planar before microwave irradiation. The concrete and granite cylinders varied by±1 mm in diameter due to the abrasion of the drill bits. The location of the specimen ID ensured that the cylinders were placed uniformly in the microwave to exclude differences in the irradiation direction. Before irradiation, we determined the wet and dry weights, exact dimensions and densities of each sample. Porosity was calculated according to the specifications given in chapter 2.3. Thin sections were prepared from all materials for microscopic and chemical analysis.

2.3. Microwave irradiation

A 5 kW single-mode microwave with a manual 3-stub tuner was deployed to pre-damage the rock samples (Fig. 3). A frequency of 915 MHz was chosen to efficiently treat a larger surface area of the rock mass and to penetrate deeper into the rock compared to the higher available frequency of 2450 MHz as recommended by Ref. 36. Furthermore, 915 MHz is more energy-efficient and its generation via magnetrons is considerably cheaper than 2450 MHz.

After initial experiments, the irradiation interval for the various materials were defined as shown in Table 3.

As the sample sets B2 and B3 started bursting, cracking, or melting after 30–50 s, irradiation was terminated earlier to prevent damage to

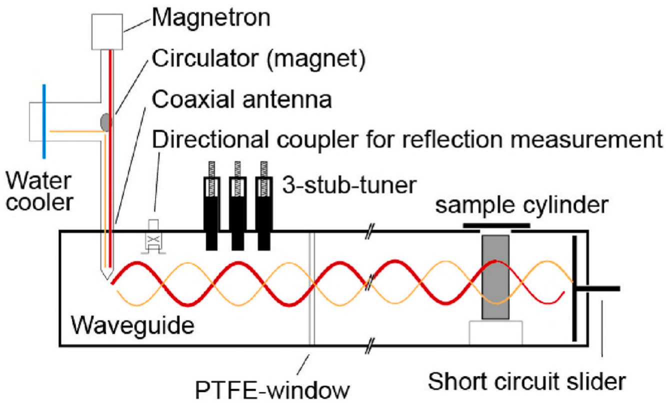

Fig. 3. Schematic of the 915 MHz 5 kW microwave system with forward power (red) and reflected power (orange). The sample cylinder is placed through the opening on the top of the Al_2O_3 insulation plates. Thus, the cylinder protrudes a few millimeters from the opening and can be safely removed again reaching into the waveguide. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Table 3
Irradiation intervals for the various materials and sample treatment types in seconds.

	Irradiation intervals in seconds		
	Dry	Humid	Quenched
Concrete B1	5, 10, 15, 20, 30, 40, 50, 60, 90, 120, 180	5, 10, 20, 30, 60, 120	10, 15, 30, 40, 50, 90, 180
Concrete B2	5, 10, 20, 30, 40, 50, 180	5, 20, 30	10, 40, 50
Concrete B3	5, 10, 15, 20, 30, 40, 180	5, 10, 20	15, 30, 40
Granite	100, 200, 300, 400, 500, 600, 900, 1200	100, 300, 500	200, 400, 600

the microwave and the waveguide. Half of the samples were irradiated in a dry state, but half of the samples were subjected to further treatment before or after irradiation (Table 3). 26 samples of each material were humidified before microwave irradiation. Humidification was ensured by placing the cylinders into 24 °C warm tab water under atmospheric pressure 24 h before irradiation. These samples were air-dried 5 min before irradiation. Another set of 104 specimens was irradiated dry, but after heating and temperature measurement they were quenched in 24 °C warm tap water for 10 s. For each test, there was at least one series without irradiation on which the initial rock parameters were determined.

A minimum of three individual tests were conducted for each geotechnical parameter, treatment mode and time. For the determination of UCS, specimen cylinders with plane-parallel grinded end surfaces were used. These cylinders were geometrically perfect for determining the specific heat capacity, the useable pore space, the dry bulk density, and the P-wave velocity. For PLI, the sample cylinders were divided into halves after irradiation. Thus, at least 6 subsamples were available for the determination of the PLI. After the test, the residues could be used further for determination of the LCPC abrasivity coefficient and the LCPC friability coefficient. For the TS, a sample cylinder was sawed into 3 subsamples after irradiation. The residues from the TS test were used to determine the CAI. Additional sample cylinders were available for each series in case the specimens burst during irradiation. The heterogeneity in the results is represented by the standard variations given in the results section.

2.4. Thermal analysis

The surface temperature of each sample was measured with the *FLIR ThermaCAM P640* thermal camera. The camera provided the minimum and maximum temperatures of the cylinder and a thermal image showing the temperature distribution on the surface of the sample. The temperatures were taken from the side facing towards the microwave path approximately 15 s after the end of irradiation.

The specific heat capacity C_p [kJ/(kg*K)] was determined calculating the ratio between the thermal effusivity e_f [W*s$^{1/2}$/(m^2*K)] and the thermal conductivity k [W/(m*K)] multiplied by the dry bulk density p_b [g/cm^3] (equation (1)). Thermal effusivity and conductivity were measured using *C-Therm's TCi Thermal Conductivity Analyzer*.

$$C_p = \frac{e_f^2}{k \times \rho_b} \tag{1}$$

2.5. Geotechnical testing and material properties

Useable pore space p_0, also called open porosity, describes the space that can be filled by water. This value excludes closed pore spaces and can be determined by water storage. The measurement of the water storage was carried out in accordance with Ref. 73. The value was calculated from the ratio between dry bulk density and apparent bulk density. The dry bulk density, ρ_b, is the ratio of the dry mass to the raw volume including all voids. The measurements of the specimen cylinders for the unconfined compression test were used to determine the volumes, since the cylinders have defined specimen geometries. The determination of the P-wave velocities was carried out according to Ref. 74. The sample cylinders' primary wave velocities were measured in axial direction from both directions. Thereby, before and after irradiation, an average value was calculated for each sample. A maximum of 21 unidirectional measurements per core were made parallel to the longitudinal axis perpendicular to the irradiation direction, which were lined up at a distance of 0.5 cm.

The UCS was determined according to Recommendation No. 1 of the Working Group on Rock Testing of the German Geotechnical Society (DGGT),[75] using the "ToniNORM" testing equipment from Toni Technik Baustoffprüfsysteme GmbH. During the tests, the stress-strain curve and the deformation modulus were also recorded. The PLI was determined according to Recommendation No. 5 ″Point Load Tests on Rock Specimens" of the Working Group on Rock Testing of the DGGT,[76] using a WILLE handheld device on "standing" cylinders. The TS was determined according to Recommendation No. 10 of the Working Group on Rock Testing of the DGGT,[77] using the "ToniNORM" testing equipment. The loading direction was perpendicular to the irradiation direction for all subsamples so that any anisotropy would not affect the results.

The CAI was determined according to Recommendation No. 23 ″Determination of the abrasivity of rocks with the CERCHAR test" of the Working Group on Rock Testing of the DGGT.[78] The LCPC abrasivity coefficient (LAK) and LCPC breakability coefficient (LBK) were determined according to Ref. 79 and 80, respectively.

2.6. Thermoelectrical properties

The specific performance (P_{sample} in W) was calculated by using C_p (J/kG*K), mass m (kG), temperature difference of the samples while heating ΔT (K) and irradiation time t (s):

$$P_{sample} = c_p * m * \Delta T * \frac{1}{t} \tag{2}$$

Note that the highest temperature for a sample was always considered for the calculation, ignoring temperature differences towards the top, middle and bottom of the cylinder. However, the temperature measurement was conducted approximately 15 s after irradiation ended, and the entire cylinder started to heat by conduction. Additionally, C_p

increases with temperature and also with crack formation.[81] Furthermore, low efficiency proves that most of the irradiation was not absorbed by the sample, probably due to the small sample size. Therefore, this equation serves as a first approximation to quantify the specific performance in our trials.

This specific performance (Equation (2)) can be divided by the incoming performance, resulting in the electric efficiency e (%):

$$e = \frac{P_{sample}}{P_{microwave}} \quad (3)$$

3. Results

Microwave irradiation had two immediate effects on all tested materials depending on the treatment interval: The samples heated up and started to get cracks, exploded, or melted. In total, 19 concrete cylinders burst after 20–62 s. Among them, mainly the concrete types B2 with 9 cores and B3 with 8 cores were affected. Of concrete B1, only two cores burst. Granite started to mostly get cracks, perpendicular to the long side of the cylinder (Fig. 4a, d & e), but without spalling. The evolution of large cracks was accompanied by loud cracking and creaking. Especially B2 and B3 concrete showed bursting of the entire sample cylinder or spalling of individual areas, at temperatures between 200 and 300 °C (Fig. 4b and c). All samples showed increased dimensions during irradiation with a lateral expansion of up to several millimeters. Hence, some very warm samples did not fit through the initial sample opening (5.1 cm) after irradiation. The opening was then enlarged by several millimeters in diameter. Furthermore, some concrete specimens, especially from B3, showed melting spots inside the core, which also led to major cracking of the samples. In some cases, the melt also leaked out of the core, which led to immediate termination of the tests. In general, as can be seen in Fig. 4b and d, the melt originated from the cement of the concrete while the gravel components remained intact.

3.1. Heating and internal parameters

The specific heat capacity of B1, B2 and B3 concrete is hardly indistinguishable with 0.92, 0.91 and 0.89 kJ/(kg*K), while the granite has 0.78 kJ/(kg*K). Since the correlation coefficients are in the range of zero and the values hardly show a correlation with the irradiation time, the specific heat capacity is considered constant for different heating intervals. The differentiation of the various dry, humid and quenched treatment modes does not result in different outcomes. Microwave irradiation had no influence on the specific heat capacity of the tested materials.

In contrast to the constant specific heat capacity, all samples show a significant increase in temperature during irradiation. Fig. 5a shows the heating gradients for all irradiated granite and concrete samples. B3 concrete heats up fastest, followed by B2 and B1. Granite gets also heated, but at a much lower rate. All three concrete types reach 150–200 °C after 40–60 s, but then the increase in temperature is much slower. Additionally, almost half of the concrete samples, i.e. B3, spalled or melted between 40 and 180 s of irradiation, which means that only very few samples reached 300 °C. Tests were stopped when spalling or melting occurred. Hence, no concrete sample was irradiated for more than 180 s. Granite heats up much slower than concrete, requiring 200–300 s to reach 200 °C. Even though some samples cracked during continued heating, most granite samples reached between 350 and 450 °C after 500–600 s.

As presented in Fig. 6, the temperature was always measured at the hottest part in the middle of the cylindrical sample. This is where the microwave beam was centered on, whereas the top and bottom of the sample did not encounter any heating initially. The hottest part was found at the backside of the sample and, if the sample broke, in the inside of the cylinder. Due to heat conduction after several minutes, the samples heat gradually distributed uniformly over the samples. Fig. 6 also shows, that the most heated part in the middle of the sample also exhibits a color change. The initially grayish feldspars changed their color and became brighter. Besides the color change, the most important change in the samples was the P-wave velocity. While all materials generally showed an initial P-wave velocity of 4500–5000 m/s, this velocity was reduced towards the middle section of a sample to less than 3500–4000 m/s. This reduction in P-wave velocity occurred in all samples, as was faster again in concrete, but more pronounced in granite after greater irradiation intervals.

The average original mean P-wave velocity for all non-irradiated samples at B1 was 4172 m/s, at B2 it was 4621 m/s, at B3 4739 m/s and at G 5252 m/s. The absolute values for especially granite varied considerably depending on the block used for irradiation. For better comparability, the P-wave velocity reduction is normalized and presented in Fig. 5b. Accordingly, the reduction of P-wave velocity at B1 is 24% after 120 s and at B2 is 16% after 50 s. The reduction of P-wave velocity at B3 was 11% after 40 s and at G 51% after 1200 s. Selected cores were measured parallel to the longitudinal axis perpendicular to

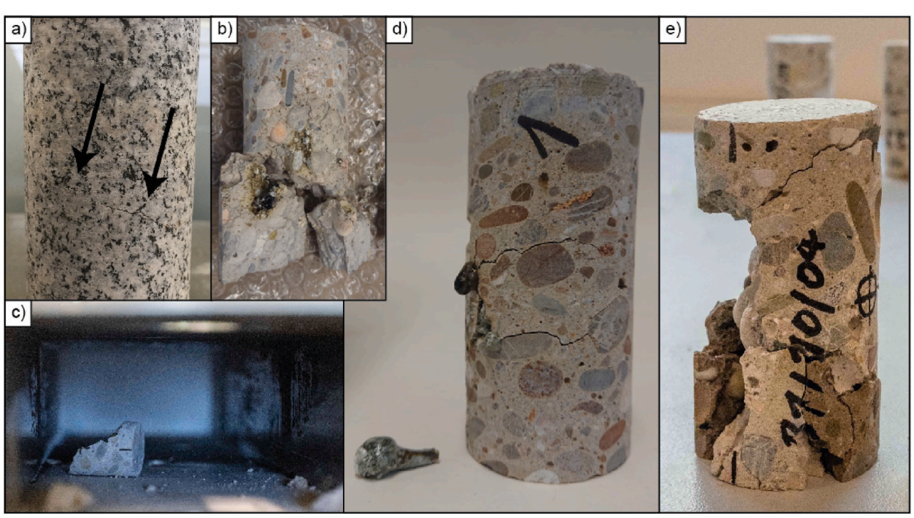

Fig. 4. Typical damage pattern in granite and concrete after long irradiation intervals. (a) shows a granite after 600 s of irradiation, clearly showing several centimeter long cracks. (b) Burst and partially melted B3 concrete after irradiation of 141 s. (c) View inside the waveguide with an exploded B3 concrete sample after 34 s of irradiation. (d) B2 concrete with cement melt drops after 270 s of irradiation. (e) Partially exploded B3 concrete after 62 s of irradiation. The sample diameter is 5 cm.

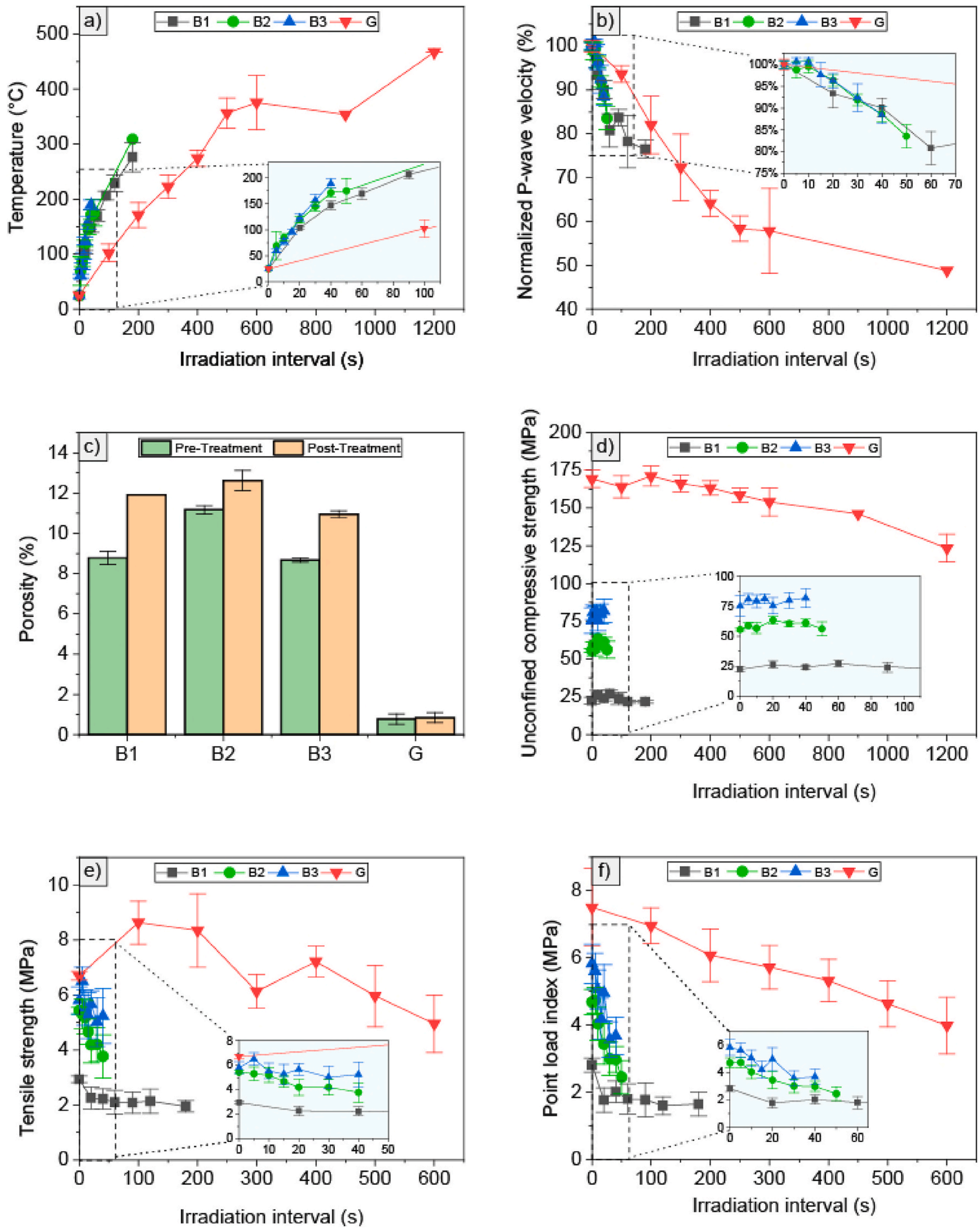

Fig. 5. Results of microwave irradiation of B1, B2, B3 concrete and granite (G). (a) The temperature evolution with irradiation time. Note that higher temperature could not be reached for concrete due to intense spalling, bursting, and melting of the samples. (b) P-wave velocity significantly decreased with irradiation time for all material types. (c) Increase in porosity for all materials. Treatment times are: B1: 120 s, B2: 50 s, B3: 30 s, G: 600 s. (d) The UCS results show an unclear picture; only granites at longer irradiation intervals show a decreasing strength trend. (e) Evolution of the tensile strength with irradiation time. All materials show a clear reduction of TS. (f) The reduction of the PLT with irradiation time is distinct for all tested materials.

the irradiation direction, in order to determine how the anisotropic irradiation of the microwaves affects the P-wave velocity of the materials. The average results are presented in Fig. 6c.

Porosity is directly linked with the P-wave velocity. All materials clearly showed an increase in porosity with irradiation time as presented in Fig. 5c. The time for reaching a certain increase in porosity is dependent again on the material. B1 concrete shows an up to 81% increase in porosity after 60 s of irradiation, with slightly lower porosity with further irradiation. B2 concrete shows a slight increase of porosity of 18% between 0 and 50 s of irradiation. B3 concrete shows a 31% increase in porosity after 40 s of irradiation. The values for granite are much lower than for the three concrete types and vary considerably. In the best case for dry granite, the porosity almost doubles from 0.56 to 1.03% after 600 s of irradiation.

As the porosity values suggest, there is no significant variation in density related to irradiation for granite. B1 concrete shows a minor

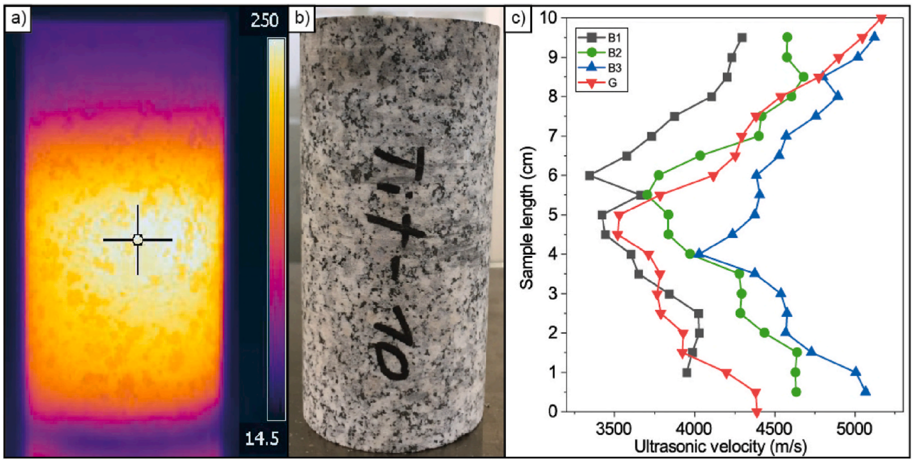

Fig. 6. Correlation between (a) heat distribution, (b) color change and (c) P-wave velocity in radial direction. Note that the highest temperature was reached approximately 0.5 cm below the sample center, on the side opposed to the microwave direction. The top of the cylinder was not heated at all by microwave irradiation due to mechanical reasons, it could therefore have retained its slightly darker color. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

trend with a density decrease of −2% after 90 s of irradiation. The density reduction rate for B2 is −0.5 mg/cm^3*s and is slightly more pronounced for dry than for humid samples (0.8 vs. 0.2 mg/cm^3*s). The variability of the measured density of B2 concrete before irradiation is larger than the density changes after treatment. A small decrease of density of −0.2% could only be measured for dry B2. The overall change rate in density for B2 is −0.06 mg/cm^3/s. B3 concrete shows a density decrease of −0.7% after 40 s of irradiation at a density reduction rate of −0.4 mg/cm^3*s. For all three treatment types, granite shows a small density reduction of −0.5% after 1200 s of irradiation and a much lower density reduction rate of −0.05 mg/cm^3*s.

3.2. Rock strength

Different parameters were tested in order to detect changes in material strength. As explained above, the unconfined compressive strength (UCS) is one of the most important rock parameters related to TBM speed. This parameter only experienced minor changes with 5 kW irradiation for the three concrete materials (Fig. 5d). For B1, no considerable change was noted, and most values are distributed within the range of 20–30 MPa. However, there seems to be a slight trend in increase of rock strength, especially for the humid samples for short irradiation intervals. After 180 s, a very small decrease of about 6% of the UCS can be measured. For B2, most values are within the range of 55–65 MPa. In general, no significant trend can be observed. For B2, the strength also seems to initially increase slightly with irradiation (15% after 20 s) and decrease with longer irradiation intervals (3% after 50 s). Notably, many samples melted or were subject to spalling after 40–50 s. For B3, strongly varying results between 70 and 90 MPa can be reported, without any clear trend related to the irradiation time. The granite shows a stable rock strength of 160–180 MPa for the first 200 s of irradiation (or even a slight increase), with clearly decreasing UCS for longer irradiation interval. The UCS decreases up to 27% after 1200 s of irradiation. No significant difference for the various sample treatment methodologies was observed.

The results for tensile strength (TS) testing are compiled in Fig. 5e. B1 obtained an initial TS of 3 MPa. The BTS for B1 was reduced by 39% after 180 s of irradiation. The decrease in TS can be best described as linear. B2 shows a decrease of TS of 31% from 5.5 MPa to 3.8 MPa. The TS of B3 was decreased by 25% after 30 s. For granite, the TS increases for small irradiation interval up to 42% after 200 s and decreases for 600 s of irradiation to less than 35% below the initial TS of 6.7 MPa. No significant difference between various treatments can be observed for all 4 materials.

The point load index (PLI) for B1 already drops by roughly 1/3 after 20 s of irradiation, reaching the lowest PLI of 1.5 MPa after 120 s (which marks a 47% decrease). For B2, the initial PLI of 4.7 MPa gradually decreases down to 2.4 MPa after 50 s of irradiation time, which corresponds to a 48% decrease. The PLI of B3 was reduced by 40% after 30 s, decreasing from 5.8 MPa to 3.5 MPa. The granite shows a clearly linear decreasing trend of PLI. The initial PLI of 7.5 MPa gradually decreases with irradiation time down to 3.9 MPa after 600 s, which corresponds to a 48% decrease. The results for PLT are presented in Fig. 5f. No significant difference between various treatments can be observed for all four materials.

3.3. Abrasivity

The initial CERCHAR abrasivity index (CAI) of B1 was 0.7, of B2 1.9 of B3 2.1 and 4.4 for G. The variations for CAI values after microwave irradiation are presented in Fig. 7a. While the average CAI for B1 increases by 32%, the average CAI for B2 and B3 decreases by 27% and 5%, respectively. The average CAI for G remains the same. Due to the high variation in CAI values especially in concrete, no significant trend in general CAI increase of decrease was observed with increasing irradiation intervals of any material. Tests were conducted for LCPC abrasivity and breakability coefficients (LAK and LBK) with the results presented in Fig. 7b. G could be classified as extremely abrasive, while B1 to B3 are very abrasive. For G, a slight decrease in abrasivity can be noted with 150 g/t after 600 s of irradiation. The grindability of the granite can be classified as high, small for B1 – B3 as small. The grindability of granite increases to very high (from 62 to 86%) after 600 s of irradiation.

3.4. Microscopic analysis

Multiple thin sections of B1, B2 and B3 concrete and granite have been analyzed in order to better understand the fracturing mechanism in the individual mineral grains. The analysis shows that the fracturing process in concrete is strongly linked to the very fine-grained cement matrix which makes it hardly visible. For granite, various inter- and intragranular microcracks developed with irradiation and heating. Fig. 8 shows the differences in crack distribution between irradiated and non-irradiated granite. Additionally, it shows that already existing cracks are opened to a greater extent. However, further analysis with REM-EDX did not reveal any distinct chemical or mineralogical changes between irradiated and non-irradiated grains in granite. The color change in the alkali feldspars could probably be explained with an oxidation of Fe. For larger-scale metasomatic processes detectable with REM-EDX the temperature was probably not high enough and more importantly, too little fluids for changes in mineralogical compositions were available.

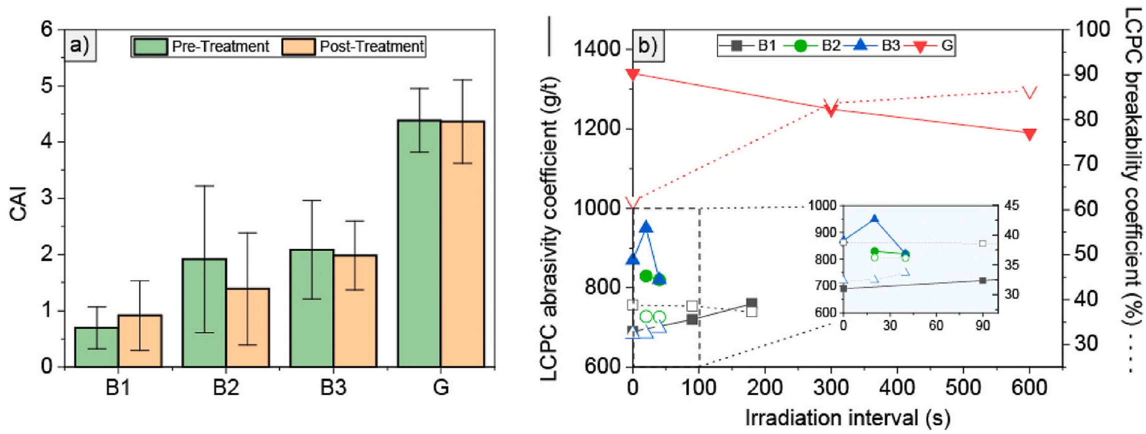

Fig. 7. Change in abrasivity with microwave irradiation: (a) No considerable change in CAI is observable with microwave irradiation. Treatment times are: B1: 180 s, B2: 50 s, B3: 30 s, G: 600 s; (b) Variation of LAC and LBC with irradiation time. Note the favorable trend in terms of material abrasivity.

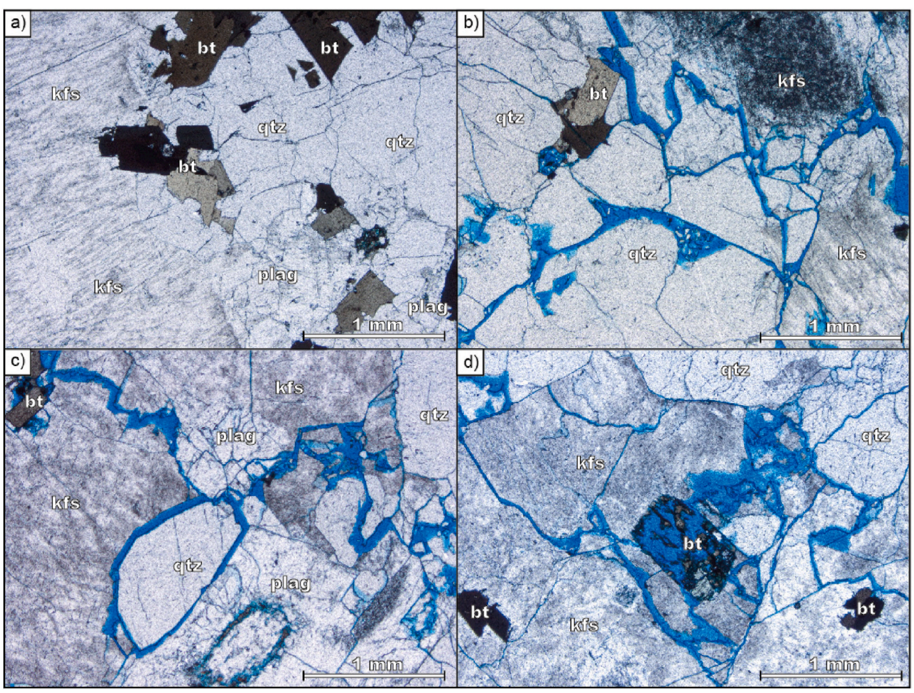

Fig. 8. Optical images show the change in microscopic texture in granite and concrete with irradiation: (a) is showing a non-irradiated granite under cross-polarized light, while (b), (c) and (d) show the same granite after 600 s of irradiation with 5 kW and distinctly more open, blue colored cracks. Note the inter- and intragranular cracks especially in quartz (b). (c) Shows a pronounced intragranular crack around a quartz grain. (d) Shows very fractured alkali feldspar (albite) and a completely damaged biotite (bt-biotite; kfs-alkali feldspar; plag-plagioclase; qtz-quartz). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

4. Discussion

Our results show that the temperature of various materials increases with microwave irradiation based on their dielectrical properties. The specific heat capacity was measured for all materials and is comparable with the values given in Ref. 37 for granite. Concrete heats much faster than granite, because of its high content of water, cement, and water-bearing minerals such as Portlandite and Ettringite. B3 concrete, which has the highest amount of water and cement, has the highest and fastest tendency to melt and spall. Granite, consisting mostly of quartz, heats much slower. Samples, that were humidified before, did not heat significantly faster or slower. Fig. 6 clearly shows the correlation between irradiation, heating of the samples and the resulting weakening due to the creation of cracks, directly measured by the great reduction in P-wave velocity. However, the visible cracks in granite could also have their origin in larger-scale temperature differences between heated and nearby non-heated areas, hence creating macrocracks. Due to the test setup, the cylindrical samples could enlarge and increase in volume while heating, which would not be the case in a triaxially confined rock mass. Therefore, it is likely that more macrocracks and spalling would occur with (much) larger samples size, as also suggested by the tests conducted by Ref. 42 and applied by Ref. 54.

4.1. Geotechnical properties

Our tests revealed a reduction of almost all tested geotechnical parameters. However, the strength reduction is significantly more pronounced in the BTS and PLI tests, while UCS shows less of a clear trend. Granite samples with clearly visible cracks created during irradiation (such as the samples shown in Fig. 4a or 6b), did not necessarily show a significant reduction in UCS, while PLT and BTS decreased considerably. One possible explanation could be that stress, resulting from force per area, triggers various kind of failure modes. Considering the force input in a uniaxial compression test, a crack (Fig. 9a) will be compressed in a UCS test. Shear resistance and friction are generated, defined by the fracture's frictional forces, which have to be overcome in order to propagate the crack. The individual crack areas add up and more force is required in the fracture area. In the point load or splitting tensile test, no

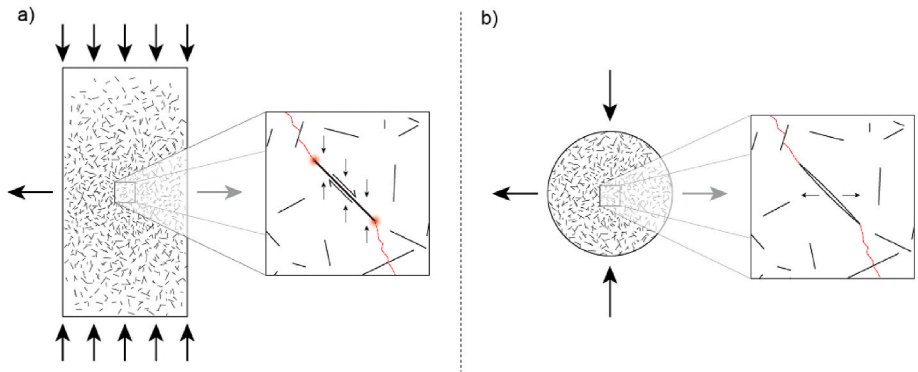

Fig. 9. Crack propagation at (a) unconfined compressive strength and (b) brazilian tensile strength tests. In the UCS test, shear resistance and friction are generated and have to be overcome in order to propagate the crack. In the point load or splitting tensile test, no shear forces exist in the crack and the crack areas do not add up to the total fracture area. Therefore, less force is necessary in order to propagate the crack.

shear forces exist in the crack and the crack areas do not add up to the total fracture area (Fig. 9b). Less force is required here. Furthermore, another possible explanation could be found in the isotropic distribution of the cracks. Assuming that all directions of the cracks are present in the specimen cylinder due to irradiation, this would mean that some angles are more favorable and others less suitable for fracturing in the various strength tests. The fact, that micro- and macrocrack are created is confirmed by visual inspection and by the significant reduction of the P-wave velocity, which was also noted by Ref. 55 for Diorite at a similar microwave power level. The variations in strength results in concrete can be partially explained by the large component grain size, which was required in order to achieve high UCS values. It should be also noted that the large component size in concrete in combination with the limited sample dimensions was outside of the norm. In parallel, the maximum size of the sample cylinders was limited by technical constraints of the deployed microwave setup. Therefore, the strength on the concrete cylinders, especially B3, could be reduced due to the large grain size of the components, which facilitate the creation of cracks. However, our rock strength reduction results are in good agreement with the observations made by Ref. 36; the reduction in P-wave velocity was also confirmed by Ref. 43 for granite, but was not tested for concrete. The results for the UCS tests are not very clear, especially for short irradiation intervals. Compared to Ref. 37, we could not reproduce the clear decreasing trend for granite with 5 kW irradiation, even though heating was even more effective in our tests for some granite specimens.

Further experiments have to show whether this trend gets more pronounced with higher microwave performance, as indicated by further experiments conducted by Ref. 37. Other reasons why our UCS results are more variable could either be the chemical composition of the tested granite and concrete, or a potential (negative?) influence of the deployed low frequency of 915 MHz, while they used a 2.45 GHz system with up to 15 MW power.

No significant difference between the three treatment types was observed which leads to the conclusion that material properties are more important than water content. During initial heating, UCS values especially tend to increase slightly before decreasing, especially at low power rates. This effect was also documented in sedimentary rocks such as sandstone by Ref. 39 and could be explained by a curing process in the rock at low and slowly increasing temperatures. This process, which leads to the increase of strength with low microwave performances is not yet understood satisfactorily. The damaging of the samples happens afterwards during the initial heat-up process and is not enhanced considerably by quenching. This observation is also further proof of the rock damaging mechanism that was deployed at the ancient fire-setting in many medieval and older mining sites, confirming the assumptions from Ref. 22. The change in crystal structure and the increase in volume leads to tension between the grains due to the heating of minerals. This tension could result in cracks in the grain boundaries; hence rock strength is reduced. However, the experiments show that all samples have increasing UCS/BTS and UCS/PLI ratios with increasing temperatures (Fig. 10). Even though the term brittleness in rock engineering is inconclusive,[82,83] experience from tunneling shows that high UCS/TS and UCS/PLI ratios enhance the rock cutting rate. Two attempts for a differentiation between brittle and tough rock behavior are shown in Fig. 10. The irradiation results clearly show that UCS/TS and UCS/PLI ratios are strongly temperature dependent. The longer the irradiation takes, the higher the temperature and the more brittle the behavior of all four tested materials. Furthermore, these results also show that the conversion factor to convert a PLI to a UCS value can vary for both concrete and granite samples by up to 100%, depending on the irradiation time and heating (Fig. 10b). Therefore, a fixed conversion factor for PLI to UCS, as various approaches summarized in Ref. 84 suggest, seems even more unrealistic.

4.2. Electrical efficiency

The electrical efficiency is the difference between the input power of the microwave (5 kW) and the power transmitted into the sample via temperature increase. As a first approach, we assumed the whole sample was heated to the same temperature. However, in Fig. 6 it can be seen that the maximum temperature was obtained in the middle section, while the top and the bottom of the sample remained much cooler in the beginning. On the other hand, temperature was measured on the average 15 s after the irradiation ceased, which results in a much lower temperature reading. Therefore, the error in sample temperature increase is considered relatively small. However, more advanced techniques for determining sample heating that would lead to more precise results, could not have been implemented in this study.

Considering the limitations described in chapter 2.6, the overall efficiency of the heating process is presented in Fig. 11 and is between 5 and 10% for G, declining with decreasing strength of the rock. The efficiency for concrete is initially much higher, but then also drops to a low level of 10–30%. In other words, the efficiency decreases with increasing temperature of the sample. This trend was also observed for Kimberlite and Basalt by Ref. 88, who introduced the term HOME (Heat over Microwave Efficiency), describing the ratio between heat absorbed and microwave energy input. The low overall efficiencies are probably due to the small sample size (i.e. diameter), which is also more than 6 times smaller than the wavelength of the microwaves (32.8 cm) and which does only cover 15% of the cross-section of the waveguide. Furthermore, strength reduction could be increased with larger samples, enhancing the creation of macrocracks.

For granite, the correlation between the increase in temperature and the strength reduction is linear for the chosen 5 kW 915 MHz microwave

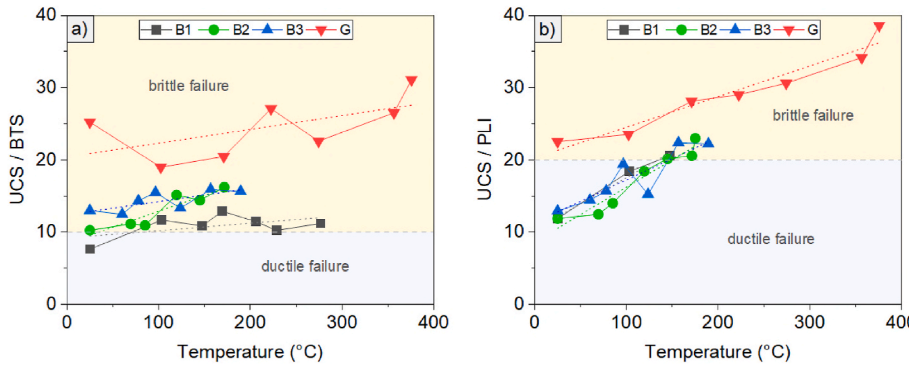

Fig. 10. Increase of UCS/BTS (a) and UCS/PLI (b) ratios as a function of the temperature of a sample. Thresholds for brittle failure behavior are adopted from Ref. 85 (a), Ref. 86 and 87 (b).

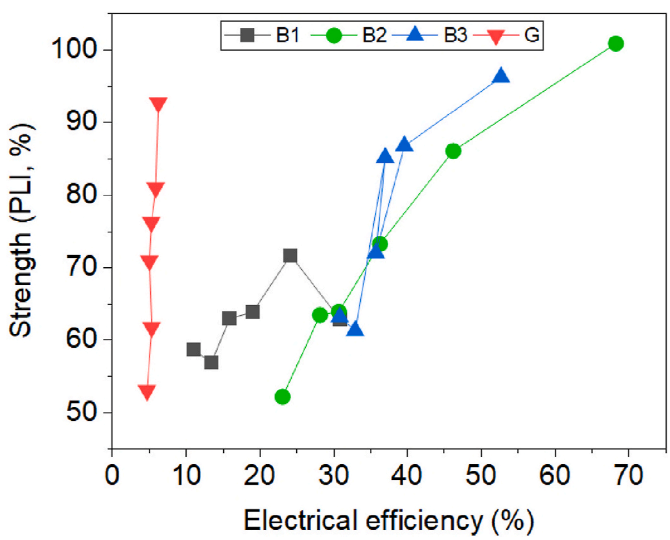

Fig. 11. Efficiency of the irradiation of rock and concrete samples with the deployed 5 kW 915 MHz microwave setup.

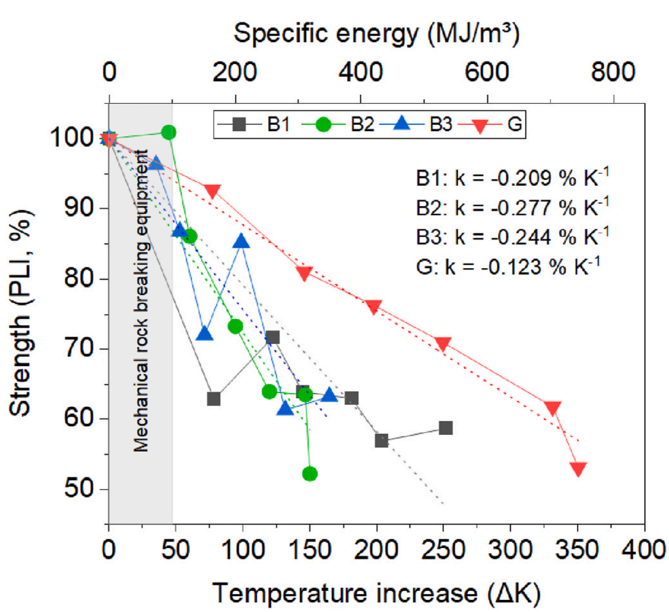

Fig. 12. Specific energy necessary for temperature-dependent strength decrease with the deployed 5 kW 915 MHz microwave setup.

setup, as visible in Fig. 12. A factor of 0.12% strength reduction (PLI) per 1 K temperature increase could be determined. For the two stronger concrete materials, B2 and B3, a less pronounced linearity of the trend could be observed with strength reduction ratios of 0.24 and 0.28% K^{-1}. This trend could be also observed for B1, but the strength reduction is not necessarily linear.

Furthermore, the specific energy related to a strength (PLI) reduction was calculated (Fig. 12). B1 to B3 concrete reach a 40–50% strength reduction with 200–500 MJ/m^3. Granite shows a clear linear trend that reaches a 50% strength reduction at around 700 MJ/m^3. These values are significantly higher than the specific energy required for conventional mechanized hard rock cutting technology, which is in the range between 1 and 100 MJ/m^3 for the overall cutting process in tunneling and mining.[89,90] However, as previously stated, there is plenty of optimization potential in terms of energy efficiency.

Recent research conducted by Ref. 88 defines the percentage of strength reduction achieved per microwave energy input measured in units of kWh/t as WOME (Weakening over Microwave Energy). Considering that we calculated the WOME with the PLI strength reduction (in contrast to the UCS used in the reported literature), a maximum WOME for granite of 4.78% per kWh/t was achieved, slightly lower than the 5.35% per kWh/t for Basalt and much higher than the 1.3% per kWh/t for Kimberlite reported by Ref. 88. However, much higher WOMEs were achieved for concrete, with up to 8.99% per kWh/t for B2 and 11.08% per kWh/t for B3. Only B1 is considerably lower at 3.14% per kWh/t. This significantly higher efficiency could be explained by the lower frequency used, by the consideration of the PLI and the generally very good microwave absorption behavior of concrete.

In general, it is well known that the creation of micro- and macrocracks influences the cutting process positively. For example, Ref. 8 has demonstrated a considerable influence of the joint spacing of the rock mass on the advance rate of a roadheader. Therefore, the calculation of heating efficiency and the specific energy based on small-scale, cylindrical samples can be misleading when compared to conventional hard rock cutting techniques. In order to give a more precise indication of the efficiency of combined microwave irradiation and subsequent cutting technique, further investigations are recommended.

4.3. Future work

Our findings suggest that further tests should be undertaken with a microwave power level much higher than used in this study. We recommend microwave power levels of 80–100 kW or above, in order to transfer sufficient energy into the rock in as little time as possible. More energy in a shorter time leads to higher differential stresses in the minerals, rocks and rock masses, resulting in more pronounced micro- and macrocracks. Even though some articles cover the subject of which frequency is best suited to damage rock prior to cutting, this effect is not sufficiently studied with high-performance microwaves. Of course, this influence would have to be tested on samples of different rock types. Additionally, the influence of spot size and area, both in simulation and in real tests must be understood. Our results show that more application-related results will be obtained by deploying an open-end microwave applicator, which does not have the reflections of a cavity or a standing wave in a waveguide.

Equally important is a much larger sample size, which should lead to much higher efficiencies. Most lab tests – ours included – focused on the irradiation of small-scale cylindrical samples. We advise irradiation of full-face rocks, as these are naturally confined triaxially and since volumetric changes can only act in one direction, the tunnel or face itself, which is very beneficial for rock destruction mechanism. A fully confined rock mass can only expand forward, towards the face, which will lead not only to cracks but also to spalling of the rock mass. At this point, it becomes obvious that the exclusive measurement of changes in geotechnical parameters is only of limited significance for determination of the possible increase in mining or tunneling speed. Future tests should be large enough to characterize the variations in speed or penetration, wear and electrical efficiency for a full-scale hard rock cutting machine.

5. Conclusion

More than 700 samples consisting of granite, low, medium and high strength concrete were prepared and irradiated with microwaves and tested for various properties. Depending on the irradiation time and the mineralogical composition of the samples, they altered, cracked, spalled, burst, or melted. For the first time, a comprehensive geotechnical testing program on the influence of microwave irradiation on granite and concrete was conducted. Besides the P-wave velocity, porosity, specific heat capacity, density and temperature difference, the following geotechnical parameters were determined for heating intervals between 5 and 1200 s. Microwave irradiation at 915 MHz and 5 kW heated concrete much faster than granite. The porosity of especially the concrete samples increased substantially, and the P-wave velocity was reduced between 10 and 50% for all materials. While no clear trend was observed in UCS variation except for irradiation intervals above 400 s, the PLI and BTS were decreased significantly for all materials. The reason for the observed behavior is believed to be the crack propagation mode, which is dependent on the geotechnical test procedure. The longer the irradiation takes, the higher the UCS/BTS and UCS/PLI ratios for all materials, and the more brittle the behavior of all four tested materials. Microwave irradiation has no significant effect on the CAI of the tested materials, but the LAC was decreased, and the LBC increased, but especially for granite. In other words, abrasivity and therefore wear on future tunneling and mining machinery is expected to decrease when incorporating microwave technology. Treatment of the rocks in terms of humidification or quenching before or after irradiation had no beneficial effect in terms of rock damaging.

In addition, the internal structural changes of the materials were analyzed by comparing thin sections of irradiated and non-irradiated materials, revealing the formation of inter- and intragranular cracks. No change in chemical composition could be detected with REM-EDX. It was demonstrated that rock pre-conditioning works with microwave performances as low as 5 kW, with considerable reduction especially in PLI and BTS and abrasivity which would theoretically lead to a higher penetration rate and less wear. However, the long irradiation intervals are not tolerable for industrial applications, which indicates that much higher microwave power level must be applied in the future. The electrical efficiency of microwave irradiation decreases with increasing temperatures of the sample. The specific energy to achieve a 50% reduction in PLI rock strength was roughly calculated at 200–700 MJ/m^3, and this is therefore still considerably higher compared to conventional hard rock cutting or mining technologies. However, especially for granite, the efficiency of the deployed microwave setup is low, but can be increased by using much larger sample sizes and high-performance microwaves. This could not only further reduce the amount of energy necessary to pre-condition rock surfaces to a state that could be attractive for industrial applications, but it could also pave the way for a new technology, that promises to cut hard rocks faster, more economically, safer and in a more sustainable manner.

CRediT authorship contribution statement

Gabriel Lehmann: Term, Methodology, Writing – Original Draft, Formal Analysis, Investigation, Data curation, Visualization, Project administration, Funding acquisition. **Martin Mayr:** Resources, Data curation. **Heiko Käsling:** Conceptualization, Writing - Review & Editing, Supervision. **Kurosch Thuro:** Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Gabriel Lehmann reports financial support was provided by Herrenknecht AG.

Data availability

Data will be made available on request.

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Appendix B – Conference proceedings & extended abstracts

Appendix B-1

Title:	**Untersuchungen zum Einfluss der Mikrowellenbestrahlung auf die Änderung der Festigkeitseigenschaften von unterschiedlichen Gesteinsarten**				
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Untersuchungen zum Einfluss der Mikrowellenbestrahlung auf die Änderung der Festigkeitseigenschaften von unterschiedlichen Gesteinsarten

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Zusammenfassung

Bereits seit mehreren Jahrzehnten wird über den Einsatz von Mikrowellen zum Abbau von Festgestein diskutiert. Durch die Mikrowellenbestrahlung wird das Gestein erwärmt, wodurch Spannungen im Gestein entstehen und eine Reduzierung der Festigkeit des Gesteins herbeigeführt wird. Die Erwärmung und die Zerstörung des Gesteins hängen dabei maßgeblich von dessen dielektrischen Eigenschaften ab. Um die Auswirkung der Mikrowellenbestrahlung auf die Zerstörung bzw. Festigkeitseigenschaften zu untersuchen, wurden Versuchsreihen an unterschiedlichen Gesteinsarten durchgeführt. Dabei wurden verschiedene Einflussfaktoren wie z. B. die Bestrahlungsdauer variiert und die Festigkeit in Punktlastversuchen und einaxialen Druckversuchen bestimmt. Im Rahmen des Beitrags werden die wesentlichen Ergebnisse und die daraus gewonnen Erkenntnisse der Versuchsreihen vorgestellt und erläutert.

1. Einleitung

Seit mehreren Jahrzehnten wird über den Einsatz von Mikrowellen zum Abbau von Festgestein diskutiert. Durch die Mikrowellenbestrahlung wird das Gestein erwärmt, wodurch Spannungen im Gestein entstehen und eine Reduzierung der Festigkeit des Gesteins herbeigeführt wird. Die Erwärmung und die Zerstörung des Gesteins hängen dabei maßgeblich von den dielektrischen Eigenschaften des Gesteins ab [1].

Die dielektrischen Materialeigenschaften beschreiben das Verhalten eines Festkörpers beim Anlegen eines elektrischen Wechselfeldes, das im Material einen elektrischen Strom verursacht, Wärme erzeugt und mit der Dielektrizitätskonstante (Permittivität) definiert wird. Zu den dielektrischen Materialien gehören schwach- oder nichtleitende Materialen, mitunter Gesteine und Mineralien, deren dielektrische Eigenschaften verantwortlich für die Erwärmung und beispielsweise abhängig vom Wassergehalt, Korngröße, Porosität, Temperatur und der angelegten Mikrowellenfrequenz sind.

Um die Auswirkung der Mikrowellenbestrahlung auf die Zerstörung bzw. Festigkeitseigenschaften zu untersuchen, wurden bereits verschiedene Versuche bzw. Forschungsprojekte (vgl. [2] bis [8]) durchgeführt. Die untersuchten Gesteine umfassenden dabei magmatische Gesteinsarten wie z. B. Granit, Basalt, Granodiorit und Norit. Sedimentgesteine wie z. B. Sandstein oder Kalkstein wurden i. d. R. dabei nicht untersucht. Hier liegen bisher keine Erkenntnisse vor bzw. wurden hierzu keine Ergebnisse aus Versuchen veröffentlicht.

Um die Auswirkung einer Mikrowellenbestrahlung auf die Festigkeitseigenschaften von Sedimentgesteinen zu untersuchen, wurden Versuche am Odenwälder Buntsandstein (s. Abs. 2.1., Abs. 3.1 und Abs. 4.1) und am Eibelstädter Muschelkalk (s. Abs. 2.2, Abs. 3.2 und Abs. 4.2) durchgeführt. Insbesondere wurde der Einfluss des Wassergehaltes der Probekörper analysiert. Aufgrund der Ergebnisse aus den Versuchen am Odenwälder Buntsandstein und am Eibelstädter Muschelkalk wurden zusätzliche Versuche an einer magmatischen Gesteinsart, dem Tittlinger Granit (s. Abs. 2.3, Abs. 3.3 und Abs. 4.3), durchgeführt.

2. Untersuchte Gesteinsarten

Im Rahmen der durchgeführten Versuche wurde folgende Gesteinsarten untersucht:

- Odenwälder Buntsandstein
- Eibelstädter Muschelkalk

- Tittlinger Granit

2.1 Odenwälder Buntsandstein

Der im Natursteinsektor als Odenwälder Buntsandstein bezeichnete Quarzsandstein aus dem Unteren Buntsandstein wurde für die Versuche aus dem Steinbruch Grasellenbach entnommen. Er ist feinkörnig und überwiegend dickbankig ausgebildet. Die Körner weisen einen Überzug aus Eisenoxiden auf, die dem Gestein seine charakteristische rotbraune Farbe geben. Im Gegensatz zu anderen Buntsandsteinen aus der Region, besitzt dieser keine Karbonatzementflecken oder die daraus entstehenden Hohlräume. Die Sandsteinbänke sind überwiegend massig oder schräg geschichtet und besitzen ebene Bankflächen. Sie sind durch dünne, tonig-schluffige Zwischenlagen voneinander getrennt. Einzelne Gesteinsproben besitzen kleine Tonlinsen im Gefüge (s. Bild 1). Hauptbestandteile des Odenwälder Buntsandsteins sind Quarz, Plagioklas und Kalifeldspäte.


Bild 1: Odenwälder Buntsandstein

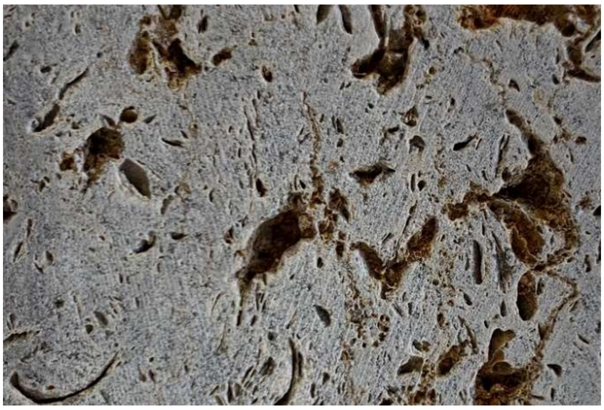


Bild 2: Eibelstädter Muschelkalk

2.2 Eibelstädter Muschelkalk

Bei den untersuchten Probekörpern, die aus den Steinbrüchen der Kirchheimer Kalksteinwerke GmbH stammen, handelt es sich um den sog. Eibelstädter Muschelkalk, der dem oberen Muschelkalk zuzuordnen ist. Der unregelmäßig porige Kalkstein mit einer gräulichen Grundfarbe weist rotbräunlichen Poren auf (s. Bild 2). Die Größe und die Häufigkeit der Poren variieren in den einzelnen Schichten. Viele Poren sind durch ein gelblich bis überwiegend rötliches gefärbtes Material, vermutlich ein Eisenoxid zusammen mit etwas Ton, gefüllt. Der Hauptbestandteil ist Calcit. Untergeordnet können Quarz, Pyrit und Feldspat vorhanden sein.

2.3 Tittlinger Granit

Der sog. Tittlinger Granit, der aus dem Steinbruch Höhenberg im Bayerischen Wald stammt, ist ein graues, relativ homogenes, gleichkörniges, mittelkörniges Gestein (s. Bild 3). Die Hauptbestandteile sind Quarz, Plagioklas und Alkalifeldspat (vgl. [9]).


Bild 3: Tittlinger Granit

3. Laborversuche und Versuchsdurchführung

3.1 Versuche Odenwälder Buntsandstein

An insgesamt 144 Versuchskörpern (Handstücke mit den Abmessungen 29 mm bis 51 mm x 40 mm bis 89 mm x 42 mm bis 94 mm) wurde untersucht, wie sich der Wassergehalt der Sandsteinproben und die Dauer der Bestrahlung durch Mikrowellen auf die Druckfestigkeit der Versuchsköper auswirken. Das Versuchsprogramm gliederte sich dabei in drei Untersuchungsschritte.

Im ersten Schritt wurde an zwölf Proben die Ausgangsfestigkeit mittels Punktlastversuch (s. Bild 4) bestimmt. Zwölf weitere Proben wurden vor dem Punktlastversuch getrocknet. Dies diente zum einen zur Bestimmung des Wassergehalts und zum anderen, um Unterschiede in der Festigkeit zwischen feuchter und trockener Probe aufzuzeigen. Die Trocknung erfolgte mittels der Ofentrocknungsmethode nach DIN EN ISO 17892-1 bei 105°. Die Proben wurden mindestens 24 Stunden lang getrocknet. Weitere zehn Proben wurden vor dem Punktlastversuch unter Atmosphärendruck in Wasser gesättigt („nasse“ Probe). Dazu wurden diese Proben 43 Stunden in Wasser gelagert. Dies sollte aufzeigen, ob das Gestein hierdurch seine Festigkeitseigenschaft verändert. Hierbei wurde unter anderem die Festigkeit als weiterer Referenzwert für die Untersuchungen im dritten Schritt bestimmt.

Im zweiten Schritt wurde untersucht, welchen Einfluss verschiedene Bestrahlungszeiten auf die Festigkeitseigenschaften des Sandsteins nehmen. Jede der bestrahlten Probe wurde dabei ohne Veränderung des natürlichen Wassergehalts bestrahlt. Für die Bestrahlungszeiten wurden im Vorfeld mehrere Probeläufe durchgeführt. Durch diese Probeläufe wurden die Bestrahlungsintervalle festgelegt und eingegrenzt. Aus den Probeläufen wurde ein Untersuchungsbereich zwischen 30 s und 300 s mit Intervallen von je 30 s festgelegt. In jedem Intervall wurden jeweils zehn Proben bestrahlt, um die Ergebnisse der Punktlastversuche nach Versuchsoption 2 der Empfehlung Nr. 5 „Punktlastversuche an Gesteinsproben“ 2010 des Arbeitskreises 3.3 „Versuchstechnik Fels“ der DGGT (vgl. [10]) durchführen zu können. Diese Auswertungsmethode bietet ein Mindestmaß an statistischer Genauigkeit, ohne den Versuchsrahmen zu sprengen. Die Bestrahlung erfolgte mittels einer handelsüblichen Mikrowelle mit einer Frequenz von 2,45 GHz und einer maximalen Leistung von 3,2 kW. Der Probenkörper wurde auf einer Glasschale so positioniert, dass er sich im Zentrum der Mikrowelle befand (s. Bild 5), um eine möglichst homogene Bestrahlung der Probe zu gewährleisten.

Bild 4: Punktlastgerät


Bild 5: Position der Probe in der Mikrowelle

Im dritten Schritt wurde der Einfluss des Wassergehalts auf den Wirkungsgrad der Mikrowellen untersucht. Hierfür wurden jeweils zehn Proben im trockenen, feuchten und nach Sättigung unter Atmosphärendruck erreichten Zustand bei einer Bestrahlungszeit von maximal 300 s bei voller Leistung mit Mikrowellen bestrahlt.

3.2 Versuche Eibelstädter Muschelkalk

An insgesamt 169 Versuchskörpern (Quader mit den Abmessungen 50 mm x 50 mm x 50 mm) wurden wie bei den Versuchen am Odenwälder Buntsandstein zur Bestimmung der Druckfestigkeit Punktlastversuche durchgeführt. Auch hier wurden der Wassergehalt und die Bestrahlungsdauer variiert. Die Versuchsdurchführung entspricht der Beschreibung im Abs. 3.1 für den Odenwälder Buntsandstein. Bei den Versuchen mit dem Eibelstädter Muschelkalk wurden die Intervalle auch mit jeweils 30 s festgelegt. Die maximale Bestrahlungszeit wurden allerdings auf 180 s beschränkt, da in Vorversuchen mit einer längeren Bestrahlungszeit deutlich wurde, dass eine längere Bestrahlungszeit keinen nennenswerten Einfluss auf die Druckfestigkeit der Versuchskörper aufweist.

Bei den Versuchen mit dem Eibelstädter Muschelkalk wurden unmittelbar nach dem Punktlastversuch Messungen der Kerntemperatur mit einem Temperaturmessgerät in der Mitte im Bereich der Bruchfläche durchgeführt. In Bild 6 sind exemplarisch die Messepunkte (rote Kreise) für die Messung der Kerntemperatur dargestellt.

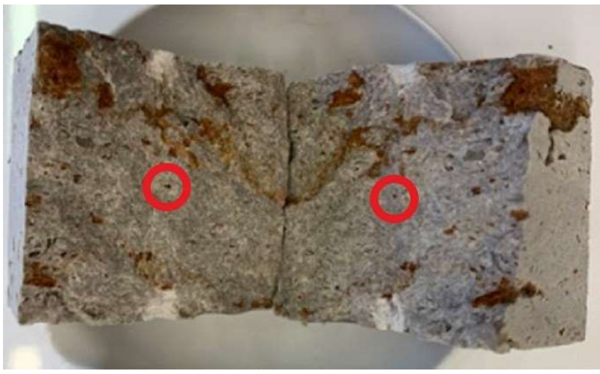


Bild 6: Messpunkte für die Temperaturmessung im Kern eines Probekörpers des Punktlastversuches

3.3 Versuche Tittlinger Granit

An insgesamt 10 Versuchskörpern (Zylinder mit den Abmessungen Durchmesser 49,1 mm bis 50,7 mm und Länge 103,5 mm bis 104,650 mm) wurden zur Bestimmung der Druckfestigkeit Einaxiale Druckversuche entsprechend der Empfehlung Nr. 1 „Einaxiale Druckversuche an zylindrischen Gesteinsprüfkörpern“ 2004 des Arbeitskreises 3.3 „Versuchstechnik Fels“ der DGGT (vgl. [11]) durchgeführt (s. Bild 7). Die Bestrahlung erfolgte ohne die Veränderung des natürlichen Wassergehalts. Die Bestrahlungszeiten lagen bei 20 s, 40 s, 60 s, 90 s, 120 s, 255 s und 390 s.

Bild 7: Einaxialer Druckversuch am Tittlinger Granit

4. Versuchsergebnisse

4.1 Versuchsergebnisse Odenwälder Buntsandstein

Bei Betrachtung des Wassergehaltes der Proben zeigte sich eine Schwankungsbreite von 1,83 % bis 6,40 %. Der Mittelwert lag bei 4,32 %.

Bei Bestrahlung der Proben begann das Wasser nach ca. 20 s bis 30 s Bestrahlungszeit zu verdampfen. Teilweise bildeten sich Blasen beim Verdampfen des Wassers. Dies konnte allerdings nicht bei allen Proben beobachtet werden. Nach einer Bestrahlungszeit von 30 s waren die Proben teilweise noch feucht. Nach einer Bestrahlungszeit von 60 s war das Wasser augenscheinlich vollständig verdampft.

Durch die Bestrahlung konnten keine äußerlichen Risse an den Proben beobachtet werden.

Die Punktlastversuche erfolgten ausschließlich an unregelmäßig geformten / quaderförmigen Prüfkörpern. Bei keinem der Punktlastversuche war eine unzulässige Bruchform festzustellen (s. Bild 8). Um vergleichbare Ergebnisse erzielen zu können, wurden die Prüfkörperabmessungen auf die Standardabmessungen 50 mm x 50 mm umgerechnet. Dies erfolgte nach der empirischen Gleichung nach [12] mit der nachfolgenden Formel:

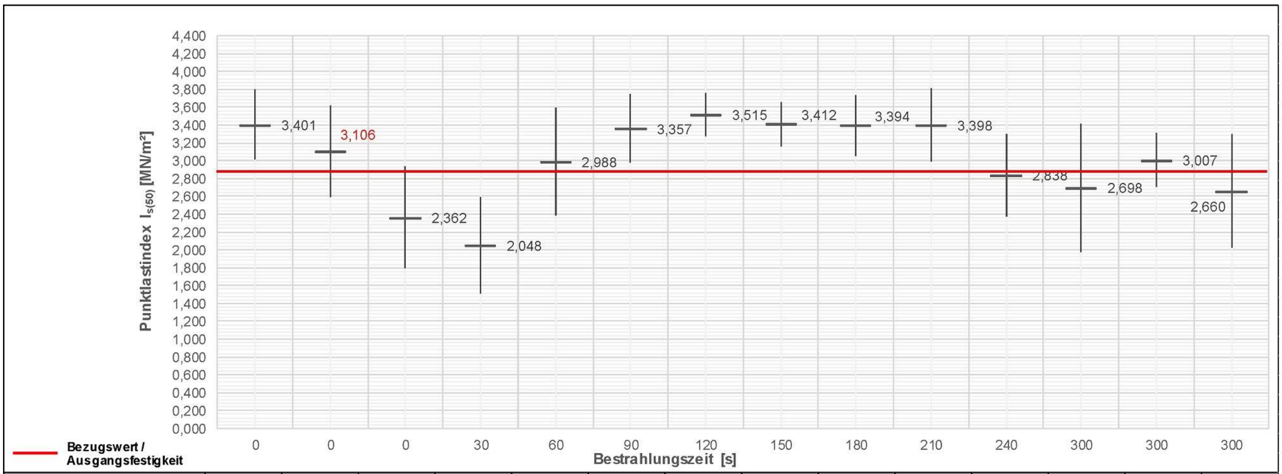
$$i_{s(50)} = (A/2500)^{0,225} \times i_s \qquad (1)$$

Dabei bezeichnet $i_{s(50)}$ den Punktlastindex mit Standardabmessungen von 50 mm x 50 mm. i_s stellt den Punktlastindex aus dem Einzelversuch dar und A definiert die Probenkörperfläche. Bei der Auswertung der Punktlastversuche wurde auf eine Umrechnung der Punktlast in die einaxiale Druckfestigkeit verzichtet.

Bild 9 zeigt die Versuchsergebnisse der 144 Probekörper in Abhängigkeit von den Bestrahlungszeiten und dem Wassergehalt. Die Ordinate gibt den Punktlastindex $i_{s(50)}$ an. Auf der Abszisse ist die Bestrahlungszeit aufgetragen. Die Versuche Probe 1 bis 24 und 125 bis 134 zeigen, dass ohne eine Mikrowellenbestrahlung, die trockenen Proben höhere Druckfestigkeiten und die wassergesättigten „nassen“ Proben geringere Druckfestigkeiten aufweisen. Die Probekörper 25 bis 114 zeigen einen deutlichen Einfluss der Bestrahlungszeit auf die Druckfestigkeit der Proben. Mit einer Bestrahlungsdauer von 30 s weisen die Probekörper die geringste Druckfestigkeit auf. Bei zunehmender Bestrahlungsdauer steigt die Druckfestigkeit bis zu einer Bestrahlungszeit von 120 s an. Ab 120 s Bestrahlungszeit bewegt sich die Druckfestigkeit der Proben bis 210 s Bestrahlungszeit auf einem konstanten Niveau. Ab einer Bestrahlungszeit von 210 s verringert sich dann die Druckfestigkeit der Proben. Beim Vergleich der Druckfestigkeit bei einer maximalen Bestrahlungszeit von 300 s (Probekörper 105 bis 124 und 135 bis 144) ergibt sich wie bei den unbestrahlten Probekörpern ein ähnliches Bild: Die trockenen Proben weisen höhere Druckfestigkeiten und die wassergesättigten „nassen“ Proben geringere Druckfestigkeiten auf. Allerdings liegen hier die Druckfestigkeiten der „feuchten“ Proben auf einem ähnlichen Niveau wie die „nassen“ Proben.

Bild 8: Beispiel Odenwälder Buntsandstein Bruchfläche der Probe nach Bestrahlung und nach Punktlastversuch a) Probe vor Bestrahlung von oben b) Probe vor Bestrahlung von der Seite c) Bruchfläche der Probe nach Bestrahlung und nach Punktlastversuch d) Probe nach Bestrahlung von oben

Beim Vergleich der trockenen Proben (1 bis 12) ohne Bestrahlung mit den „feuchten“ Proben (45 bis 94) mit Bestrahlungszeiten von 90 s bis 210 s fällt auf, dass diese eine Druckfestigkeit in derselben Größenordnung aufweisen. Erst ab einer Bestrahlungsdauer von 240 s kommt es zu einer Reduzierung der Druckfestigkeit. Daraus kann geschlussfolgert werden, dass es erst nach einer längeren Bestrahlungsdauer zu einer Strukturänderung im Gestein kommt. Hier wurde testweise ein zusätzlicher Versuch mit einer Probe gefahren. Die Probe wurde dabei 840 s lang bestrahlt. Im Punktlastversuch ergab sich ein deutlich reduzierter Punktlastindex von $i_{s(50)} = 2{,}095$ MN/m².



Bezeichung Proben	1 bis 12	13 bis 24	125 bis 134	25 bis 34	35 bis 44	45 bis 54	55 bis 64	65 bis 74-1	75 bis 84	85 bis 94	95 bis 104	105 bis 114	115 bis 124	135 bis 144
Art der Probe	Trockene Probe	Feuchte Probe	Nasse Probe	Feuchte Probe	Feuchte Probe	Feuchte Probe	Feuchte Probe	Feuchte Probe	Feuchte Probe	Feuchte Probe	Feuchte Probe	Feuchte Probe	Trockene Probe	Nasse Probe
Anzahl Proben	12	12	10	10	10	10	10	10	10	10	10	10	10	10
Wassergehalt [%]	0,0	1,8 - 6,4	4,3	1,8 - 6,4	1,8 - 6,4	1,8 - 6,4	1,8 - 6,4	1,8 - 6,4	1,8 - 6,4	1,8 - 6,4	1,8 - 6,4	1,8 - 6,4	0,0	4,3
Bestrahlungszeit [s]	0	0	0	30	60	90	120	150	180	210	240	300	300	300
Mittelwert Punktlastindex Is(50) [MN/m²]	3,401	3,106	2,362	2,048	2,988	3,357	3,515	3,412	3,394	3,398	2,838	2,698	3,007	2,660
Punktlastindex + Standardabweichung [MN/m²]	3,792	3,621	2,933	2,588	3,587	3,743	3,763	3,662	3,736	3,808	3,302	3,417	3,308	3,297
Punktlastindex - Standardabweichung [MN/m²]	3,010	2,591	1,790	1,508	2,388	2,972	3,268	3,163	3,053	2,988	2,374	1,978	2,706	2,022
Standardabweichung [MN/m²]	0,391	0,515	0,571	0,540	0,599	0,385	0,247	0,250	0,341	0,410	0,464	0,719	0,301	0,637

Bild 9: Mittlere Punktlastfestigkeit und Streuung für verschiedene Bestrahlungszeiten und Wassergehalte Odenwälder Buntsandstein

4.2 Versuchsergebnisse Eibelstädter Muschelkalk

Beim Eibelstädter Muschelkalk lag der Wassergehalt der Proben zwischen 1,83 % bis 6,40 %. Der Mittelwert betrug 0,7 %.

Grundsätzlich waren bis zur einer Bestrahlungsdauer von 120 s bei den feuchten und trockenen Probekörpern keine Auffälligkeiten, zu beobachten. Zudem waren auch mit bloßem Auge keine äußerlichen Veränderungen zu erkennen. Bei einer Bestrahlungszeit über 120 s traten teilweise kritische Reaktionen auf. Bei den wassergesättigten „nassen“ Proben war nach ca. 10 s der Beginn der Wasserverdunstung zu beobachten. Mit zunehmender Bestrahlungszeit waren Dampf- und Bläschenbildungen an den Probekörpern zu sehen. Ab einer Bestrahlungsdauer von ca. 50 s bis 60 s schienen die Probekörper äußerlich vollständig trocken zu sein. Einige Probekörper, die länger als 120 s bestrahlt wurden, wiesen nach der Bestrahlung eine Farbveränderung auf. Sie wurden stellenweise heller. Mit zunehmender Bestrahlungsdauer waren auch Stellen mit dunkelweißem Farbton zu erkennen. Nach 180 s waren an allen Probekörpern Veränderungen der Farbe zu sehen. Ein erster Probedurchlauf zur Erprobung der maximalen Bestrahlungszeit erzeugte innerhalb der Mikrowelle starke Reaktionen und führte zum Abbruch des Versuchs. Der Probekörper begann nach ca. 180 s an einer der rotbraunen Porenstellen, mit einem Durchmesser 0,5 cm bis 0,8 cm, zu glühen. Nach kürzester Zeit sprühten zusätzlich Funken, sodass sich die Mikrowelle nach einer Bestrahlungszeit von 195 s wegen Überhitzung automatisch abschaltete. Der Probekörper schien äußerlich unversehrt zu sein. Ähnliche Reaktionen in schwächeren Ausprägungen wurden auch an weiteren Probekörpern beobachtet. Diese Reaktionen entwickelten sich hauptsächlich in den Versuchsgruppen der feuchten und trockenen Probekörper, die einer Bestrahlungszeit von 180 s ausgesetzt wurden. Das Einsetzen der Glutbildung variierte zeitlich von Probekörper zu Probekörper. An den Porenstellen lufttrockener Probekörper kam es ca. 5 s bis 10 s vor dem Ende der Bestrahlungsdauer zu erkennbarer Glutentwicklung (s. Bild 10). Die ofentrockenen Probekörper bildeten ca. 15 s bis 30 s vor dem Ende der Bestrahlungszeit auffällige Glutstellen. Jedoch blieben Funken und weitere extreme Reaktionen aus. Deshalb konnten diese Versuche bis zu dem Bestrahlungsende durchgeführt werden. Die Glut an den betroffenen Probekörpern war lokal und ausschließlich an den rötbräunlichen Porenstellen in einem Ausmaß von ca. 0.5 cm bis 1,5 cm.

Bei der Durchführung der Punktlastversuche am Eibelstädter Muschelkalk (s. Bild 11) waren von den 169 Versuchen 38 Versuche ungültig. Die ungültigen Versuche traten verstärkt bei den feuchten Probekörpern auf. Bei der Analyse der Bruchbilder der ungültigen Versuche war deutlich zu erkennen, dass es primär zu Brüchen an Stellen mit einer ausgeprägten Porenbildung kam. Dies zeigt deutlich die Problematik von Punktlastversuchen an inhomogenem Material auf.

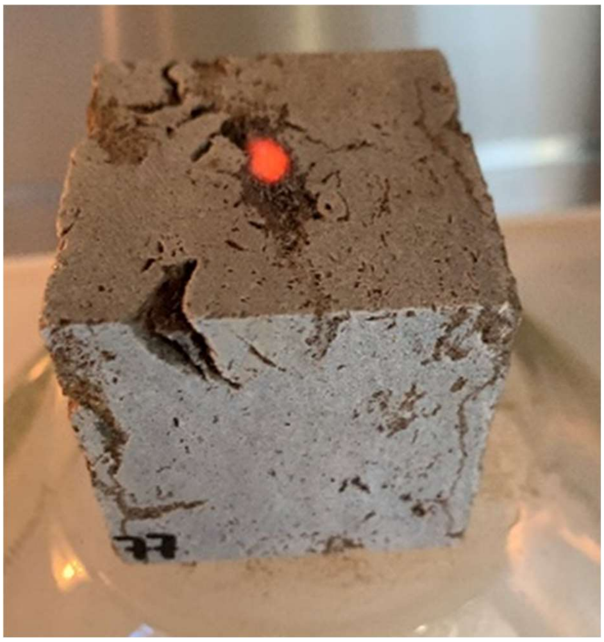


Bild 10: Beispiel Probekörper Eibelstädter Muschelkalk Glutstellen während der Bestrahlung

Bei der Auswertung der Punktlastversuche wurde auf eine Umrechnung der Punktlast in die einaxiale Druckfestigkeit verzichtet.

Bild 13 zeigt die Versuchsergebnisse der 130 gültigen Versuche in Abhängigkeit von den Bestrahlungszeiten und dem Wassergehalt. Die Ordinate gibt den Punktlastindex $i_s(50)$ an. Auf der Abszisse ist die Bestrahlungszeit aufgetragen.

Die Versuche der Versuchsgruppen 1 (VG 1), VG 6 und VG11 zeigen, dass ohne eine Mikrowellenbestrahlung, die feuchten Proben höhere Druckfestigkeiten und die wassergesättigten „nassen“ und die trockenen Proben geringere Druckfestigkeiten aufweisen. Nach einer Bestrahlungsdauer von 30 s kommt es bei den feuchten und wassergesättigten „nassen“ Proben (VG 2 und VG 9) zu einer deutlichen Reduktion der Druckfestigkeiten. Bei den trockenen Proben (VG12) ist im Grunde keine Reduktion der Druckfestigkeit feststellbar. Ab einer Bestrahlungsdauer von 60 s ergeben sich auch für die trockenen Proben (VG 3) wesentlich geringere Druckfestigkeiten bzw. liegen diese auf dem Niveau der feuchten und wassergesättigten „nassen“ Proben.

Im Rahmen der Punktlastversuche am Eibelstädter Muschelkalk wurden die Temperaturen im Bereich des Kerns (s. Abs. 3.2) gemessen. Im Bild 12 sind die Mittelwerte der Oberflächentemperatur im Bereich des Probenkerns in Abhängigkeit von der Bestrahlungszeit aufgetragen. Hier lässt sich ein linearer Zusammenhang feststellen.


Bild 11: Beispiel an einem Probekörper aus Eibelstädter Muschelkalk nach einer Bestrahlungsdauer von 120 s.

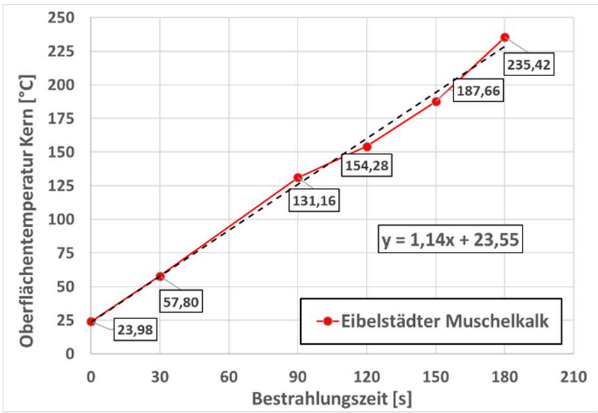
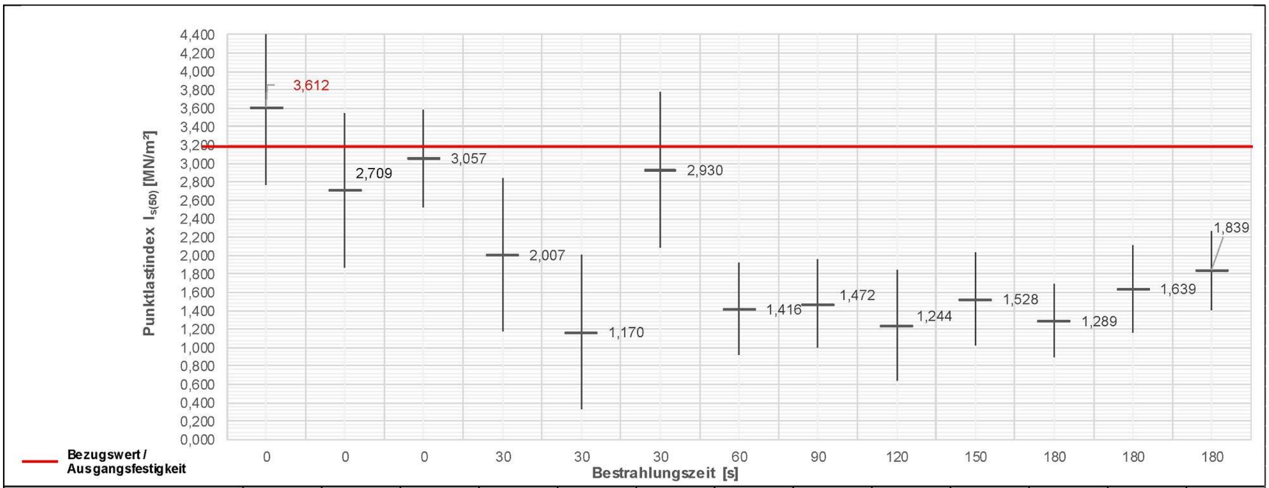


Bild 12 Mittelwerte Oberflächentemperatur Kern Eibelstädter Muschelkalk

4.3 Versuchsergebnisse Tittlinger Granit

Da sich bei den Versuchen mit dem Odenwälder Buntsandstein (s. Abs. 4.1) im Gegensatz zu den Versuchen mit dem Eibelstädter Muschelkalk (s. Abs. 4.2) zeigte, dass es nach einer Bestrahlungsdauer von 30 s zu einer Zunahme der Druckfestigkeiten kommt, wurde eine weitere Gesteinsart dem Tittlinger Granit untersucht. Die Druckfestigkeiten wurden bei diesen Versuchen



Bezeichung Proben	VG 1	VG 8	VG 11	VG 2	VG 9	VG 12	VG 3	VG 4	VG 5	VG 6	VG 7	VG 10	VG 13
Art der Probe	Feuchte Probe	Nasse Probe	Trockene Probe	Feuchte Probe	Nasse Probe	Trockene Probe	Trockene Probe	Feuchte Probe	Feuchte Probe	Feuchte Probe	Feuchte Probe	Nasse Probe	Trockene Probe
Anzahl Proben	10	10	10	10	10	10	10	10	10	10	10	10	10
Wassergehalt [%]	0,1 - 1,3	1,9	0,0	0,1 - 1,3	1,940	0,0	0,1 - 1,3	0,1 - 1,3	0,1 - 1,3	0,1 - 1,3	0,1 - 1,3	1,900	0,0
Bestrahlungszeit [s]	0	0	0	30	30	30	60	90	120	150	180	180	180
Mittelwert Punktlastindex Is(50) [MN/m²]	3,612	2,709	3,057	2,007	1,170	2,930	1,416	1,472	1,244	1,528	1,289	1,639	1,839
Punktlastindex + Standardabweichung [MN/m²]	4,453	3,550	3,590	2,841	2,010	3,771	1,913	1,954	1,844	2,029	1,685	2,110	2,266
Punktlastindex - Standardabweichung [MN/m²]	2,772	1,868	2,524	1,174	0,329	2,090	0,920	0,991	0,644	1,027	0,892	1,168	1,412
Standardabweichung [MN/m²]	0,841	0,841	0,533	0,833	0,841	0,841	0,497	0,482	0,600	0,501	0,396	0,471	0,427

Bild 13: Mittlere Punktlastfestigkeit und Streuung für verschiedene Bestrahlungszeiten und Wassergehalte Eibelstädter Muschelkalk

nicht mit dem Punktlastversuch sondern mit dem einaxialen Druckversuch (s. Bild 14) ermittelt. Dabei ging es im ersten Schritt darum, eine Tendenz bei der Veränderung der Druckfestigkeit durch die Mikrowellenbestrahlung festzustellen.

In Bild 15 sind die einaxialen Druckfestigkeiten in Abhängigkeit von der Bestrahlungsdauer dargestellt. Hier zeigte sich, dass es nach einer Bestrahlungsdauer von 60 s zu keiner signifikanten Änderung der Druckfestigkeit kommt. Bei einer längeren Bestrahlungsdauer ist eine Zunahme der Druckfestigkeit messbar. Nach einer Bestrahlungszeit von 255 s ist eine Reduktion der Druckfestigkeit in geringeren Maße erkennbar. In einen darauffolgenden Versuch zerbrach der Probenkörper nach einer Bestrahlungsdauer von 390 s.

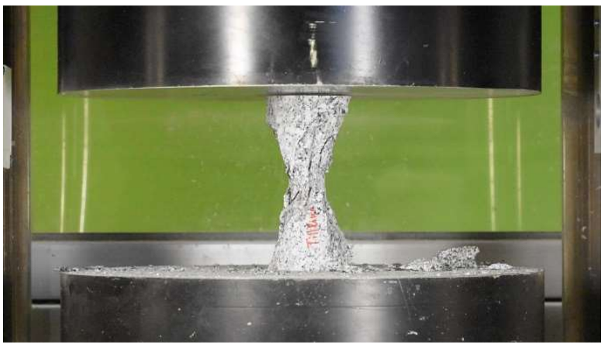


Bild 14: Beispiel Bruchbild Probekörper Tittlinger Granit

Weitere Versuche mit dem Tittlinger Granit werden zurzeit durchgeführt.

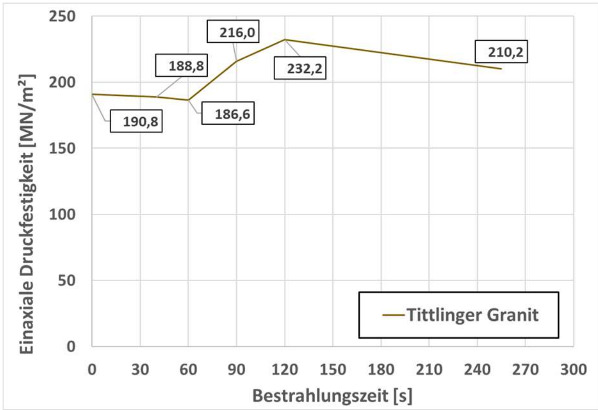


Bild 15: Einaxiale Druckfestigkeit für verschiedene Bestrahlungszeiten Tittlinger Granit

4.4 Vergleich der Versuchsergebnisse

Beim Vergleich der Ergebnisse der Versuche mit dem Odenwälder Buntsandstein und dem Eibelstädter Muschelkalk zeigen sich deutliche Unterschiede (s. Bild 16). Während beim Odenwälder Buntsandstein nach einer Bestrahlungsdauer von 30 s eine deutliche Reduktion der Druckfestigkeit erfolgt, steigt bei längeren Bestrahlungsdauern die Druckfestigkeit an. Erst ab einer

Bestrahlungsdauer von 210 s reduziert sich die Druckfestigkeit merklich. Dagegen kommt es beim Eibelstädter Muschelkalk kontinuierlich mit zunehmender Bestrahlungsdauer zu einer Reduktion der Druckfestigkeit, die nach einer Bestrahlungsdauer von 60 s auf einem Niveau stagniert. Beim Vergleich der Ergebnisse zwischen den Versuchsergebnissen des Odenwälder Buntsandstein mit denen des Tittlinger Granit (s. Bild 15) ist eine ähnliche Tendenz in der Entwicklung der Druckfestigkeiten in Abhängigkeit von der Bestrahlungsdauer zu erkennen.

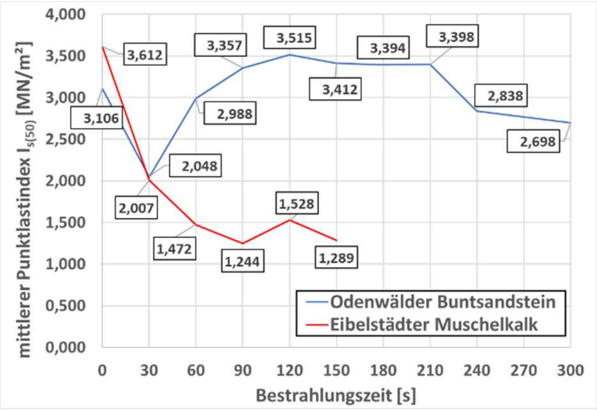


Bild 16: Vergleich Odenwälder Buntsandstein / Eibelstädter Muschelkalk Mittlere Punktlastfestigkeit für verschiedene Bestrahlungszeiten „feuchte“ Proben

Tab. 1: Quarzanteil der einzelnen Gesteinsarten

Gesteinsart	Quarzanteil	Quelle
Odenwälder Buntsandstein	63,9 %	[13]
Eibelstädter Muschelkalk	3,18 %	[14]
Tittlinger Granit	23,8 %	[15]

Bei der Betrachtung des Quarzanteils der einzelnen Gesteinsarten (s. Tabelle 1) fällt auf, dass der Eibelstädter Muschelkalk nur einen sehr geringen Quarzanteil im Gegensatz zum Odenwälder Buntsandstein bzw. Tittlinger Granit aufweist. Danach scheint ein hoher Quarzgehalt im Gestein dazu zu führen, dass sich nach einer Bestrahlungsdauer, die länger als 30 s bzw. 60 s ist, die Druckfestigkeit des Gesteins vergrößern. Erst nach längeren Bestrahlungszeiten ergeben sich dann geringere Druckfestigkeiten im Gestein.

5. Zusammenfassung und Ausblick

Die durchgeführten Versuche am Odenwälder Buntsandstein und Eibelstädter Muschelkalk zeigen deutlich, dass die Druckfestigkeit abhängig vom Wassergehalt und von der Bestrahlungszeit durch die Mikrowellen ist. Dabei hat die Bestrahlungszeit den maßgebenden Einfluss. Wieso beim Tittlinger Granit dieses Phänomen bei den bisherigen Versuchen nicht klar erkennbar ist, ist Inhalt weiterer Untersuchungen. Ein Grund hierfür kann das Gefüge sowie der Quarzgehalt der Gesteine sein.

Bei den Versuchen am Eibelstädter Muschelkalk ist eine lineare Abhängigkeit der Oberflächentemperatur im Bereich des Probenkerns von der Bestrahlungszeit festzustellen.

Die hier vorgestellten Ergebnisse zeigen jedoch auf, dass noch weitere Untersuchungen erforderlich sind. Hierbei sollen weitere Randbedingungen (z. B. weitere Gesteinsarten, längere Bestrahlungsdauern, höhere Bestrahlungsleistungen) analysiert sowie weitere Parameter (z. B. Porosität, Ultraschallgeschwindigkeit) untersucht werden.

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Appendix B-2

Title:	**Rock tunnelling in small diameters: latest trends and technologies**				
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NASTT 2022 No-Dig Show
Minneapolis, Minnesota
April 10-14, 2022

TA-T2-01

Rock tunnelling in small diameters: latest trends and technologies

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1. ABSTRACT

In small diameter rock tunnelling, the continuous further development of technologies plays a key role to overcome the limitations in drive length and to improve performance. During the last decades the application range of slurry microtunnelling has been considerably extended and more demanding projects have been designed for underground utilities installations.

Nevertheless, the ground conditions still play a key role and determine the limits for alignment design and the possible use of the different trenchless construction methods. In hard rock conditions, the applicability of slurry microtunnelling has been especially limited in the non-accessible diameter range in the past. With the new AVN 800 HR for hard rock, Herrenknecht has developed a machine concept, equipped with a stronger main bearing, three times higher push force and an adapted cutting wheel design using TCI (Tungsten Carbide Inserts) cutters. These cutting tools offer a high degree of wear resistance, enabling drives of up to 200 meters without interventions as proven in internationally referenced projects.

For the smaller diameters of AVN 400 to AVN 600, a new rock cutterhead generation has been designed with Tricone cutters, having a comparable wear-resistance as the TCI solution. These developments, also combined with the new jet pump system for long drives in small diameters, wear protection and monitoring lead to a new powerful generation of slurry machine concepts for rock conditions. In the future, this will further push the boundaries of microtunnelling and alternative methods like E-Power Pipe® and Direct Pipe® in challenging ground to make trenchless solutions even more attractive for consultants and clients.

2. INTRODUCTION

For Utility Tunnelling the current focus is on longer drives, in particular in the small-diameter range. With longer drives the required capability of the Microtunnel Boring Machine (MTBM) to cope with a wider geological range on one single drive is significantly increased. That was one of the driving factors for the development of the AVNS technology utilizing a jet pump for the slurry discharge system down to 18 inches in diameter for different applications like the new E-Power Pipe method and small-diameter Direct Pipe for underground cable or pipeline installations.

In standard slurry microtunnelling, the new AVN 800 HR (for hard rock), has been developed to provide more power, higher torque, jacking loads, and penetration to meet the design criteria for potential harder rock along the alignment. The design of cutting wheel and tools have been fundamentally changed with previous experiences of new cutting tools in the mining and pipeline industry. The new hard rock tool is a multi-ring, conical TCI cutter with Tungsten Carbide Inserts. Successful reference projects like the 'Water Main Improvement Project' in Hong

Kong in 2020 show the capability of the new machine design in abrasive hard rock conditions. The AVN 800 HR is not limited to hard rock applications. It can also be equipped with a standard or mixed soil cutting wheel, according to the prevailing conditions.

Another trend in urban utility installations is the design of deeper tunnel alignments, especially for sewage disposal. The main reason for this trend is the enormous number of existing utilities in the inner-city areas and the overall intention of municipalities to minimize the amount of pumping stations by tendering gravity flow tunnels. With the increasing depth, not only does the likelihood of encountering hard rock grow, but also the groundwater pressure to be handled by the MTBM.

In this context, digitalization will offer ever improving possibilities for data recording and evaluation in order to obtain a valid assessment for wear prediction and tool change for optimum tunnelling performance. An example of this was a previous investigation made of several small-diameter hard rock MTBM projects resulted in developing a device to control the roll of the MTBM in hard rock sections.

As in all trenchless projects, a thorough geotechnical investigation and assessment is the basis to select the most appropriate trenchless method and tools. Special attention must be paid to the correct determination of the relevant geotechnical parameters to enable predictions on performance and wear. These values are often insufficiently considered in small-diameter rock excavations, but they are of great importance, also for the success of the project particularly because of the small, non-accessible machine diameter and the special demands on the machine technology in hard rock.

3. ROCK CLASSIFICATION

In a strictly geological classification, rocks are classified based on their origin and their stratigraphic and lithologic properties. Most rocks on the earth's surface are sedimentary rocks, while igneous and metamorphic rocks play a minor role. Rock as engineering material can be defined as lithified or indurated, crystalline or non-crystalline material. Rock is encountered in masses and as large fragments which have consequences to design and construction differing from those of soil. Classifications of igneous, metamorphic, sedimentary, and pyroclastic rocks can be applied, but more important are its engineering descriptive criteria and the physical properties of the rock and the rock mass.

3.1. Weathering

Rock can be subject to chemical or mechanical weathering, generally decreasing the strength of the material and changing its chemical physicochemical properties. Therefore, a fresh rock with no visible sign of material weathering, very high strength, and high rock mass indices could gradually change over slightly and highly weathered to completely weathered material described as intact friable soil which may be weakly cohesive. The final product of rock weathering would be soil again, where the original rock fabric is completely destroyed. This soil material is also called sediment, which could be compacted again and eventually form a sedimentary rock. Due to their generally small overburden, many small-diameter utility tunnels are constructed in weathered rock.

Table 1. Grades of weathering

DEARMAN, 1976 // IRSM, 1977		
grade	term	description
VI	residual and colluvial soils	All rock material is converted to soil. The original rock structure is completely destroyed. The point of geological pick indents easily in depth. When the rock material is struck by the hammer doesn't emit sound.
V	**completely** weathered rock	All rock material is completely discolored and converted to soil, but the original mass structure is still visible. The point of geological pick indents easily. When the rock material is struck by the hammer it emits a dull sound.
IV	**highly** weathered rock	All rock material is discolored. The original mass structure is still present and largely intact. The point of a geological pick not indents easily. The rock material makes a dull sound when it is struck by the hammer.
III	**moderately** weathered rock	The rock material is discolored, but locally the original color is present. The original mass structure is well preserved. The point of geological pick produces a scratch on the surface. The rock material makes an intermediate sound when it is struck by the hammer.
II	**slightly** weathered rock	Discoloration is present only near joint surface. The original mass structure is perfectly preserved. The point of geological pick scratches the surface with difficulty. The rock material makes a ringing sound when it is struck by the hammer.
I	**fresh** rock	The rock material isn't discolored and has it's original aspects. The point of geological pick scratches the surface with high difficulty. The rock material makes a ringing sound when it is struck by the hammer.

3.2. Rock values

Rock can be described based on its petrographic, mineralogical, or geotechnical properties. For small-diameter tunnelling, especially the geotechnical properties are important for several aspects of the project. After a successful borehole campaign, important rock values can be measured in the laboratory, strongly influencing the design and application of MTBMs. The most common rock laboratory values are strength values, comprising:

- uniaxial compressive strength σ_c (UCS)
- tensile strength σ_t (TS)
- point load strength index (PLI)

Table 2. Rock classification

IRSM (1978) grade	description	approx. range of uniaxial compressive strength (MPa)	Point Load Index I_s (MPa)
R0	extremely weak rock	0,25 - 1,0	rocks with a uniaxial compressive strength below 25 MPa are likely to yield highly ambiguous results under point load testing
R1	very weak rock	1,0 - 5,0	
R2	weak rock	5,0 - 25	
R3	medium strong rock	25 - 50	1 - 2
R4	strong rock	50 - 100	2 - 4
R5	very strong rock	100 - 250	4 - 10
R6	extremely strong rock	>250	>10

These values are required for any kind of performance prediction and are key factors for the machine type recommendation, cutterhead design and cutter selection. The deformation modulus or the modulus of elasticity (=E-Modulus, Young's modulus) is of less interest for the appropriate selection and design of a MTBM. The abrasivity of the rock can be characterized by the following parameters:

- Cerchar abrasivity index (CAI)
- Drilling rate index (DRI) / cutter life index (CLI) / bit wear index (BWI)
- Equivalent quartz content (Equ)

Table 3. Cerchar Abrasivity Index

CAI	CERCHAR (1986) (pin hardness 54)
0,3 - 0,5	not very abrasive
0,5 - 1,0	slightly abrasive
1,0 - 2,0	abrasive
2,0 - 4,0	very abrasive
4,0 - 6,0	extremely abrasive
6,0 - 7,0	-

It has to be stated that the CAI is easy to obtain and considered industry standard, while the DRI, CLI and BWI can only be measured by very few laboratories worldwide which makes them very much less common, especially for small-diameter tunnelling projects.

Another interesting property of mostly sedimentary rock is slaking. The following tests describe and measure the disintegration behavior of the rocks, which is especially important when it comes to the layout of the slurry circuit and the design and dimensioning of the slurry treatment plant (STP).

- L.A. Abrasion apparatus value (LAV)
- Slake durability index test
- LCPC abrasivity test

Furthermore, some rock types tend to swell in combination with water, which is important to measure and understand for example for the design of the overcut and the selection of the right bentonite mixture:

- pressure swelling & swelling displacement tests (HUDER & AMBERG, HENKE & KAISER, PAUL (DGEG), IRSM, THURO & SPAUN)

Of course, all parameters must be obtained from samples from the tunnel depth or at least from rocks which are representative of what is believed to be characteristic for the tunnel alignment. Therefore, the location of the boreholes should be not exactly on, but also not too far away from the planned route (some meters of distance are recommended) and the frequency and therefore data quality should be high. Even for the smallest hard rock project, the basis of every geotechnical report must be a comprehensive description of the rock types including pictures of the boreholes and a detailed geotechnical profile, allowing to connect the geological and technical information.

3.3. Rock mass classification

In contrast to the rock values, which describe the geotechnical properties of one sample, also the whole rock mass can be classified from a geotechnical perspective. Most of the classification systems are composed of the above-mentioned rock parameters and other parameters including information about the fracturing and groundwater. The purpose of these classification systems is the assessment of geological conditions in terms of construction engineering. They provide a recording of the characteristics into appropriate categories and an interpretation of their effects on the stability of the rock structure or cavity to be excavated (i.e., their geomechanical effects). Some of them result in proposals for excavation and securing measures for the different rock classes. The most important rock mass classification systems are:

- Rock Quality Designation (RQD); DEERE et al. 1966
- Rock Mass Rating (RMR, BIENIAWSKI1974 (Council for Scientific and Industrial Research (CSIR) Geomechanic Classification)
- Q-system, BARTON et al. 1974 (NGI-index)
- Geological Strength Index (GSI), HOEK 1995

Table 4. Rock Quality Designation, Rock Mass Quality

RQD %	Rock Quality Description [DEERE & DEERE, 1989]
0 - 25	very poor
25 - 50	poor
50 - 75	fair
75 - 90	good
90 - 100	excellent

Norw. Geol. Inst. (NGI) Q	Class	Rock Mass Quality for tunnelling
< 0,01	G	exceptionally poor
0,01 - 0,1	F	extremely poor
0,1 - 1,0	E	very poor
1,0 - 4,0	D	poor
4,0 - 10,0	C	fair
10,0 - 40,0	B	good
40,0 - 100,0	A	very good
100,0 - 400,0	A	extremely good
> 400,0	A	exceptionally good

4. TYPICAL ROCK FORMATIONS IN NORTH AMERICA

The basement of North America is basically formed by four major units. The Precambrian shield which covers the center and most of the eastern part of Canada consists of very old and often very competent rocks like gneiss, shist and other metamorphic rocks. The interior platform consists of a basement made of metamorphic and igneous rocks which are covered by sedimentary rocks like sandstones and mudstones. The Paleozoic unit, found in the Appalachian Belt is dominated by sedimentary rocks like limestone and siliclastica. In the west, the Mesozoic and Cenozoic Cordilliera, dominated by volcanic and plutonic rocks, forms the Rocky Mountains, the Basin-and-Range Province, and the Sierra Nevada. It encloses the Colorado Plateau, consisting of many sedimentary layers over Precambrian rock, which manifest spectacularly in the Grand Canyon. The south-eastern Atlantic plain around the Gulf of Mexico is composed primarily of sedimentary rock and unlithified sediments, hosting the hydrocarbon occurrences of Texas and the Gulf of Mexico.

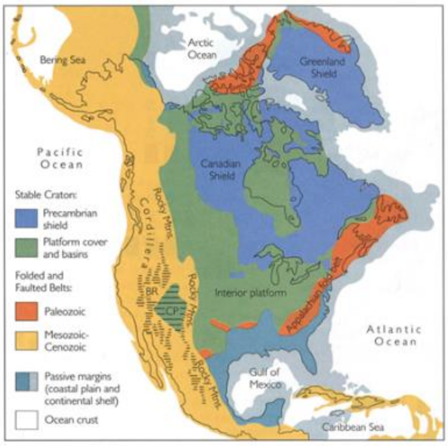

Figure 1: Geological-tectonic Units of North America (Source Press & Siever, Understanding Earth)

Small-scale areas and locations have their own typical rock conditions like the very hard granite in New York, the sandstones, siltstones, and shale in Rhode Island or San Francisco's Franciscan rock complex, consisting of shale, sandstone, greenstone, chert, greywacke, and serpentinite. Finally, the northern part of the North American continent was subject to glaciation, resulting in the exposure of previously covered rock masses but also in the deposition of large-scale glacial deposits containing everything from clay to car-sized, extremely strong boulders which behave like hard rock.

5. MTBM DESIGN FOR HARD ROCK APPLICATIONS

Based on a thorough geotechnical investigation, the trenchless method and equipment is selected. Knowing the harsh conditions in hard rock, more attention is paid to the MTBM performance factors, and the design of the critical components described later in this chapter, such as cutting wheel, tooling, capacity of main bearing or anti-roll measures. It is important to note, that all components and their capacity have to be adjusted to each other. Thus, successful small-diameter tunnelling is determined by the successful incorporation of all components into one functioning system. In order to increase performance, it is important to find the system's bottleneck and increase its capacity. The whole system can be only as effective as its weakest component allows. This chapter presents the equipment parts which are key to further increase the performance of a MTBM.

5.1. Critical rock properties for MTBM performance

In order to choose the correct MTBM type, to design the best possible cutting wheel and to predict the tunnelling performance, all rock and rock mass properties described above are advisable. However, it is well known that for small-scale, small-diameter projects it is not possible to determine all parameters. However, the most important and minimum parameters for each project should be the following:

- Strength: UCS; TS, PLI
- Abrasivity: CAI
- Rock mass: RQD, (Q)
- Information about groundwater (pressure, composition etc.)

The basis for these parameters should always be a sound geological profile, where the geological and geotechnical information can be linked with project-specific information like the depth of the tunnel alignment. On the basis of these parameters, a basic performance prediction for the project is possible.

5.2. Cutting wheel design for hard rock conditions

The cutting wheel´s tooling composition is the most critical part in rock applications. Tool size and arrangement are determined based on the rock properties. This arrangement leads to reasonable rock chip sizes which can be handled by the discharge system. Wear protection plates and hard facing play a key role in protecting the cutting wheel steel structure from excessive wear.

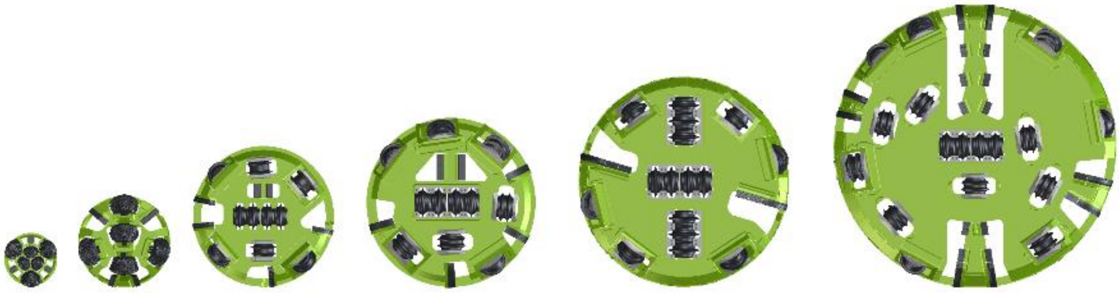

Figure 2: Exemplary hard rock cutting wheel designs for AVN 400 up to AVN 2500

New cutting wheels have been developed for microtunnelling in hard rock to provide:

- extra wear protection, like TCI cutters with hard facing and sandwich wear plates on the rim
- high performance bearing of the cutters for higher loads
- stable solid structure to take the higher loads on the cutters

5.3. Hard rock tools and tool selection process

For MTBMs, three main cutting tool types can be considered. The most common cutting tool remains the disc cutter, which is well known from large diameter hard rock TBMs. However, due to space constraints, the disc cutter is normally modified into a double- or triple disc cutter, which decreases the spacing and therefore leads to faster chipping of the rock. On the other side, the larger number of rings on cutters decreases the available thrust force per ring and therefore decreases the probability of creating tensile cracks which lead to chipping. This makes it important, that small-diameter hard rock AVN machines have a capability of high jacking forces and both a strong main bearing and cutter bearing.

Figure 3: Overview of hard rock cutting tool types for microtunnelling: disc cutter, TCI cutter, milled tooth cutter (from left to right)

If this problem cannot be solved with a technical solution, or if high requirement on the lifetime of the cutters exists, TCI or button cutters are recommended. This cutter type exerts a point load force on the rock, resulting in numerous small chips. Due to the tungsten carbide insert, the TCI cutter is considered especially wear-resistant, which is beneficial for long drives in small diameters, where cutterhead interventions are not possible.

Milled tooth cutters can fill a niche in small-diameter tunnelling based on the observation that normal disc and TCI cutters have comparably low performances in low strength, ductile-behaving rocks. The rocks are extremely difficult to chip, and conventional cutters tend to create marks or track grooves into the face, but no tensile fractures resulting in chips. Therefore, a tooth cutter can be an option in low-strength rocks in order to ensure high penetration rates. The tooths penetrate deeply into the rock and lever the sometimes already loosened rock pieces out of the rock mass. Furthermore, it must be stated that typical soft to mixed ground tools like chisels, rippers, knifes and scrapers can make a significant contribution to the rock cutting in low-strength rocks.

5.4. Wear calculation

Wear prediction for small-diameter hard rock MTBMs can be based on two pillars, both empirical and semi-theoretical approaches. However, it has to be stated that the wear prediction for small diameter MTBMs is a largely undeveloped field with very little academic research and scarce information which has preciously been kept within the companies involved. There are several lab tests which quantify the wear of a rock on a steel material (e.g. CAI, Los Angeles Abrasion Machine Test or the LCPC). Several attempts were made to convert the resulting values into a lifetime of a cutter.

The NTNU Trondheim developed an alternative approach while trying to determine the drillability (including the drilling rate, bit wear, and cutter life) based on the brittleness, the surface hardness, and the wear capacity of a rock. The cutter life index is calculated by use of surface hardness and the wear capacity on cutter ring steel quality.

However, this value is rarely determined on a global scale, which can only be obtained by a quite complicated test. This test is not often deployed outside Scandinavia, especially when talking about small-diameter projects.

Therefore, semi-theoretical wear calculation for small-diameter tunnelling projects is based on the CAI, which gives a good indication of abrasivity. A first order estimation of the wear caused by a measured lab abrasivity is given in Figure 4. However, these values are valid for 17” cutters and can be confirmed or corrected by the wear calculation based on the CSM model. Here, also smaller-size cutters can be deployed. Besides the input parameters already used for the penetration prediction, the CAI plays a key role at the CSM model. For wear prediction, using the proportionality between the abrasion of the cutting ring and the rolling path, the maximum length of the cutting path is first determined as a function of the abrasivity of the rock. Since this relationship only takes into account the primary wear, this is reduced and related to the drill head geometry to obtain the mean net tool life.

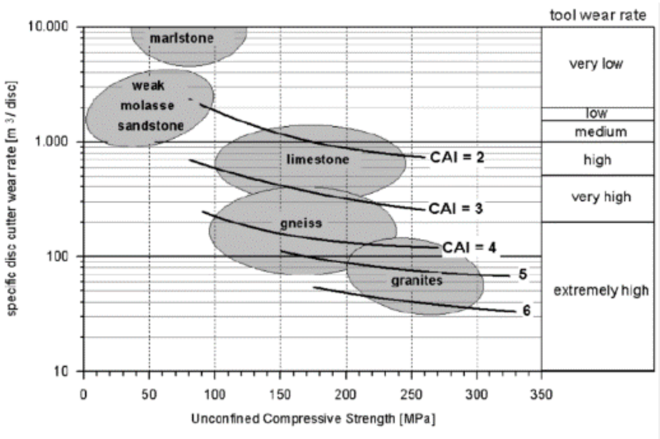

Figure 4: Wear prediction in hard rock excavation for 17” disc cutters. (MAIDL, B., SCHMID, L., RITZ, W., HERRENKNECHT, M., 2008. Hardrock Tunnel Boring Machines. Wiley. https://doi.org/10.1002/9783433600122.)

Even if the results are in the same ranges as proposed by Maidl et al. (2008) and can or must be backed by empirical data gathered from previous projects, most of these results are only valid for large diameter cutting heads. Corrections must be made for the smaller diameter of the cutter on small MTBMs, and maybe also made for different material and the number of rings, which generally is larger than 1 for small cutters. Therefore, the spacing gets smaller, but the forces which can be applied by one ring decrease. Smaller cutters also result in much less wear volume. It is also worth mentioning that the cutterhead of a small diameter MTBM is substantially differently designed compared to a large cutterhead. The share of center and caliber areas on the cutterhead surface grows with decreasing MTBM diameter. Therefore, wear can be very irregular, and a precise wear prediction of one specific cutter cannot be made. It is recommended to provide an average value for the whole set of cutters, keeping in mind that the center and caliber cutters might wear faster than the cutter at the face area. Due to this uncertainty in wear prediction of the cutters, it is generally advisable - if applicable - to reduce the cutterhead intervention intervals especially at the beginning of the project and to invest in high quality, wear-resistant cutters.

5.5. Main bearing and main drive

The main bearing is the critical link between the cutting wheel and the jacking system of the MTBM including the steering cylinders. It has not only to transfer the jacking loads via the cutting wheel to the tunnel face, but at the same time, it has to deal with the torque generated by the main drive and the rotation speed of the cutting wheel to chip the rock. At the same time, the main bearing seals off the excavation chamber against the atmospheric pressure in the tunnel. That is why the design of the main bearing is considered as crucial for the success of the tunnel operation. In order to minimize the risk of main bearing failures, especially on hard rock projects where used equipment is allowed, a refurbishment or even its replacement should be considered.

5.6. Steering cylinders

The steering cylinders need to be strong enough to transfer the necessary thrust force to overcome the ground water pressure and the contact force of the cutters to chip the rock. In addition, the stroke of the steering cylinders needs to be long enough to enable the machine to do curved drives and operate the machine on the given tunnel route.

5.7. Telescopic station

A telescopic station is vital especially for longer drives. It consists of a ring of hydraulic cylinders assembled directly behind the MTBM cans. With the telescopic station the frictional loads of the MTBM are separated from the tunnel alignment. By operating the telescopic station, the thrust loads can be maximized and sensitively control the advancement of the machine, without overloading the tools.

5.8. Anti-roll solutions

An anti-roll unit is another important factor in hard rock microtunnelling. Especially in small diameters, good lubrication leads to little friction between the shield and the surrounding rock. Therefore, the MTBM tends to roll already at low torque. However, high thrust forces, high revolution, and all available torque is required especially in a small cutterhead with small, multi-ring cutters in order to transfer thrust forces per cutter, which are high enough to chip the rock. From a technical side, anti-roll units can be divided in grippers just behind the telescopic station and in roller disc cutters mounted on hydraulic cylinders inside the shield. These measures make sure that full thrust can be applied to achieve maximum performance rates.

Figure 5: Exemplary anti-roll units: gripper version (left) or disc cutter version (right)

5.9. Intermediate jacking stations

Intermediate jacking stations are important, especially for long drives, providing intermediate thrust force on a longer tunnel section. They assure that the MTBM can be moved even when the friction on the pipe section is too high, or the pipes reach their jacking capacity. They are another key success factor for MTBMs to be able to drive long distances and especially in hard rock applications.

5.10. Main jacking station

The main jacking station is located in the launch shaft and has the purpose to move the MTBM and the product pipes towards the exit shaft. However, its thrust capacity is oftentimes limited by the design and loads of the pipes itself, which leads to limited alignment length or the more frequent use of the intermediate jacking stations.

5.11. Jacking pipes

Jacking pipes need to be strong enough to transfer the jacking loads from the main – or intermediate jacking station to the MTBM at the front end of the pipe string. Various types of jacking pipe materials are being used worldwide including steel, RCP, FRP. Crucial for the success is the design, with sufficient safety factor, quality in manufacturing and quality control before and during installation in the launch shaft.

A further critical component is the pipe joint, which has to transfer the jacking loads from pipe to pipe and needs to be strong enough to avoid damage. This is extremely important in curved alignments where only part of the pipe cross section can be utilized for the load transfer.

6. AVN 800 HR FOR HARD ROCK

For microtunnelling in hard rock, Herrenknecht has developed a new AVN 800 HR (OD 975 mm), equipped with a stronger main bearing and an adapted cutting wheel design. The machine excavates the rock with a three times higher jacking force on the cutting wheel in comparison to the traditional AVN of the same size. A flushing ring at the bottom of the machine with remote-controlled ball valve prevents fine particles in the annulus, thus reducing jacking forces.

Technical improvements:

- For rock with high UCS: up to 200 MPa
- High wear-resistance of TCI cutter discs
- Extended drive length: up to 200 m
- Torque: 55 kNm
- Increased rotation speed of cutting head: up to 26 rpm @ 260 l/min
- Compact jacking frame to achieve a small launch shaft of Ø 3.2 m
- Operation by standard control container C20 possible
- Flushing ring: fine rock particles to be kept away from annulus
- Extension kit OD 1295 mm with rock cutting wheel, up to 80 MPa possible

Instead of the 2-ring cutter discs, the cutting wheel is fitted with conical TCI cutters. Made for hard rock, these tungsten carbide cutting tools offer a high degree of wear resistance which makes longer drives without interventions possible. TCI cutters have already proved successful in the operation of Herrenknecht Mining Raise Boring Rigs and of the Full-Face Hole Opener for Horizontal Directional Drilling.

Figure 6: AVN 800 HR for hard rock with compact jacking station

After several tests at the Herrenknecht yard in Schwanau, the machine had its first operation on a 34 m test drive in Clara mine, Germany, where rock strengths of up to 140 MPa (Ø 60 MPa) have been handled successfully. The peak performance of the machine was 35 mm/min (Ø 21 mm/min).

7. REFERENCE PROJECT HONG KONG, WATER MAINS IMPROVEMENT PROJECT

7.1. Project description

The pipe jacking project is part of the larger water and saltwater mains improvement project with an overall length of 56 kilometers. It involves installation and commissioning of new pipelines, and rehabilitation and surveying of existing pipelines with diameters of up to DN 1400. The project is located in Hong Kong and is owned by the Water Supplies Department. Pipe jacking has been selected as the preferred method to install the section on Wood Road in the Wan Chai area. Hong Kong´s contractor VTEC (Victory Trenchless Eng. Co. Inc.) has been awarded to install the 107 meters long section, with a constant radius of 153 meters. The complete tunnel alignment leads through granitic rock (grade II) with maximum UCS of 200 MPa.

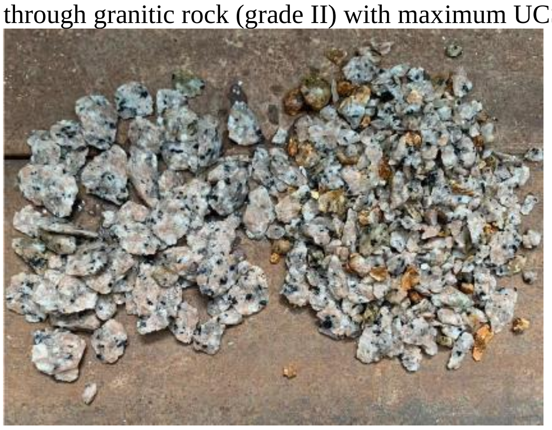

Figure 7: Granite rock chips from the separation

7.2. Jacking pipe

A steel pipe with 3 meters length has been selected for the installation. It proved being beneficial to provide enough support for the higher jacking loads encountered in this hard rock application. An additional benefit of the welded steel pipes for hard rock is the capability to counteract the roll, generated by the higher cutting wheel torque needed to chip the rock.

7.3. Selected MTBM

Due to the hard rock condition with a UCS of up to 200 MPa and the small diameter of only 960 mm (OD), an AVN 800 HR has been selected. As cutting tools, conical 317mm cutters with TCI inserts have been selected as shown in Figure 8. Due to the high abrasivity of the rock, the cutting wheel has been armored with additional protection plates especially in the rim area and additional hard facing in all critical zones. The AVN 800 HR has an installed power of 90 kW, enabling a cutting wheel rotation of max. 26rpm @ 260l/min and a maximum torque of 55kNm.

Figure 8: AVN 800 HR designed for operation in hard rock

7.4. Performance data

It took an overall 60 days to complete the drive, including several idle days. Average daily performance was 4m/day. During a learning section at the beginning of the drive, the cutting wheel drive was adjusted to maximize the performance. The adjustment measures included the replacement of hydraulic pump in the control container to facilitate a higher cutting wheel rotation speed of up to 26 rpm.

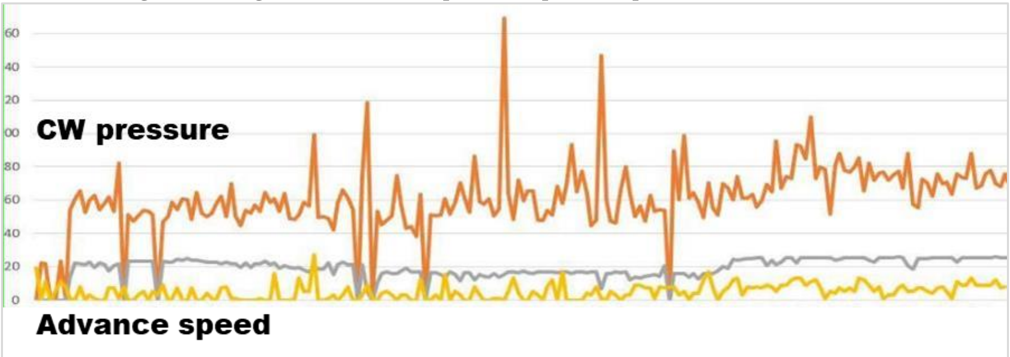

Figure 9: Exemplary cutting wheel pressure and MTBM advance speed

7.5. Jobsite setup

As usually known for projects in Hong Kong, space to set up the equipment for the tunnelling operation is very limited. This resulted in additional challenges, not only for the assembly of the machine, but also for the regular pipe extension and welding with an average welding time of 2-3 hours. An extremely compact launch shaft design had been chosen with approx. dimensions of 3.5 m width and 6.5 m length. Given the abrasivity of the rock, there was only moderate wear of the cutting tools (see Figure 10).

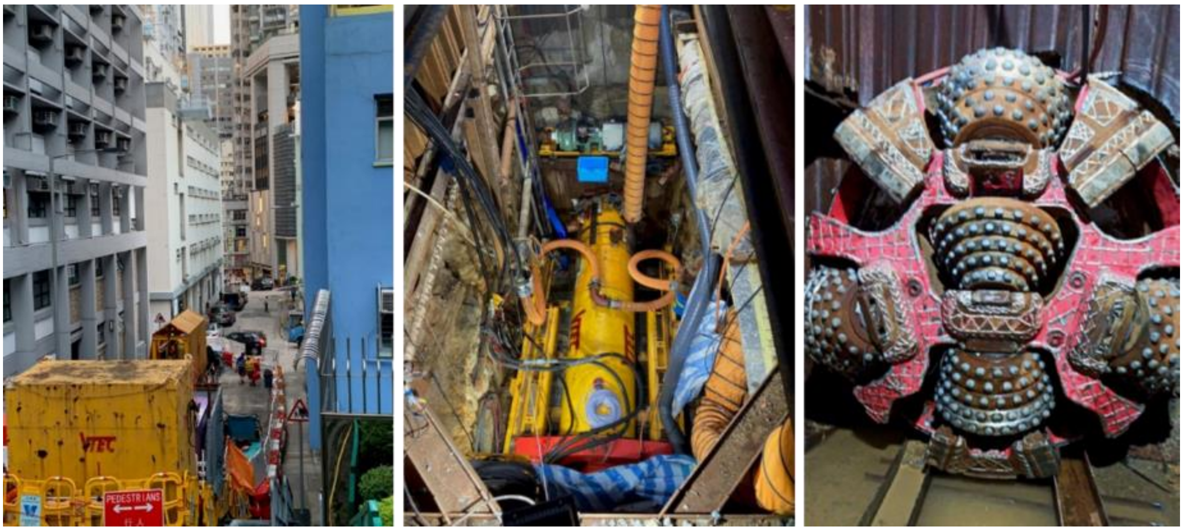

Figure 10: Jobsite surroundings, launch shaft and AVN 800 HR after breakthrough

8. CONCLUSION

In recent years, the trend towards smaller diameters and longer drives has been increased, which puts a larger focus on the design and selection of efficient MTBM equipment. With the latest technological innovations, such as the jet pump technology, drives of over 1,000 meters are possible with diameters down to 18 inches. New small-diameter cutting wheel designs and most importantly cutter tools have been developed to support these achievements, especially when it comes to hard rock or challenging mixed ground conditions. Based on a geotechnical investigation which should be as detailed as possible, the MTBM system can be configurated, incorporating the latest state of technological solutions described above.

In order to further increase tunnelling performance in future small-diameter pipe jacking projects, the availability of all relevant machine performance data is key. It is the basis for a continuous improvement process. Advancing digitalization will improve the possibilities for data recording and evaluation in future. The availability of all data on any computer or handheld device worldwide is a key part for a transparent jobsite operation and remote troubleshooting. Furthermore, a valid assessment for wear prediction and tool change can be achieved.

The machine performance data will also form the basis for the development of intelligent assistance systems in the future, in order to increase overall performance. All this will lead to faster, safer, and more efficient trenchless operations, to the benefit of all parties involved.

Appendix B-3

Title:	**Small-diameter tunneling in difficult ground – Analysis of TBM performance in hard rock**				
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Small-diameter tunneling in difficult ground – Analysis of TBM performance in hard rock

Small-diameter tunneling in hard rock is increasingly widespread due to the need for new and longer utility tunnels comprising sewer, stormwater, freshwater, or hydropower as well as cable tunnels and casings for pipelines transporting gas or hydrogen. Utility tunnels have to deal with a wide range of geological settings, like small overburden, weathered rock, rock–soil transitions, as well as fractured or intact hard rock with high strength and abrasivity. A database has been created including 35 hard rock projects with diameters between 1 and 5 m as well as more than 70,000 m of tunnel alignments, with a median drive length of less than 500 m. Challenges in creating it and some early interpretations based on the contents of the database are presented. Details about an exemplary pipe jacking project in basement rocks in Brittany, France, are given. The large variety in this small-diameter range in hard rock includes different TBM types, cutterhead designs, cutter types, and geotechnical conditions. Potential pitfalls in small-diameter TBM data analysis are shown and general drive parameter trends and penetration prediction approaches are presented and set in relation to the geotechnical conditions. Our analysis shows that difficult ground conditions do not only incorporate rocks with very high strength, but also generally weak rocks like schist or limestone could be responsible for low penetration rates and high thrust forces.

Keywords utility tunneling; pipe jacking; case study; hard rock; small diameter

Tunnelbau mit kleinem Durchmesser in schwierigem Untergrund – Analyse der TBM-Leistung in hartem Fels
Die Anzahl an Tunnelbauprojekten mit kleinen Durchmessern in Gesteinen mit hohen Festigkeiten nimmt seit einigen Jahren stark zu, da neue und zunehmend längere Versorgungstunnel benötigt werden. Diese sogenannten Utility Tunnels sind mit einer Vielzahl von geologischen Gegebenheiten konfrontiert, wie geringe Überdeckung, starke Alteration der Gesteine, heterogene Ortsbrustbedingungen sowie Gesteine mit hoher Festigkeit und Abrasivität. Eine Datenbank mit zurzeit mehr als 35 Hartgesteinsprojekten mit Durchmessern zwischen 1 und 5 m sowie 70.000 m Tunneltrassen mit einer mittleren Projektlänge von weniger als 500 m wurde erstellt. Die Herausforderungen bei der Erstellung der Datenbank sowie einige erste Interpretationen auf der Grundlage des Inhalts der Datenbank werden vorgestellt. Weiterhin werden Details über ein beispielhaftes Rohrvortriebsprojekt im Grundgebirge der Bretagne, Frankreich, präsentiert. Die große Vielfalt in diesem kleinen Durchmesserbereich im Hartgestein umfasst unterschiedliche TBM-Typen, Schneidkopfdesigns, Werkzeugtypen und geotechnische Bedingungen. Es werden mögliche Fallstricke bei der Analyse von TBM-Daten aus Projekten mit kleinen Durchmessern aufgezeigt und allgemeine Trends bei den Antriebsparametern sowie Ansätze zur Vorhersage der Penetration vorgestellt und in Bezug zu den geotechnischen Bedingungen gesetzt. Unsere Analyse zeigt, dass schwierige Untergrundverhältnisse nicht nur Gesteine mit sehr hoher Festigkeit umfassen, sondern auch geringfeste Gesteine wie Schiefer oder Kalkstein für niedrige Vortriebsraten und hohe Anpresskräfte verantwortlich sein können.

Stichworte Utility Tunneling; Rohrvortrieb; Fallstudie; Hartgestein; kleine Durchmesser

1 Introduction

Utility tunnels cover a wide application field comprising sewer, stormwater, freshwater or hydropower as well as pipeline casing and cable tunnels for hydrocarbons, hydrogen, fiber optic or electricity lines [1]. While much information is available in the literature about large-diameter projects, very little has been yet published about small-diameter hard rock projects and their performance [2–4]. Furthermore, no comprehensive overview over multiple such projects and their variability is available. Therefore, a database was created specifically to determine trends and relationships for small-diameter TBMs (tunnel boring machine), also called utility TBMs.

Utility tunneling projects are generally characterized by small diameters below 5 m inner diameter. However, larger-diameter exceptions exist (e.g., large hydropower projects). Most of the tunnels between 1 and 5 m diameter can be excavated with different methodologies in hard rock, including different TBM types like gripper, double shield, single shield, slurry, and EPB machines [5, 6]. Besides the TBM type and the diameter, also the cutterhead itself can be either a hard rock cutting head with cutting tools designed for chipping the hard rock or a mixed-ground adaptation in order to cut the (weaker) rock with cutting tools as well as with knives and scrapers [7]. With those kinds of cutterheads, it is impossible to rate the percentage of the cutting mechanism which is done with the cutter discs and how much the other tools like knives and scrapers contribute. The selection of the machine and its cutterhead is strongly dependent on the geotechnical conditions. Depending on the depth and location of the project, the rock conditions can vary considerably from one project to another and also within one single project, requiring special technical adaptation or compromise solutions in order to cope with the heterogeneous ground conditions [7].

Mainly due to increasing safety standards, the pipe jacking method gains more importance in soil and hard rock. Therefore, an example of a successfully finished hard rock pipe jacking project in the Brittany region of France with challenging geotechnical conditions is presented and project-specific details are provided. This example is used to explain the complexity of a database containing utility tunneling projects in different geotechnical conditions all around the world. Finally, general observations and trends visible in the database are presented.

2 Methodology

TBM data processing is an important aspect that affects several phases of the construction process of a tunnel excavated by TBM [8]. A project in France shows exemplarily the challenges in dataset creation and processing. However, comparing data from different machine and lining types, diameters, and utilization types, countries and suppliers pose special challenges to data processing. As stated in another study [8], the exact nature of some TBM parameters provided by the machine acquisition system is sometimes difficult to obtain but extremely important for the correct analysis of the data.

2.1 Dataset creation

In order to use the information for predictions in tunnel projects, all data need to be submitted in the same format. Before raw data management and filtering, checking for geotechnical information is critical. Besides geotechnical field and lab parameters, a detailed geotechnical cross-section provides necessary information, which is required to combine technical and geological information. As soon as it is ensured that sufficient high-quality geodata are available, the actual machine data processing can start. Here, a constant drilling advance must first be ensured. While new data acquisition systems can do this automatically, older data packages must have downtime sections (e.g., during pipe change or revision) deleted. The so-derived machine data can be used to calculate the penetration rate, the cutterhead contact force, and the torque. Finally, the data is subject to filtering. Reasonable values for filtering can be taken from the TBM specifications, are project and TBM dependent, and require careful selection and interpretation. Ultimately, the data is averaged in intervals like 0.1 or 1 m, as TBM operational data is temporal- but not spatial-equally distributed. If such an averaging is not undertaken, there would be the problem that there are many datapoints in areas of slow advance and fewer datapoints in areas of fast advance [9], especially for mean values for the whole tunnel or homogeneous areas. As presented in Figure 1, three database levels have been deployed and adjusted to the requirements of small-diameter projects [10].

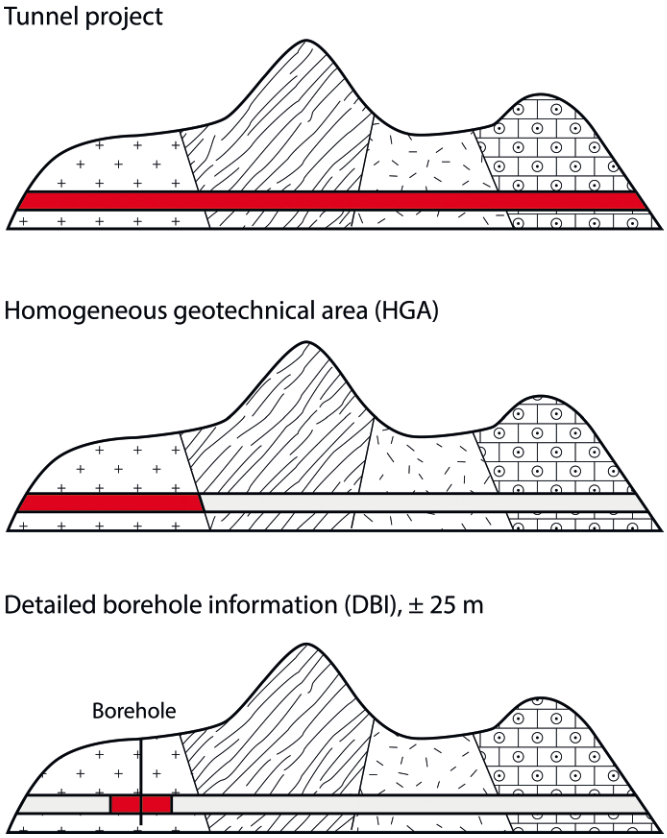

Fig. 1 Levels of detail included in the small-diameter hard rock tunneling database after [10].
Bild 1 Detailgrad in der TBM-Hartgesteinsdatenbank mit kleinen Durchmessern nach [10].

2.1.1 Tunnel project

The tunnel project includes all available information from a tunnel construction project. In the best case, geotechnical, machine, and project-specific information from the launch shaft to the receiving shaft is included. Average and mean values are calculated for all parameters, not taking into account possibly highly varying geotechnical conditions like different lithologies or strength values.

2.1.2 Homogeneous area

A homogeneous area is characterized by similar geotechnical conditions. Such an area is generally composed of the same rock type and the geotechnical parameters do not vary considerably. The machine parameters are averaged only for the corresponding area with homogeneous geotechnical conditions.

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2.1.3 Detailed area

A detailed area is based on "point-like" geotechnical information mostly from exploration boreholes or from geotechnical information received from drilling during tunneling, as well as back mapping of the face or the walls. This geotechnical information is then averaged for an interval of +/– 25 m around the (perpendicular) projection of the borehole on the tunnel trace.

The 25 m interval is a compromise necessary due to the highly heterogeneous data included in the database. In order to achieve high accuracy with the drive data, a very low averaging area around the geotechnical information would be beneficial. However, for some drive datasets, the resolution is even larger than 1 m. Furthermore, the geotechnical data should be representative of the surrounding of the borehole where it was taken. Some utility projects are very short (e.g., the shortest drive in the database is 30 m), and very little geotechnical information is available. Oftentimes, and very typical for such short drives, one borehole at the start shaft and one borehole at the receiving shaft is drilled in order to explore the ground conditions. Another aspect is the fact that the boreholes are typically not directly on the tunnel alignment but offset by a few meters (i.e., 5–20 m) and/or inclined. Furthermore, it is important to consider that the samples were taken some meters above or below the tunnel alignment. Sensitivity analysis for this averaging interval of the machine data related to the geotechnical data was undertaken. The results reveal that an interval of 1 m would lead to exceptionally fluctuating results, while an interval of 100 m shows excessively aligned results. Therefore, an interval of 25 m was used for this data analysis and can be justified with the arguments stated earlier.

2.2 Technical and geotechnical challenges

The basis for a combined geotechnical and machine drive analysis is high-quality data in terms of both quality and quantity. Furthermore, project- and machine-specific parameters must be available from the construction company and the TBM manufacturer. Due to their small project size, for many utility TBM projects around the world, either geological or drive data is available. There is a large variability in TBM drive data, and the most important differences which have to be considered are as follows.

- Technical variance: TBM type, cutterhead type and geometry, cutter type, and lining method are important.
- Data acquisition variance: frequency, parameter and sensor labeling, units, reliability, and accuracy of sensors have to be considered.
- Short-term changes: Oftentimes, shortly before the project technical parameters are changed, the start situation is different from the planning stage.

As described earlier, a comprehensive geological profile or underground model is key for combining TBM and geotechnical data. While digital underground or construction models are still not state of the art in small-diameter tunneling, most profiles—if available—are hand-drawn or 2D computer-drawn illustrations. However, some profiles are missing borehole location information, and all boreholes are always projected on the alignment even though they may be located at a considerable distance. The geological data can be quite heterogeneous, too. Known inaccuracies include the following:

- Frequency of geotechnical testing: distance between boreholes and geotechnical tests.
- Selection of samples is dependent on the jobsite personnel.
- Quality of the testing procedure: laboratory-derived values might vary considerably depending on which lab is performing the test, even for the same standard method.
- The exact tunnel path of the TBM compared to the geotechnical profile.

3 Exemplary hard rock project in Brittany

In order to give an example of a typical project included in the database, a pipe jacking project in France is presented hereafter. Brittany, in France's far west, is largely dependent on energy from neighboring regions. More than 80 % of its electricity is imported. In order to become more independent and to meet the increasing energy consumption of the Bretons, a new natural gas-combined cycle power plant with 450 MW capacity was built. To connect the power plant to an existing natural gas pipeline, a new 20 km pipeline was needed, running from Saint-Urbain to Landivisiau. Among other things, this route had to pass under the Élorn River and the Paris–Brest railway with low overburden. A 2.2 m outer diameter Herrenknecht Slurry TBM constructed a 530 m long tunnel in the Finistère department using the pipe jacking method. Starting from an 8 m deep shaft, the TBM tunneled through Variscan basement rocks comprising gneiss, granite, and schist with rock strengths of up to 185 MPa. The geotechnical conditions were very heterogeneous comprising high-strength rocks and fault zones and differed from the baseline parameters. Along the tunnel route, it tunneled a gradient of 17 %, a curve radius of 700 m, and a water pressure of up to 4 bar. Furthermore, a 26 m height difference between the entry and exit points and a 40 m drop between the entry point and the deepest point on the bore path were mastered. The successful breakthrough was celebrated on October 27, 2020, and the commissioning of the power plant was completed in February 2022. This project shows the challenges in the dataset creation for small-diameter hard rock projects, i.e., the previously described technical challenges and the allocation of geotechnical data to the correct machine drive data. The most important machine parameters are presented in Figure 2. The average ad-

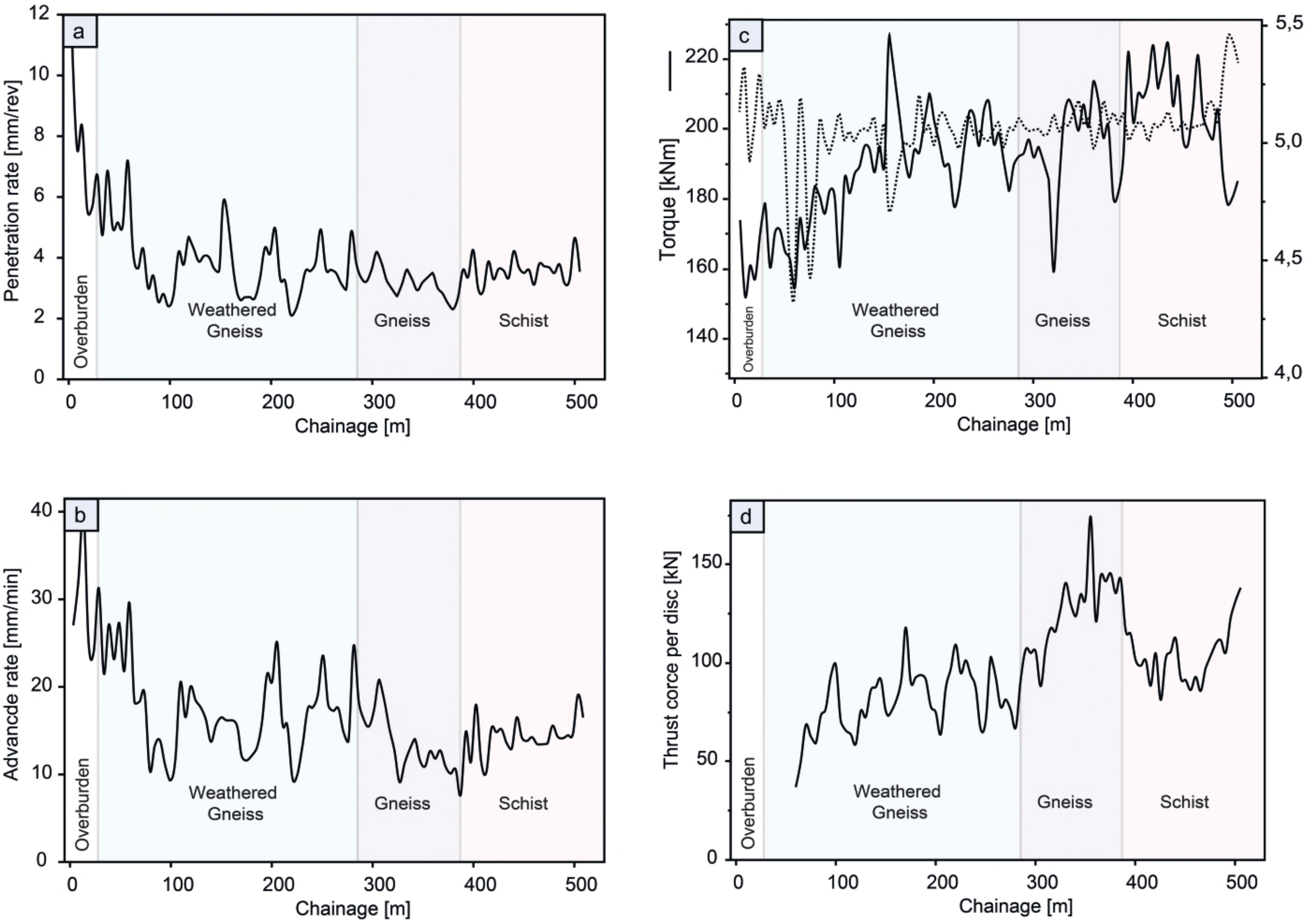

Fig. 2 Main drive parameters and performance at the pipe jacking jobsite in Brittany: a) penetration, b) advance rate, c) torque and revolution, and d) average thrust force per disc cutter.

Bild 2 Wichtigste Maschinenparameter und Vortriebsleistungen bei dem Rohrvortrieb in der Bretagne: a) Penetrationsrate, b) Vortriebsgeschwindigkeit, c) Drehmoment und Drehzahl, d) Mittlere Anpresskraft pro Schneidring.

vance rate was around 18 mm/min, while the average penetration rate was 3.4 mm/rev. The 12″ cutters were inspected and changed at every intervention, which was executed at regular intervals of 50 m due to the complex geotechnical conditions.

3.3 Geological site conditions

The project described in this article is located in the Variscan province Pays the Léon, which is located at the northwestern end of the Amorican Massif and part of the North American Zone. Pays the Léon is dominated by metamorphic rocks, which have been exposed to local anatexis. These Variscan rocks were intruded by granites of Carboniferous age (300 Ma) and were subjected to the development of ductile shear zones [11].

The tunnel alignment is characterized by Variscan Gneiss de Brest in the northwest and early-Cambrian schists and phyllites in the southeast. These basement rocks are covered with an up-to-10 m thick layer of Holocene lacustrine and fluvial formations which mostly consist of clay, sand, gravel, and stones. Figure 3 shows a geotechnical profile comprising the dominant lithological units as described in the six exploration boreholes and the tunnel alignment, while Figure 4 gives a good impression of the schist encountered at the last third of the drive. Several geotechnical tests on samples taken at the exploration campaign revealed an average unconfined compressive strength (UCS) of 30–50 MPa. However, samples from interventions during tunneling showed much higher UCS values up to 185 MPa.

4 Small-diameter TBM database

A database for small-diameter TBMs in hard rock was built using data from projects such as the one described earlier in Brittany. It appears that tunnel projects in magmatic and metamorphic rocks are generally characterized by higher rock strength values than projects in sedimentary rock like sandstone or limestone, as underlined by the previously described pipe jacking project in France (Figure 5).

Most small-diameter projects are characterized by UCS values between 5 and 100 MPa (Figure 5). Projects with high-to-very-high UCS values exist, but they are not the majority. The oftentimes low-to-medium rock strength could be explained by the generally small overburden of utility tunnels, especially compared to large-diameter traf-

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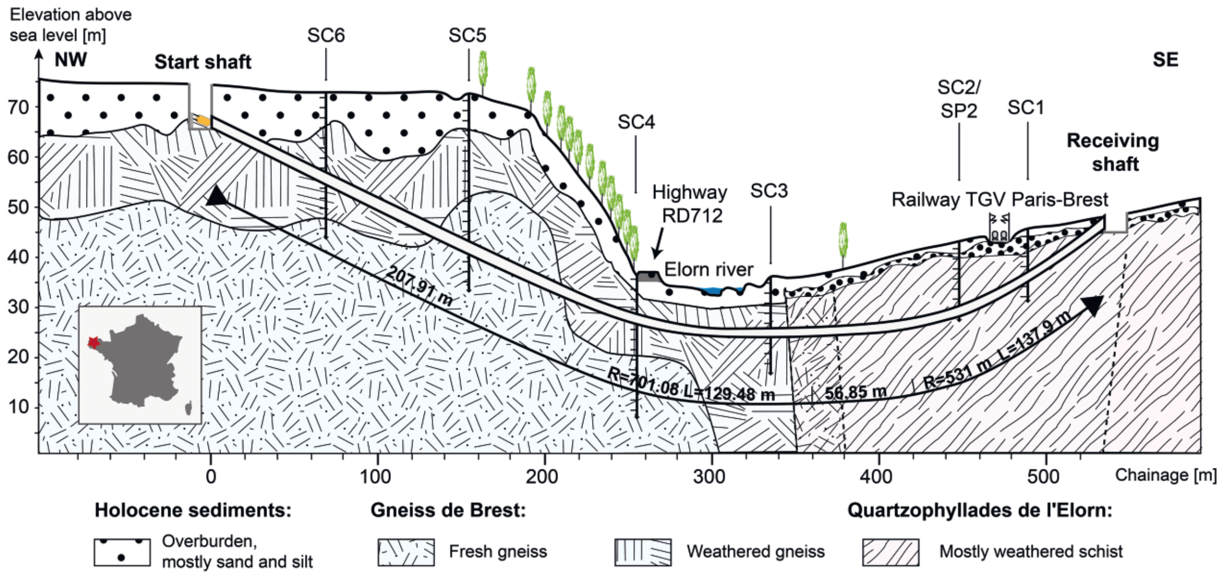

Fig. 3 Simplified geotechnical profile of the pipe jacking project in Bretagne.

Bild 3 Vereinfachtes geotechnisches Profil des Rohrvortriebprojekts in der Bretagne.

Fig. 4 Breakthrough of the TBM in the reception pit. The monoblock double-ring face and caliber cutters are visible.

Bild 4 Durchbruch der TBM im Zielschacht. Die Monoblock-Zweiring-disken und Kaliberdisken sind sichtbar.

fic tunneling projects. The small overburden enhances especially chemical weathering, reducing the strength of the rocks. Therefore, it is mainly due to their usage as utility tunnels; the large majority of small-diameter tunnels are generally characterized by weak-to-medium strong rocks.

As shown in Figure 5, for most of the projects, UCS values are available. (Brazilian) tensile strength (BTS) and especially point load index (PLI) values are less common and unavailable for most projects. However, even though much less values are available, the PLI seems to offer a certain correlation with the penetration. The tensile strength, which is besides the UCS considered the second most relevant rock strength parameter, does not show any meaningful correlation with the penetration rate in our analysis. This observation raises the question whether

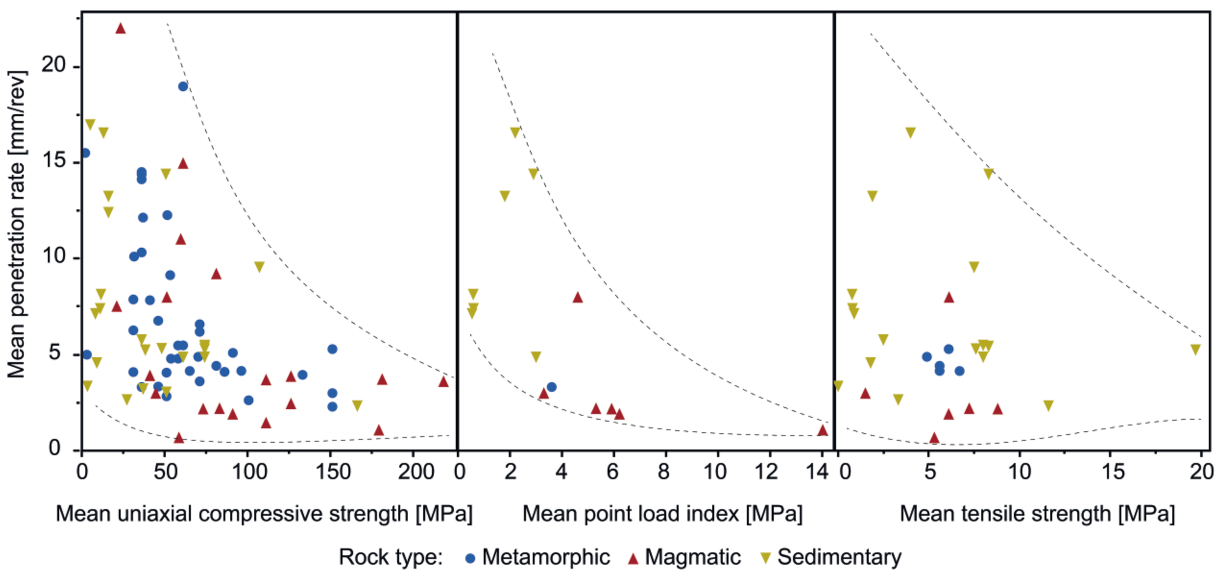

Fig. 5 Results for the homogenous area analysis for the hard rock projects in the small-diameter TBM database. Note the good fit of the PLI with the machine performances, especially in the range of low values.

Bild 5 Analyse der Werte der Homogenbereiche für die Hartgesteinsprojekte in der TBM-Datenbank mit kleinem Durchmesser. Beachtenswert ist die gute Übereinstimmung der PLI-Werte mit der Penetrationsrate, insbesondere im Bereich der niedrigen Festigkeiten.

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solely the UCS (and BTS) really is the main factor influencing the penetration of a disc cutter in hard rock and how to incorporate rock mass parameters in simple estimations. This observation is important for future approaches to improve the quality of the penetration prediction also for small-diameter TBMs in hard rock.

5 Discussion

The results in the database analysis show that the UCS is the most relevant single geotechnical parameter also for small-diameter drives (Fig. 5). However, also the PLI values show a good correlation with the achieved penetration rate, even though they are much less common. The achievable penetration rate seems to be predominantly dependent on the TBM diameter. However, it must be noted that smaller TBMs generally have a higher revolution, especially small-diameter hard rock slurry TBMs. Therefore, the advance rate of such machines can be higher as the penetration rate suggests. Still, it is worth mentioning that TBMs which are all designed for hard rock and which have the same cutting mechanism with disc cutters obtain highly differing penetration rates in the field even for similar geotechnical conditions. One possible explanation for this observation could be that the TBM diameter is representative of the power installed on the machine and also of its utilization. Further database analysis must be conducted to determine to what extent this relationship really exists and what influence it has on the prediction of penetration and advance speed of small TBMs. Further research must also show if other parameters that the PLI or a combination of several tests can show a better correlation with the achieved penetration rates, especially for small-diameter tunneling projects.

6 Conclusion

The difficulties and challenges of machine and geodata evaluation are explained for small- diameter hard rock projects for an exemplary pipe jacking project in Brittany, France. A database of more than 35 such small-diameter tunneling projects was compiled and analyzed. The main findings in this database are that the technical complexity of different small-diameter tunneling projects can be very high especially in the diameter range between 2.5 and 4.2 m. The database demonstrates that the most common geotechnical strength value is the UCS, even though other, less-common values like the PLI show good correlation with the penetration. Furthermore, it can be shown that most projects in sedimentary rock are characterized by low rock strength values, while projects in igneous and metamorphic rocks obtain generally higher UCS values. Due to their usage as utility tunnels and their generally low overburden, most small-diameter projects are in a UCS range between 5 and 100 MPa.

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Appendix B-4

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On the way to a better performance prediction for small-diameter hard rock TBMs

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ABSTRACT: Small diameter tunneling in hard rock gets increasingly widespread due to the surge of renewables energies and the need for new and longer utility tunnels. The large variety in this small diameter range in hard rock includes different TBM types, cutterhead designs, cutter types and most notably geotechnical conditions. Predicting the advance rate for such project conditions in hard rock is an important factor in tunnel project planning and execution. Data from more than 35 small diameter hard rock tunneling pipe jacking and segment lining projects has been compiled and analyzed. Our analysis showed that the achieved performance for such projects varies considerably from the prediction with industry-standard penetration models. This paper will give an insight into the wide variability of small diameter hard rock tunneling and the associated challenges in performance prediction.

1 INTRODUCTION

Since many decades, the penetration prediction of TBMs is of utmost importance for the planning of tunneling projects all over the world (Rostami & Ozdemir, 1993; Rostami, 1997; Bruland, 1998). The penetration rate is key for the right choice of the excavation method, the competition to drill and blast as well as the economics and project planning of such jobsites (Macias & Bruland, 2014). The most commonly applied penetration prediction models come from the Colorado School of Mines (CSM, Rostami, 1997) and the Norwegian University of Science and Technology (NTNU, Bruland, 1998). More and more tunnels are being built with small-diameter TBMs for the construction of utility tunnels with up to 4 m inner diameter. Utility tunnels cover a wide application range comprising sewer, stormwater, freshwater or hydropower as well as cable tunnels and casings for pipelines transporting gas or hydrogen. Thanks to technical innovations, these small TBMs have also been used increasingly in hard rock in recent years. These technical innovations include more powerful main drives, newly adopted cutter geometries such as TCI cutters, interjacking stations, telescopic stations and telescopic gripper stations, and reinforced jacking pipes for pipe jacking. In addition, thanks to digital control and monitoring of the TBM, maintenance intervals can be planned more efficiently and thus drive lengths can be achieved that would not have been feasible some years ago. At the same time, proven techniques like pipe jacking for sea outfalls have also been deployed in hard rock with great success. Until recently, implementing long-distance microtunneling in very small diameters (~ 0.5 m – 1 m) in hard rock has been difficult or even impossible.

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1.1 *State of the art*

Utility tunneling projects are generally characterized by small diameters below 4 m inside diameter. However, there are exceptions with larger diameters (e.g., large hydropower projects). These tunnels, ranging from 1 to 5 m in diameter, can be excavated in hard rock using a variety of methods, including different TBM types such as Gripper, Double Shield, Single Shield, Slurry, and EPB machines (Maidl et al., 2008; Sterling, 2020). Generally, pipe jacking is applied at small diameters below 2.5 m diameter and segment lining is widespread above 3.5 m. However, in the diameter range of 2 m to 4 m, the applications are becoming more diverse. Pipe jacking projects are venturing into increasingly difficult subsurface conditions with very hard rock or even highly fractured rock masses. With these machine dimensions uniaxial compressive strength values over 200 MPa can be handled. In addition to the TBM type and diameter, the cutterhead itself can be either a hard rock cutterhead with cutters designed to crush the hard rock or a mixed ground cutterhead to cut the (weaker) rock with both cutters, knives and scrapers (Stein, 2003). With this type of cutterhead, it is not possible to determine the portion of the cutting mechanism that occurs with the cutter discs and how much the other tools, such as knives and scrapers, contribute. The selection of the machine and cutterhead depends heavily on the geotechnical conditions. Depending on the depth and location of the project, rock conditions can vary significantly from project to project and even within a single project, requiring special engineering adjustments or compromise solutions to accommodate heterogeneous soil conditions (Stein, 2003).

All these internal and external parameters make it very challenging to accurately predict the performance of small diameter TBMs in hard rock. While many penetration prediction models are available in the literature about large diameter projects, very little has been yet published about small diameter hard rock projects and their performance (Barla et al., 2006; Sheil et al., 2016). From some projects and in the industry, it is known that the models, which work for large machines with corresponding power and large disks, give results with very variable accuracy for small projects. Thereby, a performance prediction is also important for such projects, especially if the diameter is too small for manning and maintenance entries or so-called safe havens for changing cutter tools have to be determined in advance. Furthermore, an accurate performance prediction is very important for the prediction of maximum drive length, defining the number of necessary number of shafts and the overall jobsite layout, footprint and costs.

1.2 *Penetration prediction models*

As mentioned above, plenty of penetration and advance prediction models already exist. Probably the most-deployed penetration prediction model in science and industry is the model from the Colorado School of Mines (CSM). It was developed by Rostami and Ozdemir (1993) and Rostami (1997) and refined by Rostami (2016). The reason for its popular use is the easy handling, the good results and the geological input parameters, which are limited to unconfined compressive strength (UCS) and tensile strength (TS) and thus available for the vast majority of projects. The model of the NTNU delivers similarly good or even better results (Bruland, 1998; Macias, 2016). However, a large number of geotechnical parameters (especially joint parameters) is used here, which are oftentimes not available especially for small diameter projects. Another important model was developed by Farrokh et al. (2012). It offers a simple formula with relatively little geotechnical input. The same applies to the models from Hassanpour et al. (2011) and Goodarzi et al. (2021). The model from Gehring (1995) and the updated version from Thuro et al. (2015) and Wilfing (2016) ("Alpine Model") have been largely deployed in the Alps, but also require a very precise knowledge of the numerous input variables. In recent years, many models applying AI have been published for numerous projects especially in Asia (Gao et al., 2020; Zhou et al., 2021).

However, most of these models have the problem that they are based on only a few case studies and in some cases on data that is several decades old. This is especially the case for many of the newer AI models, which work very well for the specific project(s) and geotechnical conditions for which they were developed, but are not suitable for broad application either due to lack of input parameters or due to overfitting. At this point, however, it must be stated, that the industry is not entirely innocent of this, as it is usually very difficult and expensive to obtain a sufficiently large amount of data especially at small-diameter projects.

2 METHODS AND DATABASE

A total number of 37 tunneling projects has been analyzed and their geotechnical and machine drive data has been compiled in a small diameter hard rock database. This database contains mostly information from projects between 1 m and 5 m diameter, with tunnel length ranging between several tens to several thousands of meters of drive length, obviously depending on the machine type and especially the lining procedure. This data has been subsequently homogenized and averaged for homogeneous ground areas (see Farrokh et al. (2012)). The database contains information for the following important parameters:

- TBM parameters (e.g. torque, revolution speed, advance rate, thrust, lining principle etc.)
- cutterhead design (number of cutters, cutter type, max load etc.)
- geotechnical parameters (lithology, UCS, TS, PLI, CAI, RQD, Q etc.)
- machine drive parameters (advance rate, penetration rate, torque, revolution speed, thrust force, earth/water pressure)
- project information (country, project name, length etc.)

However, it has to be stated that not always all information is available for every project. This is especially true for the geotechnical parameters, as in general the amount of geotechnical data varies considerably from tunneling project to tunneling project (Jakobsen & Babendererde, 2017). Most of the projects included in the database have been carried out in the last ten years.

3 REFERENCE PROJECTS

The following section will highlight three exemplary reference projects in different diameter ranges, introducing the large technical variability (like cutterhead design, size, cutters, TBM type etc.) and the differences in performance and geotechnical data which is characteristic for small diameter TBMs in hard rock.

3.1 *Exemplary project TBM 3000: Kowloon drainage tunnel, Hongkong*

The water drainage systems in Kowloon, Hongkong, have been constructed more than 45 years ago and owing to rapid developments and changes in land use over the last years, natural ground has been paved over and became impermeable. The inability of the drainage systems of coping with the increased surface run-off led to flooding during heavy rainstorms causing traffic disruption, properties damage and safety risk of the public. To alleviate the problem, a 2.8 km long drainage tunnel has been constructed with an inner diameter of 3 m. Therefore, a Double Shield TBM 3000 has been deployed and the tunnel was excavated in less than a year. The segment lining TBM had a cutting diameter of 3835 mm and an installed performance of 800 kW. The TBM was equipped with 24 1-Ring 17” disc cutters. Even though the strength of the granite was baselined with an average of 155 MPa, the actual geotechnical conditions seemed to be better with values averaging between 60 MPa and 120 MPa according to samples taken during tunneling. The average TS was 7.6 MPa, while the PLI (point load index) was 5.1 MPa. As usual for such projects, no information about the rock mass quality was given but some moderately to strongly weathered core sections were observed. An average advance rate of 62 mm/min was achieved (Figure 1a). With an average revolution of 12.1 rev/min, the average penetration rate was 5.2 mm/rev. The average thrust force per ring was 150.1 kN/ring.

3.2 *Exemplary project AVN 1800: Landivisiau gas pipeline, France*

In order to give an example of a typical hard rock pipe jacking project included in the database, a project in France is presented hereafter. Brittany, in France's far west, is largely dependent on energy from neighboring regions. More than 80 percent of its electricity is imported. In order to become more independent and to meet the increasing energy consumption of the Bretons, a new natural gas combined cycle power plant with 450 MW capacity was built. To connect the power plant to an existing natural gas pipeline, a new 20-kilometer pipeline was needed, running from Saint-Urbain to Landivisiau. Among other things, this route had to pass under the Élorn River and the Paris-Brest railway with low overburden. An AVN 1800 with an outer diameter of 2185 mm has constructed a 530 m long tunnel in the Finistère department using the pipe jacking method. The 250 kW TBM was equipped with 8 2-ring and 5 center cutters, all with 12”. Starting from an 8-meter-deep shaft, the TBM was tunneling through Variscan basement rocks comprising gneiss, granite and schist (Figure 1b) with rock strengths of up to 185 MPa, much stronger than the previously given 30 MPa to 50 MPa during the geotechnical exploration campaign. Along the tunnel route, the TBM tunneled a gradient of 17 percent, a curve radius of 700 meters and a water pressure of up to 4 bar. Furthermore, a 26 m height difference between the entry and exit points and a 40 m drop between the entry point and the deepest point on the bore path were mastered. The average advance rate was around 18 mm/min, while the average penetration rate was 3.4 mm/rev. The average thrust force per ring was 60.3 kN/ring. The 12”-cutters were inspected and changed at every intervention, which was executed at regular intervals of 50 m due to the complex geotechnical conditions. The successful breakthrough was celebrated in October 2020 (Figure 1c) and the power plant became operational in February 2022.

3.3 *Reference project AVN 800: Water mains improvement project, Hong Kong*

This reference is part of the larger water and saltwater mains improvement project with an overall length of 56 kilometers. It involves installation and commissioning of new pipelines, and rehabilitation and surveying of existing pipelines with diameters of up to ID 1400. The project is located in Hong Kong and is owned by the Water Supplies Department. Pipe jacking has been selected as the preferred method to install the 107 meters long section, with a constant radius of 153 meters (Figure 1c). The complete tunnel alignment leads through granitic rock with maximum UCS of 200 MPa. Steel pipes with 3 meters length have been selected for the installation. It proved being beneficial to provide enough support for the higher jacking loads encountered in this hard rock application. An additional benefit of the welded steel pipes for hard rock is the capability to counteract the roll, generated by the high cutting wheel torque needed to chip the rock. Due to the hard rock condition with a UCS of up to 200 MPa and the small diameter of only 960 mm (OD), an AVN 800 HR for hard rock has been selected. As cutting tools, conical 317mm cutters with TCI inserts have been selected. The AVN 800 HR has an installed power of 90 kW, enabling a cutting wheel rotation speed of max. 26 rpm and a maximum torque of 55 kNm. It took an overall 60 days to complete the drive, including several idle days. Average daily performance was 4 m/day. Average advance rate of 20 mm/min was achieved with penetration rates around 1 mm/rev and thrust forces of 90 to 100 kN/cutter.

4 PERFORMANCE ANALYSIS

Having presented three exemplary reference projects and their performance, a more general overview of the performance of small diameter TBMs in hard rock is necessary. Therefore, a small diameter hard rock TBM database has been compiled and excerpts are shown in Figure 2. Each datapoint corresponds to one homogeneous area, which can be either formed by a geotechnically homogeneous tunnel drive or a part of this tunnel drive. Figure 2a demonstrates a strong correlation between the UCS and the penetration rate which is especially pronounced for Double

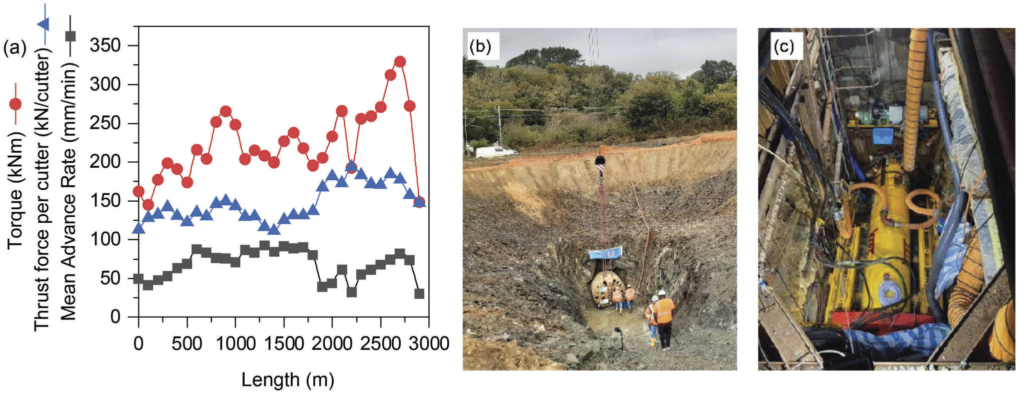

Figure 1. (a) Performance rates at the tunnel drive in Hong Kong; (b) Breakthrough of the AVN1800 after a challenging 530 long pipe jacking drive in strong to very strong Variscan basement schists. (c) Extremely compact launch shaft design with approx. dimensions of 3.5 m width and 6.5 m length for limited space available in Hong Kong.

Shield (DS) and Gripper TBMs. However, it is obvious that the small diameter Slurry TBMs (AVNs) do not reach the same penetration rate at an equivalent rock strength. The same message is transported in Figure 2b, where it is mainly differentiated between Segment Lining (SL) and Pipe Jacking (PJ) drives. In general, SL TBMs are much faster (by a factor of 2 or 3) than PJ TBMs in comparable ground conditions. This correlation is not well visible using the tensile strength (TS, Figure 2c), however, the PLI (Figure 2d) seems to have a good correlation with the achieved penetration rate. Unfortunately, a more precise specification is not possible here, since the geotechnical investigation oftentimes is very rudimentary in many projects. In many cases only a compressive strength is given and further helpful geotechnical parameters such as TS, PLI or Q are not available. Figure 2e illustrates the strong correlation between the TBM diameter and the actually used cutter thrust force per cutter ring. Here, it seems like that SL TBMs reach higher thrust forces per ring because of the fact that they have a larger machine diameter. Figure 2f shows the general dependency of high penetration rates and higher cutter thrust forces. In other words, the higher the thrust force per cutter, the higher the potential for high penetration rates. The dashed line in the graph marks the limit between inefficient and efficient chipping process (Wilfing, 2016). Finally, it can be stated that an efficient chipping process in hard rock generally needs cutter thrust forces well above 100 kN (Figure 2f).

5 PROPOSAL FOR A BETTER PERFORMANCE PREDICTION

Even though this section will not propose another updated performance model, its intention is to give some hints to properly use existing models. The CSM model works well for projects with little geotechnical data, as it only needs the UCS and TS as geotechnical input parameters. However, it is based on the chipping behavior of rocks. Therefore, it also should only be used in rock which are to be chipped with disc cutters. As the performance analysis revealed, this efficient chipping process is oftentimes not taking place for small diameter TBMs with lower thrust forces per ring. Hence, these TBM types (as presented in reference project 2 and especially 3) either have a generally lower performance, or compensate the lower penetration rate with much higher revolution. However, the rock cutting mechanism is then not chipping anymore, but much more grinding and crushing. This fact is taken into account by deploying more and more TCI cutters for very small diameter TBMs. Another important factor is the strength of the rock itself. Figure 3 clearly shows that the CSM model works best in its intended area of application and is therefore recommended for segment lining projects with UCS values above 50 – 60 MPa. A comparison of different existing penetration prediction

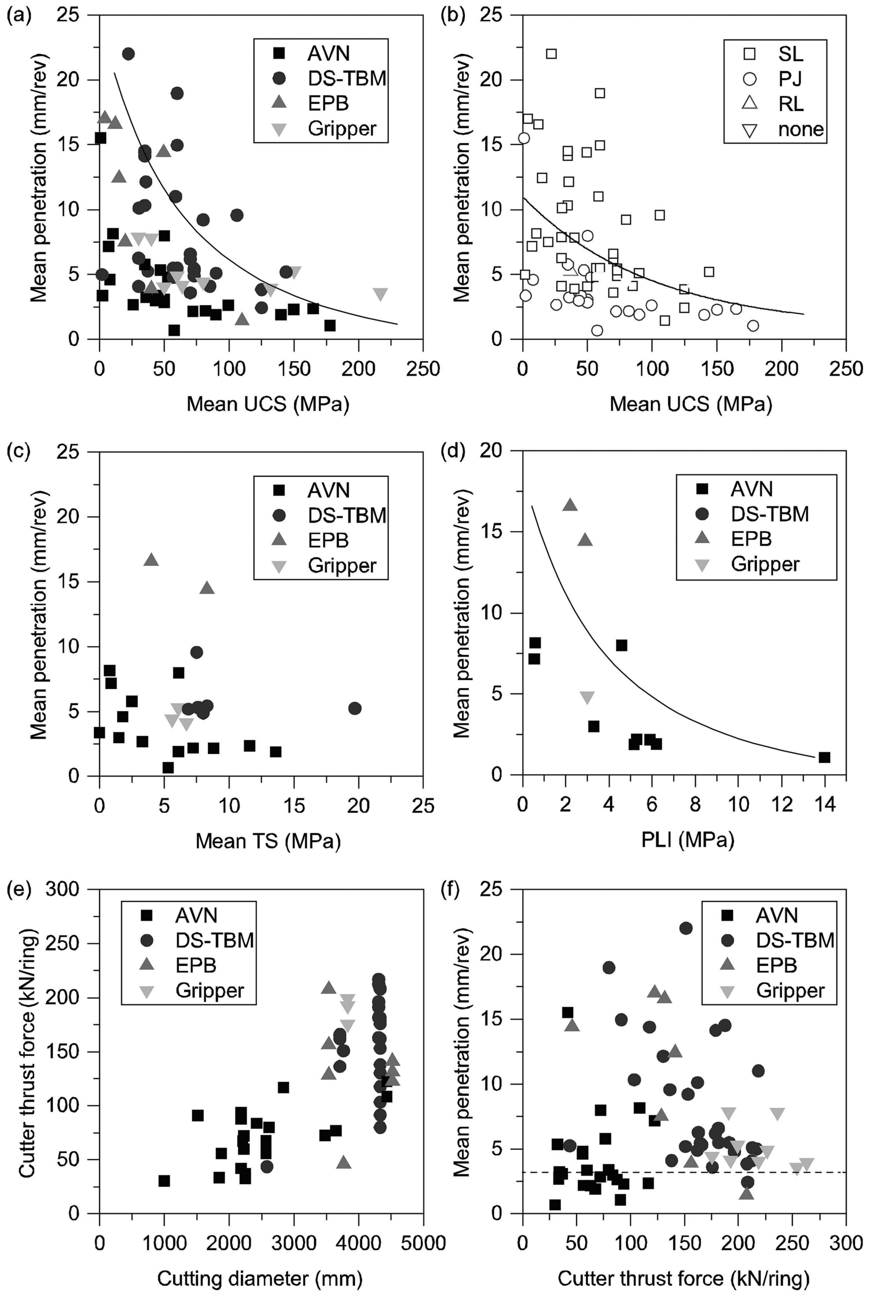

Figure 2. Performance analysis of small diameter hard rock tunnel drives. (a) and (b) are demonstrating the correlation between the UCS and the penetration rate, while (c) shows that the TS is hardly correlated with the penetration rate. However, (d) shows again a good correlation between the PLI and the penetration rate. (e) illustrated the strong correlation between the TBM diameter and the actually used cutter thrust force per cutter ring. (f) shows the general dependency of high penetration rates and higher cutter thrust forces. The dashed line in the graph marks the limit between inefficient and efficient chipping process (Wilfing, 2016). Note that AVN = Small diameter Slurry TBM, DS-TBM = Double Shield TBM, EPB = Earth Pressure Balance TBM, SL = Segment Lining, PJ = Pipe Jacking, RL = Rib and Lagging, none = no other precast lining process.

models with the performances of more than 35 recently completed small diameter projects in hard rocks revealed that the model from Farrokh et al. (2012) leads to the overall best results if little geotechnical information is available for such application scenarios. For pipe jacking projects, we found out that the model from Goodarzi et al. (2021) yields to more accurate results than other models and therefore recommend its application for penetration prediction of such projects in hard rocks. In addition, a machine learning model using the Gradient Boosting Regressor approach provides very promising results and might pave the way for an even more accurate penetration prediction in the future.

6 DISCUSSION

Already the three exemplary projects show the trend, that the achieved penetration rate mainly depends on the diameter of small diameter machines. Of course, the diameter alone makes no penetration rate, but depending on the machine diameter stronger main drives, motors, pumps, cutter and a more dedicated hard rock cutterhead can be used and positively influence the penetration rate. However, the low penetration rates of small diameter TBMs are at least partially compensated with higher revolution, which is very well true especially for the AVN 800 HR presented in the third reference project. The machine works with TCI cutters, while other small-diameter TBMs have 2- or 3-ring cutters (e.g. the second reference project). This makes it extremely difficult to deploy existing chipping-based penetration models for such small diameter TBMs. Therefore, it is suggested to use penetration models for small diameter TBMs, which are not relying on the physical chipping process but rather on a large database. A detailed study about the performance of small diameter TBM in hard rock and its penetration prediction is currently underway. Further research has to answer the question which geotechnical factors are really relevant for the penetration prediction of small diameter TBM and are easy and cost-efficient to obtain on the other side.

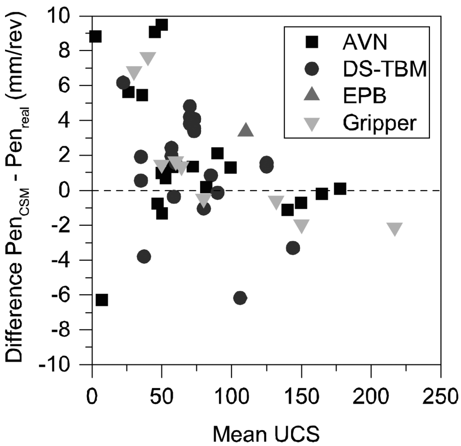

Figure 3. Difference of the CSM-predicted penetration rate and the actual penetration rate in dependency of the UCS.

7 CONCLUSION

Knowledge of the penetration rate and its prediction is key for successful hard rock tunneling and especially challenging with small diameter TBMs. Experience gained in three selected hard rock projects is presented. Data from 37 small diameter hard rock tunneling projects has been compiled and analyzed. The UCS shows the best correlation with the penetration rate, and also the PLI seems to have a good correlation. Furthermore, it can be stated that an efficient chipping process in hard rock generally needs cutter thrust forces well above 100 kN. Due to the lack of sound geotechnical exploration for such small projects, generally no information is available on the rock mass. Our analysis shows that the achieved performance for such projects varies considerably from the prediction with industry-standard penetration models. However, the model from Farrokh et al. (2012) leads to the overall best penetration prediction results for small diameter tunneling in hard rocks and the model from Goodarzi et al. (2021) works best for hard rock pipe jacking. In order to increase the accuracy of performance prediction, these models need to be refined or tuned with a large new set of data in order to pave the way for an improved performance prognosis for small diameter TBMs in hard rock.

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Appendix B-5

Title:	**Pushing pipe jacking boundaries in hard rock**				
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Pushing pipe jacking boundaries in hard rock

Gabriel Lehmann, Marcus Lübbers, Andrea Fluck of Herrenknecht AG discuss the role of an ingenious MTBM design and digitalization for successful slurry pipe jacking in hard rock.

Increased public awareness, environmental protection and sustainability goals have gained great traction in the construction industry in recent years. The conservation of resources through sustainable technologies is key, both in the planning and subsequent construction phases. Smart trenchless installation methods like slurry pipe jacking are required for the fast and safe installation of underground utilities, with a minimal impact on the surroundings. Originally from the more traditional applications of sewage and water tunnel construction, slurry pipe jacking is widely used today for challenging crossings for underground cable or pipeline routes, and outfall and intake tunnels for seawater desalination or pipeline landfalls. The method covers the entire geological spectrum, with considerable flexibility in terms of diameters, drive lengths and depths of the network to be installed. Today, new trenchless methods like E-Power Pipe® and the further development of existing technologies offer planners, grid operators and construction companies a wide range of efficient solutions for the implementation of their infrastructure projects.

Trends in slurry pipe jacking

From a geotechnical point of view, today´s utility infrastructure projects must cope with a wide range of geological settings, including minimal overburden, weathered rock, rock-soil transitions as well as fractured and intact hard rock with high strengths and abrasivity. In the past, in hard rock conditions, the applicability of slurry microtunnelling was limited to the non-accessible diameter range. Nowadays, the ever-growing number of pipe jacking projects in hard rock is mostly driven by recent technological developments that overcome limitations in drive length and also improve performance. Thanks to major technical developments such as innovations in machine performance, cutting tool design, peripheral equipment, and digital solutions, the boundaries of small-diameter slurry microtunnelling TBMs (MTBMs) in hard rock are continuously being pushed. This article describes the latest innovations in detail and presents related experiences from four challenging hard rock pipe jacking jobsites.

Rock classification and selection of MTBM

To choose the correct MTBM type, to design the best-suited cutting wheel and to predict the tunnelling performance, all rock and rock mass properties have to be considered. However, it is well known that for small-scale, small-diameter projects it is not possible to determine all parameters. The most important and minimum parameters for each project

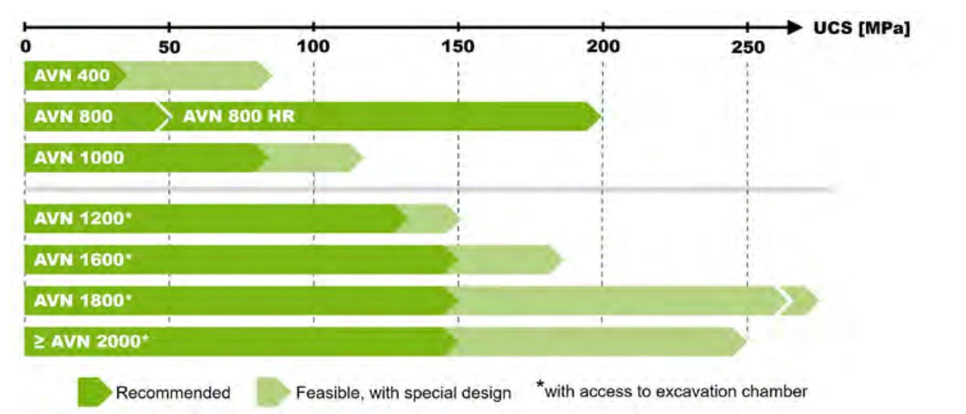

Figure 1. Recommended slurry MTBM application range in certain rock strengths.

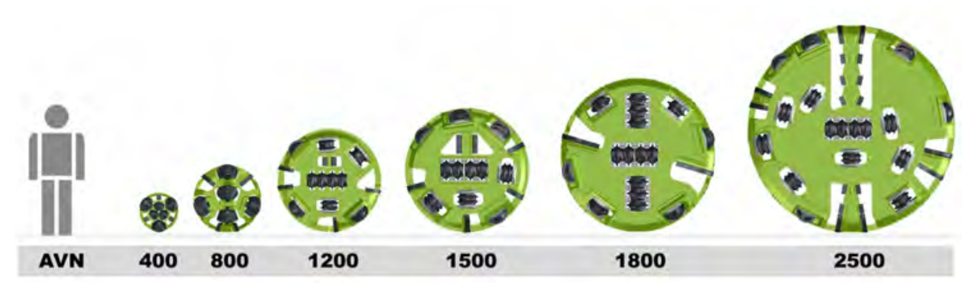

Figure 2. Exemplary hard rock cutting wheel designs for AVN 400 up to AVN 2500.

should be:
- Strength: Unconfined Compressive Strength UCS, Tensile Strength TS, Point Load Index PLI
- Abrasivity: Cerchar Abrasivity Index CAI
- Rock mass: Rock Quality Designation RQD, Q-value, Rock Mass Rating RMR
- information about the groundwater (pressure, chemistry etc.)

The basis for these parameters should always be a sound geological profile, where the geological and geotechnical information can be linked with project-specific information like the depth of the tunnel alignment. According to the most important single parameter, the UCS, an application range of slurry MTBMs is recommended as shown for different diameters in Figure 1.

Slurry MTBM features for hard rock

Knowing the harsh conditions found in hard rock, more attention must be paid to the MTBM performance factors, and the design of the critical components described later in this chapter, such as the cutting wheel, tooling or anti-roll measures. It is important to note that all components and their capacity need to be adjusted to suit each other. Thus, successful slurry pipe jacking in hard rock is determined by the successful incorporation of all components into one functioning system. In order to increase performance, it is important to find the system's bottleneck and increase its capacity. The whole system can only be as effective as its weakest component allows.

Cutting wheel design

The cutting wheel´s tooling composition is the most critical design feature in rock applications. Tool size and arrangements are determined by the rock properties and are dependent on the diameter (Figure 2). This arrangement will lead to creating reasonable rock chip sizes that can be handled by the discharge system. Wear protection plates and hard facing play a key role in protecting the cutting wheel steel structure from excessive wear.

Figure 3. Breakthrough at Hūnua 4 watermain project – drive 2 of 1,296m length. *(©McConnell Dowell Constructors Ltd)*

Reference project: Hūnua 4 watermain, New Zealand

The Hūnua 4 watermain project is the largest water pipeline project to be undertaken in New Zealand for many years. The project involves over 30km of 1.3m - 1.9m diameter steel pipeline traversing the city of Auckland. A Herrenknecht AVN 2500 (OD 3025mm) tunnelled through basaltic rocks with a UCS of up to 135MPa. Thanks to a dedicated hard rock cutting wheel design (Figure 3), an average penetration rate of 8mm/rev was accomplished. This resulted in a best weekly performance of more than 137m and a record drive length of 1,296m, which was the longest single drive in the southern hemisphere by a pipe jacking MTBM of this size.

Hard rock cutting tools

For MTBMs, three main cutting tool types can be considered. The most common cutting tool remains the disc cutter, which is well known from large diameter hard rock TBMs. However, due to space constraints, the single disc cutter is often replaced by a double or triple disc cutter, which decreases the spacing and therefore leads to faster chipping of the rock. On the other hand, the larger number of rings on cutters decreases the available thrust force per ring and therefore decreases the probability of creating the tensile cracks that lead to chipping. Therefore, it is important that small-diameter hard rock AVN machines can be capable of high jacking forces and have both a strong main bearing and cutter bearing.

Another approach to increase the thrust force of the cutting tools, or to extend their lifetime, is the use of TCI (Tungsten Carbide Insert) or button cutters. This cutter type exerts a point load force on the rock, resulting in numerous small chips. Due to the tungsten carbide inserts, the TCI cutter is considered especially wear-resistant, which is beneficial for long drives of a small diameter, where cutting wheel interventions are not possible.

Milled tooth cutters can fill a niche in small-diameter tunnelling based on the observation that normal disc and TCI cutters have comparably low performances in low strength, ductile-behaving rock. The teeth penetrate deeply into the rock and lever the sometimes already loosened rock pieces out of the rock mass. Furthermore, it must be stated that typical soft to mixed ground tools like chisels, rippers, knives and scrapers can make a significant contribution to rock cutting in low-strength rock.

Figure 4. Cutting wheel of the AVN 800 HR after breakthrough (left) and tight jobsite installation in Hong Kong (right).

Reference project: Water mains improvement, Hong Kong

Slurry pipe jacking was selected as the preferred method to install a 107m long section, with a constant radius of 153m, of a sewage project in Hong Kong, owned by the Water Supplies Department. The complete tunnel alignment lead through granitic rock with a maximum UCS of up to 200MPa. Due to these hard rock conditions and the small diameter of just 960mm (OD), an AVN 800 HR for hard rock was selected. For cutting tools, conical 317mm cutters with TCI inserts were selected (Figure 4). The AVN 800 HR has an installed power of 90kW, enabling a cutting wheel rotation speed of max. 26rpm and a maximum torque of 55kNm. Thanks to the innovative cutting tool choice, it took 60 days overall to complete the drive, including several idle days.

Anti-roll solutions

An anti-roll unit is another important factor in hard rock pipe jacking. For small diameters, good lubrication is required to minimise friction between the shield and the surrounding rock. Therefore, the MTBM will already tend to roll at a low torque. The problem is, high thrust forces, high revolutions and maximum torque are required, especially on a small cutting wheel with small, multi-ring cutters to transfer high enough thrust forces per cutter to chip the rock. From a technical side, anti-roll units can be divided in grippers set just behind the telescopic station, and disc cutters mounted on hydraulic cylinders inside the shield (Figure 5). These measures ensure that full thrust can be applied to achieve maximum performance rates. Currently, several hard rock projects are in construction with this technology.

Exploration and injection drilling

Even when tunnelling in hard rock consistently, high performance rates are essential for the success of any project. Accurate preliminary exploration of the subsoil is extremely important in maintaining these high rates of advance. Early detection of hazards along the tunnel alignment, or difficult geological zones will warn the machine operator, allowing them to apply prompt countermeasures such as introducing ground conditioning suitable for the conditions or even changing the tunnelling mode. Well known from successful application on large diameter TBMs, it is now also possible to equip MTBMs ($\geq$ 1,800mm) with a probe drill to acquire comprehensive knowledge of geological conditions prior to excavation and to allow injecting and stabilizing of the soil to guarantee smooth and safe tunnelling.

Reference project: Los Pelambres desalination plant tunnel, Chile

The Coquimbo region of Chile is characterized by large copper deposits and extreme drought. Considerable amounts of water are necessary to run the copper extraction and processing process, so as part of an ongoing sustainability goal, water is increasingly being taken from desalination plants on the Pacific coast and pumped to the copper mines. The maritime works for the Los Pelambres desalination plant consist of an underwater seawater intake system, an underwater brine outlet system and the respective bilges and loading chambers. The intake and outlet tunnels were approximately 345m and 543m long, respectively. Besides an AVND 2000, an upskinned

Figure 5. Exemplary anti-roll units: gripper version (left) and disc cutter version (right).

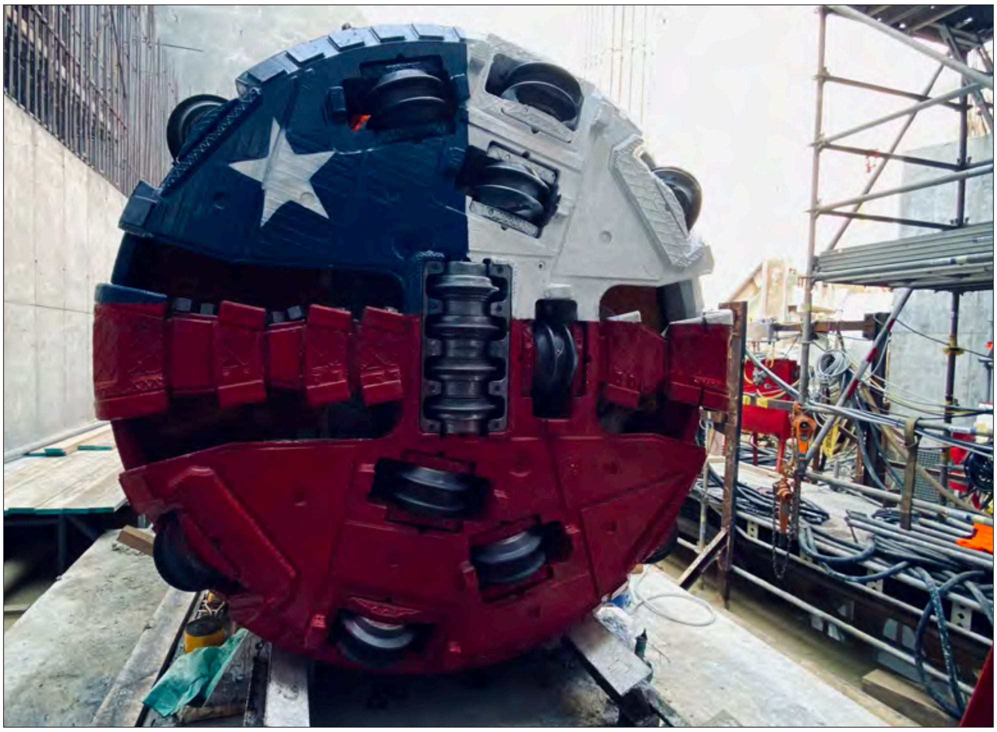

Figure 6. The AVN 1800 before launching the sea outfall drive. *(© Eurohinca)*

Figure 7. Breakthrough of the AVN 1800 in very strong basement rocks. *(© SADE Companie Générale de Travaux D´Hydraulique S.A.)*

AVN 1800 (OD 2500mm) with an exploration and injection drill were used to successfully finish the two tunnels, which were mostly through very strong diorites and gabbros with UCS values up to 250MPa. The drill was successfully installed and operated (Figure 6) to allow injection holes to be made for the successful execution of ground injections within a severe fault zone that secured the safe inspection and change of tools on the cutting wheel, just a few meters below the seabed.

Bentonite lubrication in hard rock

Control of the skin friction is an important parameter for any pipe jacking project, but for hard rock pipe jacking success, it is key. Besides the contractor´s experience and other important measures like the use of intermediate jacking stations, special attention must be paid to bentonite lubrication. The longer the drive or the larger the diameter, the more the focus should be on lubrication. Uncontrolled distribution of bentonite along the tunnel route or tearing of the lubrication film can lead to a significant increase in jacking forces. In order to maintain continuous lubrication throughout the tunnel alignment, Herrenknecht developed a volume-controlled bentonite lubrication system. The automated system offers a high level of bentonite control and automation to overcome the limitations of conventional systems. Easy handling and smart, partly automated setting of the relevant parameters assists the machine operator and avoid variations caused by personnel changes or uncontrolled pumping of bentonite.

Reference project: Landivisiau gas pipeline, France

In order to connect a new power plant in Brittany to an existing natural gas pipeline, a new 20km pipeline was needed, running from Saint-Urbain to Landivisiau. Besides other obstacles, this route had to pass under the Élorn River and the Paris-Brest railway with a low overburden. An AVN 1800 (OD 2185mm) has constructed a 530m long tunnel in the Finistère using the pipe jacking method. The 250kW MTBM tunnelled through Variscan basement rocks comprising gneiss, granite and schist with rock strengths of up to 185MPa (Figure 7). Along the tunnel route, the TBM tunnelled a gradient of 17%, a curve radius of 700m and water pressure of up to 4bar. Furthermore, a 26m height difference between the entry and exit points and a 40m drop between the entry point and the deepest point of the bore path were mastered. For such a challenging drive, bentonite lubrication using the Herrenknecht automated volume-controlled system was a key factor in controlling the friction between the pipe and the surrounding rocks and reduce the thrust force at the main jacking station.

Other factors for success

The following equipment is crucial to transfer the required thrust force from the main jacking station to the slurry MTBM and is a key factor in the success of hard rock pipe jacking (Figure 8)..

Main jacking station

The main jacking station is located in the launch shaft and has the purpose of moving the MTBM and

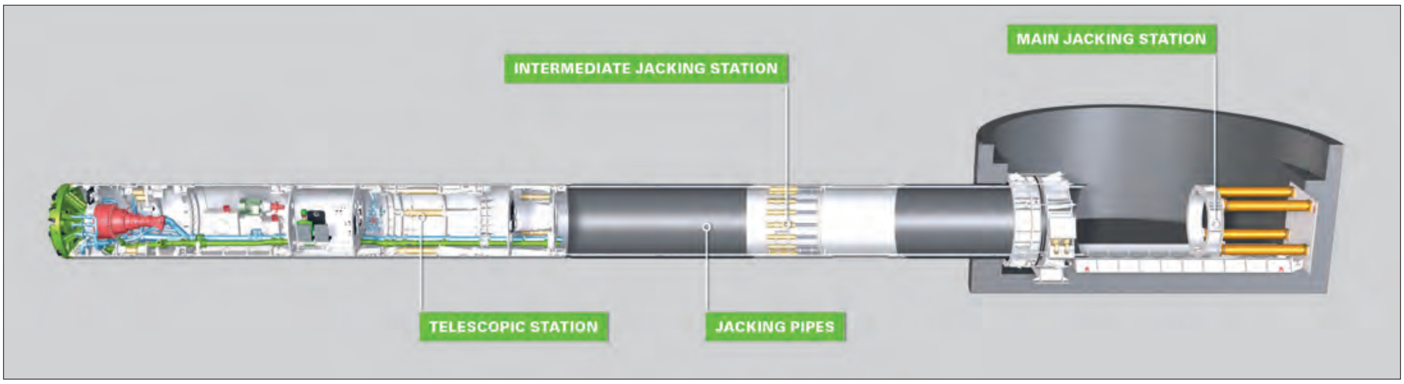

Figure 8. Pipe jacking key equipment overview.

the product pipes toward the target shaft. However, its thrust capacity is often limited by the design and loads of the pipes themselves, which leads to limited alignment lengths or more frequent use of intermediate jacking stations. For limited space applications there are also more compact main jacking station versions.

Intermediate jacking stations

Intermediate jacking stations are important, especially for long drives, providing intermediate thrust force on a longer tunnel section. They allow the MTBM to be moved even when the friction on the pipe section is too high, or the pipes reach their jacking capacity. They are a key success factor for MTBMs to be able to drive long distances, especially in hard rock applications.

Jacking pipes

Jacking pipes need to be strong enough to transfer the jacking loads from the main – or intermediate – jacking station to the MTBM at the front end of the pipe string. Various types of jacking pipe materials are used worldwide including steel or reinforced concrete (RCP). Crucial for success is the design, with sufficient safety factor, quality in manufacturing and quality control before and during installation in the launch shaft.

A further critical component is the pipe joint, which has to transfer the jacking loads from pipe to pipe and needs to be strong enough to avoid damage. This is extremely important in curved alignments where only part of the pipe cross section can be utilized for the load transfer.

Telescopic station

A telescopic station is vital especially for longer drives. It consists of a ring of hydraulic cylinders assembled directly behind the MTBM cans. With the telescopic station the frictional loads of the MTBM are separated from the tunnel alignment. By operating the telescopic station, the thrust loads can be maximized and sensitively control the advancement of the machine, without overloading the tools.

The role of digitalization

Digitalization plays a key role in recent hard rock pipe jacking projects and further pushes the boundaries of mechanized technology. Real-time tracking of all machine data enables rapid decisions to be made from all over the world to necessitate the high availability and continuous progress of the MTBM. The analysis of this data improves wear, maintenance and advance predictions. Within the Herrenknecht.Connected tool, MT.ON is a tailor-made solution for microtunnelling contractors to visualize their entire Herrenknecht MTBM fleet in one central information portal. The system provides cloud-based data processing with real-time data evaluation to procure comprehensive insights into all key MTBM parameters and processes. This includes a wide range of automated analysis functions, comprehensive dashboards and detailed sensor data evaluations.

Conclusion and outlook

Hard rock tunnelling in small diameters is specifically challenging in combination with slurry pipe jacking machines. In recent years, there has been a growing trend toward smaller diameters and longer drives, which has placed a greater emphasis on the design and selection of efficient MTBM equipment. Substantial technical progress has been made and with the latest technological innovations, such as jet pump technology, drives of far more than 1,000m with diameters as small as 457mm (18 inches) are possible. New small-diameter cutting wheel designs and, more importantly, cutting tools have been developed to support these performances, especially when dealing with hard rock or difficult mixed-soil conditions. Based on a geotechnical investigation, which should be as detailed as possible, the MTBM system can be configured using the latest engineering solutions described above.

In order to further increase tunnelling performance in future slurry pipe jacking projects, the availability of all relevant performance data of the machine is crucial. It is the basis for a continuous improvement process. Advancing digitalization will improve the possibilities of data acquisition and evaluation in the future. The availability of all data on any computer or handheld device worldwide is an essential component for transparent site operations and remote troubleshooting. In addition, valid evaluation for wear prediction and tool change can be achieved.

In the future, machine performance data will also form the basis for developing intelligent assistance systems to improve overall performance. All this will lead to faster, safer and more efficient trenchless operation, to the benefit of all stakeholders.