TECHNISCHE UNIVERSITÄT WIEN
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UNIVERSITY OF ARCHITECTURE CIVIL ENGINEERING AND GEODESY

# MASTER'S THESIS
## DIPLOMARBEIT

# Rock removal methods

## Lösemethoden von Gestein

carried out for the achievement of the academic degree of

**Diplom-Ingenieur**

under the guidance of

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## Abstract

The thesis focuses on methods performing rock removal using different cutting techniques. It examines some of the most common methods, the necessary equipment for their usage, their specific application, performance and cost effectiveness. The technologies discussed are: water jet cutting; diamond wire saw cutting; diamond circular saw cutting; disc cutting; undercutting and a conceptual rock melting machine.

The information used for the writing of this paper has been gathered and summarized from existing papers and researches concerning the individual rock removing methods. The conclusions and evaluations were made using these sources, no field or laboratory tests have been performed specifically for this thesis.

### Zusammenfassung

Die Diplomarbeit beschäftigt sich mit Methoden des Gesteinsabbaus.

Es werden einige der gängigsten Methoden, die notwendige Ausrüstung für ihre Nutzung, sowie ihre spezifische Anwendung, Leistung und Wirtschaftlichkeit aufgezeigt.

Folgende Technologien wurden untersucht: Wasserstrahlschneiden, Schneiden mit Diamantseilsäge, Diamantschnitt mit Kreissäge, Unterschnittverfahren, sowie eine konzeptionelle Gesteinsschmelzmaschine.

Die Informationen für die Erstellung dieser Arbeits wurden aus bestehenden Publikationen bzw. Untersuchungen der einzelnen Gesteinsabbaumethoden entnommen.

Schlussfolgerungen und Bewertungen wurden unter Verwendung genannter Quellen hergeleitet. Im Rahmen dieser Arbeit wurden keine Feld- oder Laboruntersuchungen durchgeführt.

## Preface

Ever since I started watching programs about big tunnel projects on the “discovery channel” years ago I thought how overwhelmingly hard and complex the work that the construction workers must complete is and I was wondering how this process must be improved so it can take less time to build a tunnel.

I was fortunate enough to have the opportunity to study transportation engineering and acquire the necessary qualification to someday actually participate in the construction process. During the last few years the advantages of tunnels and the global need for more and more tunnels for railways and highways made me certain that if possible, I would try to participate in the development of tunneling technology and construction processes. I am aware that as a graduating student there is a long way ahead of me before this can happen, but I think that the work on this master thesis is a good start.

That being said, I would like to express my gratitude to the people that helped me accomplish the task of writing this paper:

To O.Univ.Prof. Dipl.-Ing. Dr.techn. Hans Georg Jodl for taking the time to meet with me and taking my somewhat strange idea seriously enough to create a master thesis around it and accepting to be my guide for its writing.

To Assistant Dipl.-Ing. Andreas Makovec for his patience and understanding when I had difficulties and for his advice and corrections regarding the contents of the paper.

## Abbreviations:

| | | |
|---|---|---|
| ACD | – | Activated cutting disc |
| AWJM | – | Abrasive water jet machining |
| CMM | – | Continuous mining machine |
| CNC | – | Computer numerical control |
| CS | – | compressive strength |
| EPB | – | Earth pressure balance |
| FT | – | Fracture toughness |
| LP | – | Low profile |
| MDW | – | Multi diamond wire |
| MTM | – | Mobile tunneling machine |
| NATM | – | New Austrian tunneling method |
| NSTM | – | Nuclear subterrene tunneling machine |
| OCD | – | Oscillating cutting disc |
| RIHN | – | Rock impact hardness number |
| RPM | – | Revolutions per minute |
| SCHH | – | Schmidt hardness |
| SFE | – | Specific fracture energy |
| SHOR | – | Shore hardness |
| TBE | – | Tunnel bore extender |
| TBM | – | Tunnel boring machine |
| UCS | – | Uniaxial compressive strength |
| UTS | – | Uniaxial tensile strength |
| WJM | – | Water jet machining |
| YM | – | Young’s modulus |

# 1. Introduction

## 1.1. The aim of this thesis

The aim of this master thesis is to examine the most common rock removal methods used in practice today in all branches of the industry. It evaluates each of them and synthesizes the most important characteristics in a way that makes it easy to compare them as best as possible despite the big differences of their nature.

This thesis focuses mainly on the alternative rock removal methods. For "alternative", in this paper, are considered all methods that are either not used at all for tunnel construction, or their application at present is very limited. The purpose of this is to gather enough information for each method in order to summarize its effectiveness, advantages and disadvantages. With the resulting summary engineers can determine if these alternative methods are applicable for underground construction.

A secondary goal of this thesis is explore the theoretical possibility of rock removal in tunneling using cutting instead of breaking and the challenges that process holds. It is an attempt to bring to the attention of transportation engineers the advantages of alternative rock removal methods and the benefits they can bring to the tunneling industry.

## 1.2. Structure of the thesis

This thesis consists of six main parts. In the first of them, part 2, the history of tunnel construction is briefly described.

In part 3 are discussed the types of rock that engineers usually face when constructing tunnels.

Part 4 explains why, when, and where engineers have the task to remove rocks, being it above or underground.

Part 5 is dedicated to the most widely used rock removal methods in tunneling today – the drill-and-blast method and tunnel boring machines. However, although these methods are very complex and important, they are not the focus of this paper. Because of this, the content of Part 5 is very compact and the methods' features are not described so thoroughly.

Part 6 is the core of this thesis; it includes all the alternative rock removal methods examined in this paper. Each subpart is dedicated to a different method and shows the processes that it involves its performance, necessary equipment and the prerequisites for its usage for a particular job. Every subpart ends with a table which consists of the most important facts about the method in question.

## 2. Historical overlook of the development of tunneling methods

Tunnels have a long and rich history. Since ancient times, tunnels have been dug for various reasons all over the world. Those tunnels were built using only manual labor and very primitive tools such as sharpened rocks. Most of the oldest tunnels were built as a part of water management systems. The “qanat” of Persia is such a system, build over 2700 years ago and located in today’s city of Gonabad. It provided water for drinking and agricultural needs and is still in use today. It has a length of 45 km[1]. In Europe, the ancient Greek engineer Eupalinos of Megara build in 520 BC the Eupalinian aqueduct. He organized the work so that the tunnel was begun from both sides of mount Kastro. The two teams advanced simultaneously and met in the middle with excellent accuracy, something that was extremely difficult in that time. The aqueduct was of utmost defensive importance, since it ran underground, and it was not easily found by an enemy who could otherwise cut off the water supply to Pythagoreion, the ancient capital of Samos. The tunnel proper is 1,030 m long[2].
Probably one of the first transportation tunnels was built around 3rd century BC and passed through the Furlo pass located in the Apennines. Later in 76-77 by the order of roman emperor Vespasian a newer tunnel was build for the Via Flaminia, an important Roman road. A modern road still uses this tunnel.
The first defined methods are known today as classical. Those include the Belgian, English, German, Austrian, Italian and American systems. These methods had much in common with early mining methods and were used until last half of the 19th century. The excavation process was done by hand or simple drilling equipment. Supports were predominantly timber, and transportation of muck was done on trollies on narrow gauge tracks and powered by steam. Progress was typically in multiple stages i.e. progress in one drift, then support, then another drift, and so on. The final lining was out of brickwork.[3] These craft-based methods are no longer applicable, although some of their principles have been used in combination up to present day. Nevertheless some of the world’s great tunnels were built with these methods.
According to the English method, also known as the crown-bar method (Figure 1) workers began excavation from the top of the cross-section making enough room to place a couple of wooden crown bars. They were secured to the completed structure at one end and in a hole in the heading at the other. As the heading was cleared more timber bars were placed

[1] See Wilson, A.: "Hydraulic Engineering and Water Supply", in: John Peter Oleson: Handbook of Engineering and Technology in the Classical World, New York: Oxford University Press, 2008 (editor), p.291f
[2] See Burns, Al.: "The Tunnel of Eupalinus and the Tunnel Problem of Hero of Alexandria". Isis 62 (2): 172–185, 03.11.2011
[3] See http://theconstructor.org/transportation/tunneling-methods/689/, 04.11.2011

around the edge of the tunnel and perpendicular bars were placed to counter the ground's pressure. This method worked in different ground conditions as long as the pressure was low enough for the wooden frame to withstand. It required a significant amount of wood material and allowed for the whole arch of the tunnel to be erected at the same time.

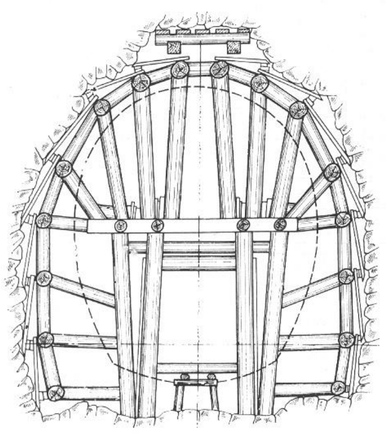

Figure 1 Crown bar method[4]

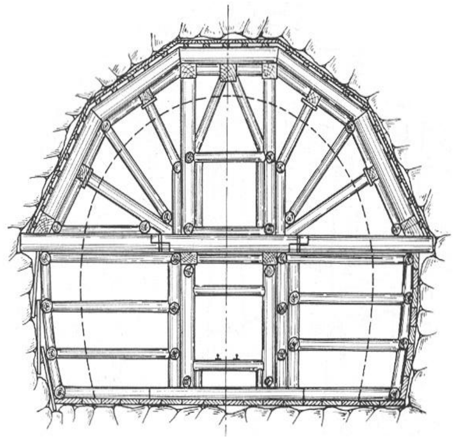

Figure 2 Cross-bar method[5]

The Austrian method, sometimes called the cross-bar method (Figure 2) also relied on a solid wooden frame. It had strong middle and bottom sections which were excavated first and the top heading was completed after that. The additional frame for the crown heading was supported by the central bars which formed a rigid structure and were positioned parallel and perpendicular to the tunnel axis. The timbering for the new lining was also propped to the existing frame for stabilization. This technique required much thicker beams which made it possible for the lining to withstand higher ground pressures.

The German method was also called core-leaving method because the workers excavated sections on both sides of the tunnel leaving the core intact to support the crown. After the sides have advanced the middle section is also removed and the arch is quickly completed to support the tunnel. This method relied on the strength of the excavated ground. This was the first method that used multiple drifts for excavation.

The last of the classical tunneling methods is the Belgian system or the flying arch method. It was called that because the top heading was always constructed first and was moving several meters before the rest of the excavation (Figure 3). After the initial advance the heading is extended enough to reach the maximum width of the tunnel. This enables workers to construct the arch that supports the ground during the excavation of the rest of the face.

[4] http://theconstructor.org/transportation/tunneling-methods/689/, 04.11.2011
[5] http://theconstructor.org/transportation/tunneling-methods/689/, 04.11.2011

This was only achievable in lower ground pressures.[6] The first major tunnel constructed using this method was in the Tronquoy tunnel in France completed in 1803.

Classical multiple face excavation

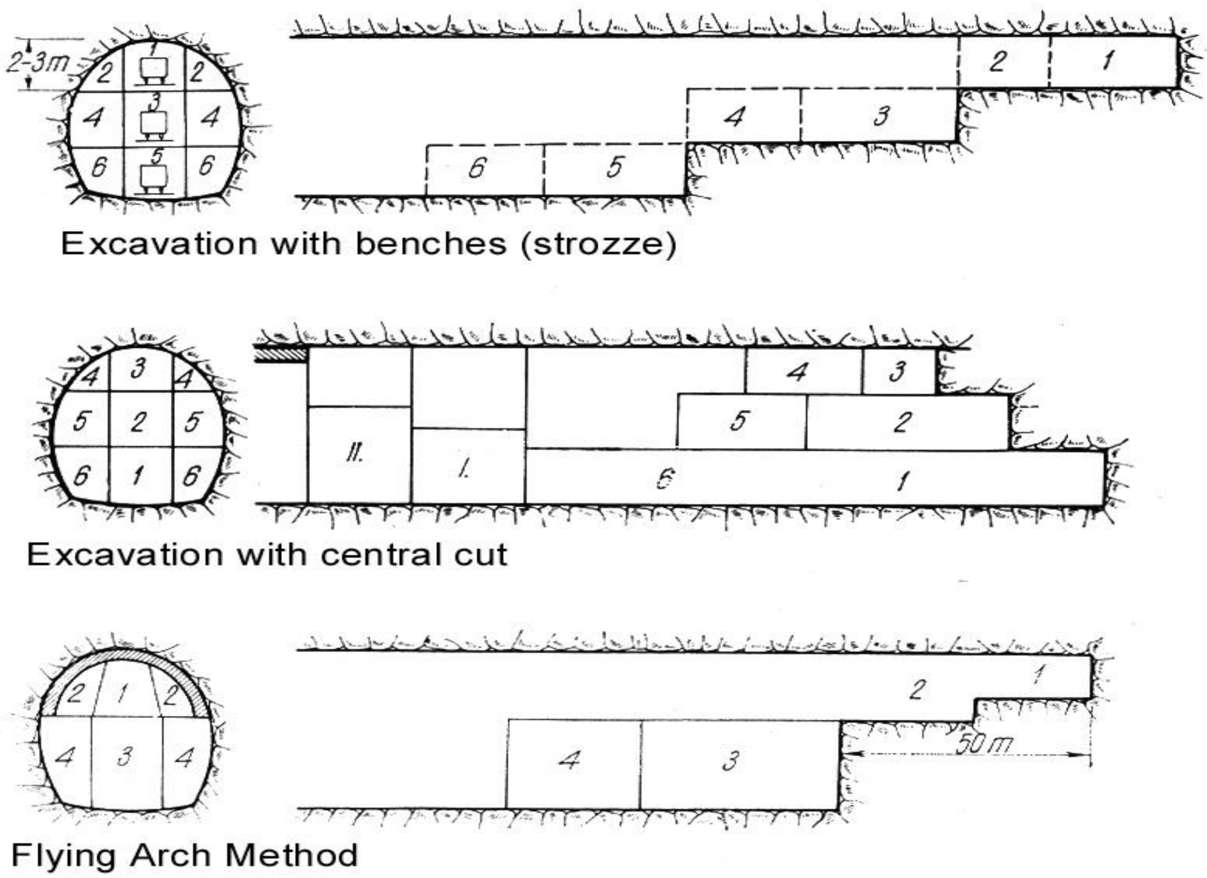


Figure 3 Different types of advances[7]

With technological advancement came the modernization of tunneling. Newer methods included various drilling and cutting machines, which greatly improved the rate of advancement. Drilling methods were mostly used for mine shafts due to the smaller surface. For bigger tunnels, as the ones that are constructed for transportation needs, the drilling was combined with explosives thus the drilling and blasting method was born. This method was used for tunneling through hard rock.

The drill-and-blast method was not very popular before industrialization and it wasn't until the invention of dynamite, a more powerful explosive, and the implementation of powered drills that it became one of the most used methods. It is so effective, that even today it's one of the most commonly used excavation methods, of course with huge improvements in both drilling

[6] See http://theconstructor.org/transportation/tunneling-methods/689/, 04.11.2011

[7] http://theconstructor.org/transportation/tunneling-methods/689/, 04.11.2011

and explosives. The performance of drilling and blasting is matched only from the tunnel boring machines.

The first functioning predecessor of modern TBMs was developed in 1825 by Sir Marc Isambard Brunel for the construction of the Thames Tunnel.[8] It is not completely accurate to compare the machine to the TBMs since it only introduced the shield protecting the workers which excavated the ground using the then common methods.

A machine with mechanized excavation process was first constructed by Henri-Joseph Maus. His machine was built in 1846 in Italy to be used in the tunnel that would connect France and Italy through the Alps. At the front of the machine 100 percussion drills were mounted and power was provided outside of the tunnel. However, historical events in 1848 interrupted the construction and reduced the funding of the project. The machine was discarded and the tunnel was completed using pneumatic drills.

The first effective TBM was constructed by James S. Robbins in the beginning of the 1950s when he was contracted to construct a tunnel for water diversion. The tunnel had to be dug through the Pierre Shale, which was considered extremely difficult at the time. The machine achieved performance ten times better than the methods that existed at the time, cutting through more than 48 meters in just 24 hours. It was Robbins that later improved his method drastically replacing the steel picks used in the machine with disc cutters. This greatly reduced the problem with wear and tear of the cutting tools. The idea was so successful that disc cutters mounted on a rotating head are used in almost all modern TBMs.

Through the years the TBM became more efficient and different types of TBMs emerged, specified for various types of rock. The spectrum of TBMs and rock and soil types will be thoroughly examined later in this paper.

Another important innovation in the tunneling industry was the development of the New Austrian Tunneling method in the period 1957-1965 in Austria[9]. It was the brain child of mainly three people – Ladislaus von Rabcewicz, Leopold Müller and Franz Pacher. During construction using the NATM the changes in the rock masses are monitored to help improve the support of the tunnel. Unlike other methods, the NATM doesn’t include a unique set of excavation processes. It increases the effectiveness of other methods by providing the data needed by the engineers to optimize the lining of the tunnel, improving the safety and reducing the costs at the same time.

Tunnel construction becomes a bigger part of infrastructure constructions every year. Countries around the world are constantly increasing their budgets for high-speed infrastructure. Railway has proven to be most effective and eco-friendly transportation

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[8] See Hapgood, F.: "The Underground Cutting Edge: The innovators who made digging tunnels high-tech",Invention & Technology Vol.20, #2, Fall 2004, 04.11.2011

[9] See Özdemir, L.: North American Tunneling 2006. Washington, DC: Taylor & Francis. pp. 246, 04.11.2011

method today. With ever increasing international goods transfer and the competition between short-distance air and rail transport, there is a high demand for high-speed railroads. With higher speeds come straighter routes which inevitably means going through obstacles instead around them. And you can’t get straight through faster than with a tunnel. That is why there are many tunnel projects being started in the past few years and even more being considered in the future. One of the main problems with tunnels, however, is their relatively long construction time and dependence on the geological characteristics. Breaking and removing thousands of tones of rock is a tedious process which not only deteriorates the machines at a very fast rate, but also poses danger to the crews working in the tunnel. Working conditions underground are the most hazardous and demanding physically and mentally. That is why a lot of institutions and private enterprises work on improving the currently used methods and researching new possibilities. This will increase productivity and safety while reducing costs.

## 3. Rock types common in rock removal practice

Earth's crust has a very rich assortment of rock types formed under different conditions and with different characteristics. Many of them have some application in various industries and many are mined and used as building materials. Additional information will be given for three types of rock so that it will be easier for the reader to assess the contents of part 6.

### 3.1. Limestone

Limestone is a type of sedimentary rock which has at least 50% of its weight formed by calcite. It forms as a result of the sedimentation. It has a grainy texture because of the skeletal and shell fragments from the organisms that were part of the sedimentation. Limestone also contains small amounts of quarts, pyrite and other minerals[10].
Limestone is the rock with the most industrial application because of his specific qualities.
Some of the applications of limestone are as a construction material. When crushed it is used as ballast under the railways or for the base in road construction. Limestone is also a key ingredient for the production of Portland cement.


Figure 4 Limestone at a road construction site[11]

[10] See http://geology.com/rocks/limestone.shtml, 10.07.2012
[11] http://www.review.net/section/detail/31679/, 10.07.2012

| | |
|---|---|
| Hardness | 3 to 4 on Moh's Scale |
| Density | 2.5 to 2.7 $Kg/cm^3$ |
| Compressive Strength | 60-170 $N/mm^2$ |
| Modulus of elasticity E | 20-70 GPa[12] |
| Water Absorption | Less than 1% |
| Porosity | Quite low |
| Weather Impact | Resistant |

Table 1 Physical Properties of Limestone[13]

Limestone is used as a cheap alternative to the harder rocks. It is a strong, dense rock and it's very durable and abrasion resistant, but still easier to process because it wears the cutting or breaking tools more slowly which makes it preferable.

## 3.2. Sandstone

Sandstone is another type of sedimentary rock. Unlike limestone, it consists almost entirely of small sand particles and rock grains. Usually sandstone's mineral content is high in quartz and/or feldspar which are the most abundant minerals in the Earth's crust. Because sandstone gets its color from the sand it can also be almost any color, usually it is tan, gray, brown or yellow[14].

Figure 5 Typical sandstone as found in nature[15]

[12] http://www.essom.com/backend/data-file/engineer/engin23_1.pdf, 29.11.2012
[13] http://www.mineralszone.com/stones/limestone.html, 29.11.2012
[14] See Pettijohn F. J., P.E. Potter and R. Siever: Sand and sandstone, 2nd ed. Springer-Verlag, 10.07.2012
[15] http://www.publicdomainpictures.net/view-image.php?image=8400&picture=sandstone-rock, 10.07.2012

| | |
|---|---|
| Hardness | 6.5 to 7 on Moh's Scale |
| Density | 2.3 to 2.4 Kg/cm$^3$ |
| Compressive Strength | 90 to 140 N/mm$^2$ |
| Modulus of elasticity E | 20-70 GPa[16] |
| Modulus of Rupture | 16-40 N/mm$^2$ |
| Water Absorption | 1.0 - 1.2 % |
| Porosity | Low to very low. |

Table 2 Physical Properties of Sandstone[17]

### 3.3. Granite

Granite is an igneous rock of the intrusive subtype which is very common within Earth's crust. It mostly consists of the following minerals – quartz (at least 20%), mica and feldspar. Depending on the exact mineral contents and chemistry of the granite its color may differ from black to gray to pink. Granite is formed under tremendous pressures and as a result is a massive rock and is one of the hardest and toughest rocks found in nature. This makes it ideal for construction material which is its most common use today.[18]

Granite usually forms into relatively small stock masses (<100 km²) which are located in batholiths and are related to the forming of orogenic mountain ranges. It has formed during different geologic periods but mostly in the Precambrian age. Granites are abundant in the continental crust and are often located beneath layers of sedimentary rocks.

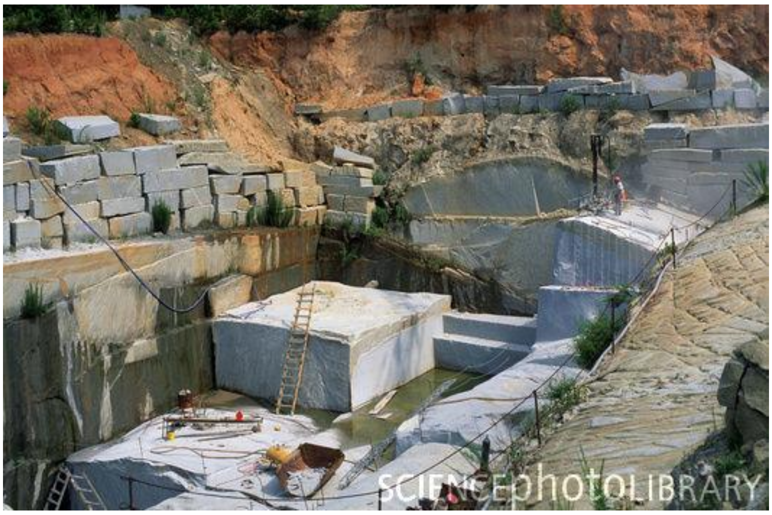


Figure 6 Granite rock quarry near Elberton, Georgia[19]

[16] http://www.essom.com/backend/data-file/engineer/engin23_1.pdf, 29.11.2012

[17] http://www.mineralszone.com/stones/sandstone.html, 29.11.2012

[18] See Weinberg, R. F., and Podladchikov, Y.: "Diapiric ascent of magmas through power-law crust and mantle", 1994, J. Geophys., 10.07.2012

[19] http://www.sciencephoto.com/media/358705/enlarge, 10.07.2012

| | |
|---|---|
| Hardness | 6 to 7 on Moh's Scale |
| Density | 2.6 to 2.8 $Kg/cm^3$ |
| Compressive Strength | 140 to 210 $N/mm^2$ |
| Modulus of elasticity E | 40-100 GPa[20] |
| Modulus of Rupture | 15 to 25 $N/mm^2$ |
| Water Absorption | 0.1-0.6% |
| Porosity | Quite low |
| Weather Impact | Resistant |

Table 3 Physical Properties of Granite[21]

[20] http://www.essom.com/backend/data-file/engineer/engin23_1.pdf, 29.11.2012
[21] http://www.mineralszone.com/stones/granite.html, 29.11.2012

# 4. Rock removal in transportation infrastructure

Rock removal has an important role in transportation infrastructure construction and it has become especially important in the last two decades. Over the years infrastructure has transitioned from avoiding geographical and man-made obstacles to going through or under them. The demand for shorter travel times means both increase in speeds and shortening of routes. Both of these factors are strongly connected, since shorter routes are straighter, giving the opportunity for vehicles to travel at greater speeds.

Rock removal is a process that is a part of almost any construction project no matter if it is for infrastructure or for something else. But since transportation projects tend to be linear and cover a larger area, the portion of rock removal compared to other types of work is far greater. Adding this volume of work to the fact that this is also one of the slowest and time-consuming processes, results in high cost. This is why a large percent of the overall cost of a project is dedicated for rock removal and earth works in general. This is the reason why alternative rock removal methods must be researched and implemented from other industries into infrastructure construction.

## 4.1. Above ground rock removal

Above ground rock removal includes mostly leveling of the earth masses along the path of the road or railway. This usually involves excavation of the trenches and building the embankments. The material excavated is usually a mixture of soil and broken rock and is used for the creation of the embankments if it is possible. When a larger rock mass is to be dealt with, the rocks are blasted and fragmented using explosives and removed using the standard equipment.

### 4.1.1. Shallow earthworks

Most road, highway or railway projects require only relatively shallow earthworks. That usually consists of removing the uppermost soil layers, which are easily breakable using standard excavation equipment. The machines (Figure 7) that are used for this types of work are various and well specialized for the task, which makes the process efficient and relatively cheap.

One of the biggest advantages of above ground construction compared to underground construction is that the number of machines that can be used depends only on the work site each machine needs and the budget of the project.

With sufficient financing work can be done simultaneously over the span of the whole route which shortens construction time drastically.

### 4.1.2. Hard rock removal

Hard rocks in above ground construction are usually removed in large quantities when the route goes through a mountainous environment. A characteristic for these types of rock is the fact that most of them are exposed to the elements and are in different phases of destruction from the natural forces. This is why their removal using on-site machinery is out of the question before the necessary precautions are taken. Geologists play an important role since they provide information for the condition of the rocks. In order to reduce construction costs and impact on the environment steeper angles are often chosen and the exposed rocks are secured using different methods: anchors, nets, shotcrete (Figure 8).

Figure 7 Drilling equipment securing a slope using metal mesh[22]

[22] http://www.therixgroup.com.au/, 16.07.2012

Above ground rock removal is generally easier and engineers have a wider variety of solutions to choose from, depending on the situation. They provide greater efficiencies at reasonable costs.

## 4.2. Underground rock removal

Underground rock removal for the transportation infrastructure consists almost exclusively of tunnel construction. A small part consists of underground parking complexes within cities.

The ever-increasing number of people living in cities and increased mobility of individuals and goods has overloaded many traffic systems in and around large metropolitan areas. Excessive building for commercial and residential needs leaves little space for transportation and engineers more and more often are forced to look for solutions underground. Almost every large city today is working on extending its subway systems and cities without one are planning and investing in the construction of one.

The subway is proven to be one of the most effective forms of mass transit. It is convenient for passengers to use and authorities to operate.

Constructing tunnels under existing buildings is a challenge for all parties involved. Cities have many layers of different types of infrastructure already in place, that must not be disturbed and older buildings' foundations are not always sufficient to dig under.  This often forces engineers to design the tunnels at greater depths but this creates new problems as it solves others.

Ground water is another problem that is common with such projects. It poses risk for both workers and equipment. Water with sufficient pressure and/or quantity can cause structural damages to the tunnel forcing project delays and increasing costs.

## 5. Modern rock removal methods in tunneling

In this part of the paper the two most commonly used methods for tunneling today will be examined – the drill-and-blast method and the tunnel boring machine method. These methods are the engineers' preferred solution for most tunnel projects in the past decade, depending on the geological conditions and the parameters of the specific project.
Either of them has its advantages and disadvantages which will be mentioned and evaluated below. Each method is a complex combination of many factors and variables that define its performance. It must be considered that not all variations can be taken into account, as this is not the primary goal of this master thesis. The intent of this part is to explain the processes that each technique includes in order for a comparison to be made later with the alternative methods for rock removal.

### 5.1. Drill-and-blast method

One of the drill-and-blast method's biggest advantages is its flexibility in terms of cross-sectional geometry. Since the holes are drilled for every individual cycle their position and number can be changed according to the current geology. The geology also determines the type of initial support that must be completed. Depending on the strength of the surrounding rock this is done either in the face area, the excavation area or the rear area.
Weaker or cracked rock masses need to be secured as close to the face as possible, while stronger masses can be supported further from the face. This can slow down the overall speed of the drill-and-blast cycle when the support measures are executed close to the face. The reason is that the drilling machines have to wait before starting the next cycle. The most commonly used means of initial support are the rock-bolts, sometimes combined with nets and shotcrete. A single cycle of the drill-and-blast method includes many processes (Figure 11). They must be planned and executed precisely in order to ensure the safety of the workers and the efficiency of the equipment. Space in tunnels is scarce and the coordination of the movement every piece of machinery involved is essential. Operators must be qualified and experienced and all safety precautions must be complied with[23]. The overall speed depends on the correct execution of every step because a new cycle cannot begin unless all the steps from the previous one are finished. Because of the many variables that this method includes engineers often prefer to use TBM if possible.

[23] See LEES, David: History of drill and blast, http://www.ats.org.au/index.php?option=com_docman&task=doc_download&gid=8 , 23.09.07

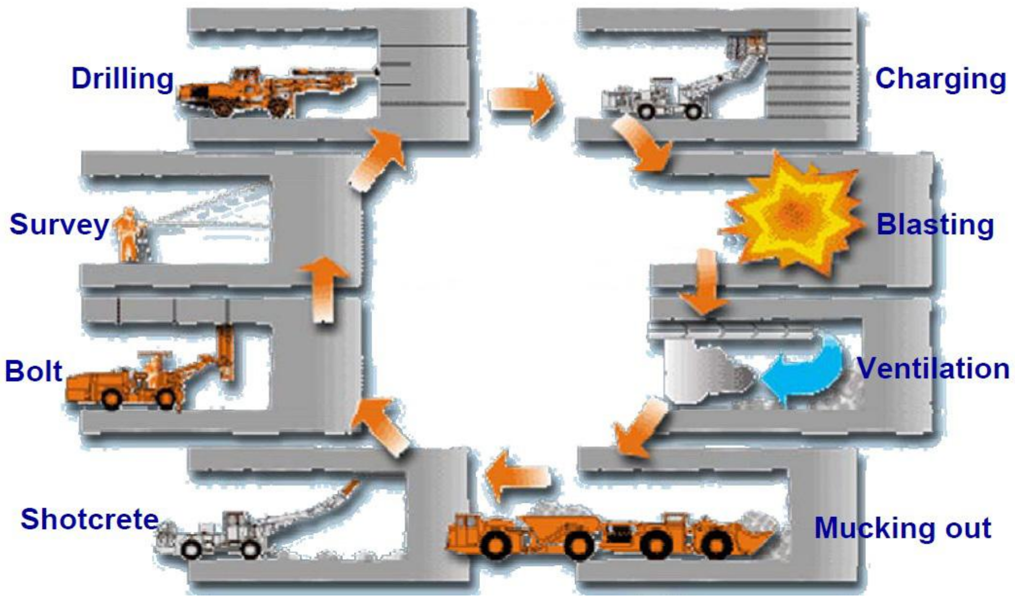


Figure 8 Sequence of the processes included in a common drill-and-blast excavation[24]

### 5.1.1. Modern high-performance Machines

The performance of every drill-and-blast excavation is strongly dependable on the machines used for the different processes. The goal for engineers and equipment manufacturers is to design machines that combine different functions to reduce their overall number. However, those machines must be capable of completing the given tasks as efficiently as a dedicated machine would. Thanks to the technological advancements in the last decades this is a realistic expectation. Modern machines are both fast and reliable and are the reason this method is still comparable to TBMs.[25]

#### 5.1.1.1. Drilling Technology

Drilling, as the name of the method suggests, is one of the main processes during each cycle. It is very important that each and every one of the holes is drilled precisely where the engineers have determined. This way each blast has maximum effect and the rock fragments are small enough to be removed. The drilling stage involves a drilling machine, sometimes

[24] ZHAO, Jian: Tunneling in rocks – present technology and future challenges, http://www.ita-aites.org/fileadmin/filemounts/e-news/doc/ITANews19/JZ_Inaugural_lesson.pdf , 24.05.07;

[25] See GIRMSCHIELD, G.; WALTI, R.: High performance drill and blast method – progress in efficiency through industrialized backup systems and process configuration, http://e-collection.library.ethz.ch/eserv/eth:462/eth-462-01.pdf, 23.07.2012

referred to as “jumbo”. It can have number of booms with different length depending on the cross-section of the tunnel (Figure 12).

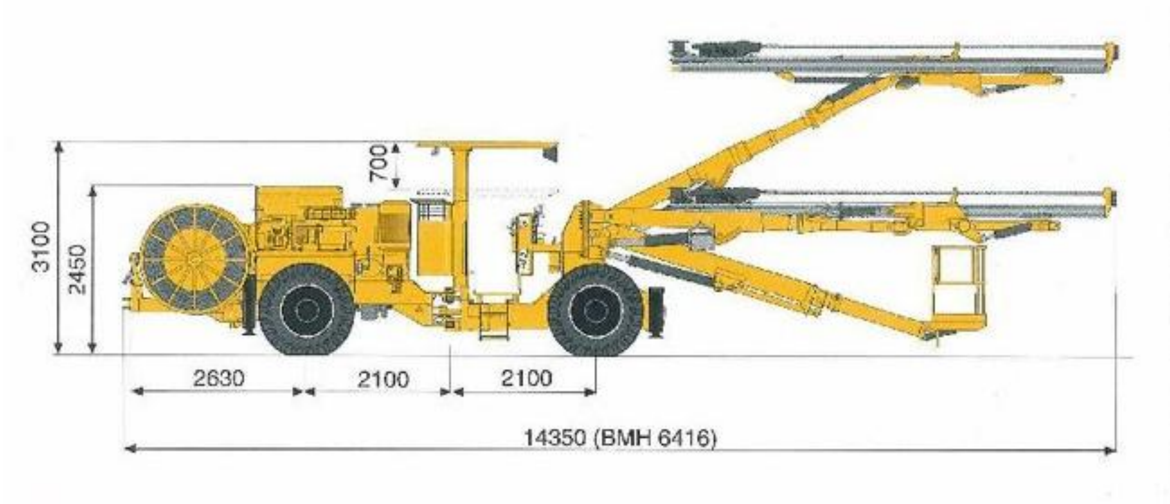


Figure 9 3-boom jumbo[26]

The operator positions the machine in front of the face and the location of each hole for the current blast is loaded into its on-board computer. Modern drilling equipment can automatically drill the holes and reposition the booms using the coordinates from the computer. They can also project the position of the holes using laser so they can be drilled manually by the operator. Some jumbos have booms with secured platforms for the workers that put the explosive charges. This accelerates the process and reduces the number of machines needed. The jumbos have high-strength heavy-duty drill bits that last longer and perform better.[27]

#### 5.1.1.2 Mucking Technology

Mucking is the process of disposing of the rock mass that was destructed after each blast. It includes gathering of the material from the blast site, loading, crushing if needed and disposal from the tunnel. The technology that is used for mucking depends highly on the type of debris that are left after the blast, their size and strength, as well as the overall volume.
The most common methods are:

- mucking trains

[26] http://www.gobizkorea.com/blog/ProductView.do?blogId=primerental&id=896192, 23.07.2012

[27] See GIRMSCHIELD, G.; WALTI, R.: High performance drill and blast method – progress in efficiency through industrialized backup systems and process configuration, http://e-collection.library.ethz.ch/eserv/eth:462/eth-462-01.pdf, 23.07.2012

- conveyors
- dump trucks

In order for a conveyor or a mucking train to be used it's usually necessary for a crusher to be installed to reduce the size of the debris. Dumpers can transport larger rocks but they need to be loaded using a front end loader requiring room to maneuver. For tunnels with smaller cross-section a side-tipper type loader can be used.

Conveyor belts and mucking trains take up less space and have a good performance but they have to be extended constantly which costs additional time.

The best performance in recent years is achieved using very powerful excavators. They are able to reach a maximum of 500t/h even in tunnels with smaller cross-section where there is little space for maneuver.[28]

### 5.1.1.3. Support Technology

Structural support is a vital part of the drill-and-blast cycle. Depending on the cross-section of the tunnel, the support is done in several stages at different locations – the face, the excavation and the rear areas.

Anchor bolts are drilled, placed and pre-stressed almost autonomously. Human intervention is only required for the positioning of the machine to the point where the bolt is designed to have the best bearing capacity. Machines can place multiple bolts simultaneously depending on the model (Figure 13).

Figure 10 -Hydraulic Driver Crawler Drilling Rig[29]

[28] See GIRMSCHIELD, G.; WALTI, R.: High performance drill and blast method – progress in efficiency through industrialized backup systems and process configuration, http://e-collection.library.ethz.ch/eserv/eth:462/eth-462-01.pdf, 23.07.2012

[29] http://www.hongwuhuan.com/en/product.asp, 23.07.2012

Steel arches are usually used as a secondary support. Since their installation is somewhat more complicated they are mounted manually. Therefore, engineers are working on ways to make that process mechanized and modular, which will greatly improve the performance.
One of the most time-consuming support measures is the netting. Equipment for mechanized net placement is still under development and because of that net is still mounted manually. Steel arches and nets are often used together to form a secure initial support.
Shotcrete support is probably the easiest to execute, even if a worker is guiding the machine the process is still fast. There are machines that cover the whole area autonomously after initial setup, using either wet or dry spraying with predetermined thickness of the concrete layer (Figure 14). The overall performance of such a machine depends highly on the viscosity of the concrete. It is recommended that shotcrete layers do not exceed 5 cm. If thicker shotcrete support is needed, several layers are sprayed with enough time between them to allow the concrete to harden and cure.[30]

Figure 11 Shotcrete machine for underground mining[31]

### 5.1.2. Blast Technology

Blast technology has improved significantly over the last decade. The manufacturers' main priorities are handling safety, toxicity and ease of borehole charging without reduction in the blast power.[32]

[30] See GIRMSCHIELD, G.; WALTI, R.: High performance drill and blast method – progress in efficiency through industrialized backup systems and process configuration, http://e-collection.library.ethz.ch/eserv/eth:462/eth-462-01.pdf, 23.07.2012
[31] http://pdf.directindustry.com/pdf/maclean-engineering-59044.html, 23.07.2012
[32] See GIRMSCHIELD, G.; WALTI, R.: High performance drill and blast method – progress in efficiency through industrialized backup systems and process configuration, http://e-collection.library.ethz.ch/eserv/eth:462/eth-462-01.pdf, 23.07.2012

### 5.1.2.1. Explosive

There are many types of explosives available today but explosives specialists prefer to use emulsion explosives for underground blasting. Emulsion explosives have several advantages: they are safer, less toxic and are charged easily. The explosive consists of two emulsions that are mixed and pumped using a machine. The machine controls the quantity of explosive pumped in each borehole which allows more precise explosions (Figure 15).

Figure 12 Emulsion Loader[33]

This process is controlled from a distance which reduces the risk for the workers. A single machine can pump different mixtures that can be more or less powerful which makes it very versatile and effective[34].

### 5.1.2.2. Detonators

Detonators also profit from technological advancements and today provide safer and more accurate explosions. Modern electronic detonators help engineers to achieve a very precise firing sequence which makes every explosion more effective and reduces costs.

However, because of the higher price of the individual electronic detonators they are often used in combination with other types of ignition techniques. For instance, tube ignition systems are used for the center of the cross-section; electronic detonators are placed in the contour zone where their precision is needed to ensure an accurate and clean break. The different types of explosives and detonators allow engineers to seek out the most cost

[33] http://www.directindustry.com/prod/maclean-engineering/explosives-carrying-loading-vehicles-emulsion-charger-59044-433066.html, 23.07.2012

[34] See GIRMSCHIELD, G.; WALTI, R.: High performance drill and blast method – progress in efficiency through industrialized backup systems and process configuration, http://e-collection.library.ethz.ch/eserv/eth:462/eth-462-01.pdf, 23.07.2012

effective solutions that ensure high performance and safety. These technologies keep the drill-and-blast method competitive.[35]

### 5.1.3. Back-up systems

Recently, engineers have developed back-up systems for drill-and-blast tunneling that help increase its performance drastically. These systems are useful for longer tunnels that have smaller cross-sections. Such a system has been introduced by ROWA for the construction of a single-track rail tunnel in Switzerland(Figure 16)

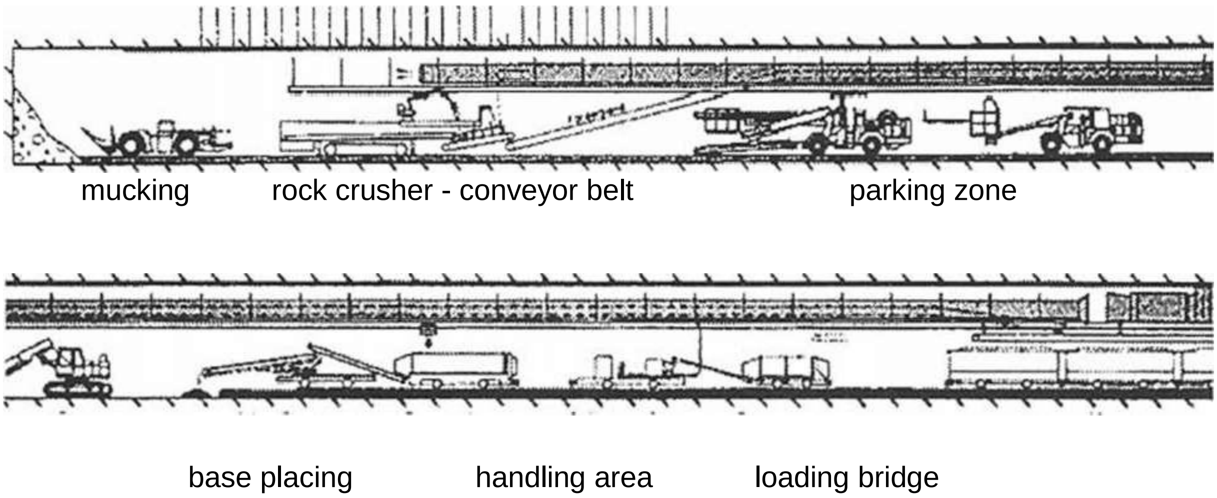


Figure 13 Back-up System Tunnel Vereina South (Switzerland)[36]

This system provides the option for different processes to be done simultaneously and handles the disposal of muck from the face of the tunnel. It also supplies the bulk materials for the construction of the tunnel. The back-up is suspended in the upper part of the tunnel which leaves most of the cross-section free for the machines involved in the different stages of construction. In addition, this system contains in itself all the vital infrastructures – cables, ventilation, water. It can also transport other necessities like compressors, emergency power aggregators, explosives even workers. The back-up smoothes the drill-and-blast cycle and eases the transition between the different steps.

[35] See GIRMSCHIELD, G.; WALTI, R.: High performance drill and blast method – progress in efficiency through industrialized backup systems and process configuration, http://e-collection.library.ethz.ch/eserv/eth:462/eth-462-01.pdf, 23.07.2012

[36] GIRMSCHIELD, G.; WALTI, R.: High performance drill and blast method – progress in efficiency through industrialized backup systems and process configuration, http://e-collection.library.ethz.ch/eserv/eth:462/eth-462-01.pdf, 23.07.2012

### 5.1.4 Evaluation

The drill-and-blast method is still viable today thanks to constant improvements made by manufacturers of drilling equipment and innovations that help speed up the process. One advantage is that the machines are relatively cheap compared to TBMs. They are easily maintained and can be used for many different projects during their exploitation period. With the addition of on-board computers the machines are easily operated and more efficient.

However efficient the machines are, the biggest disadvantage of this method lies in its main component. Blasting, even as strictly regulated and executed as it is in tunneling still poses danger for both workers and existing structures. Risk for the workers in the tunnel is minimized by following safety procedures. However, the unpredictability of rock masses and their exact response to a certain blasts leaves an unknown parameter before every blast. This seems to be enough for many authorities to either highly restrict the use of explosives within urban areas or prohibit them altogether. This means that the drill-and-blast method often cannot be used for the removal of the hard rock usually encountered when constructing low subway tunnels.

This method is then preferred for by-pass type tunnels for road or railway infrastructure where the use of a TBM is impractical.

Drill-and-blast firmly holds its position in the tunneling industry, and its effectiveness and versatility are hard to beat, which makes its utilization for future projects unarguable. Although it is one of the oldest methods, it has been shown that there is enough room for improvement to answer the challenges of modern tunneling.

## 5.2. Tunnel boring machines

Tunnel boring machines have existed for hundreds of years but today's machines that are the focus of this part have all one thing that distinguishes them as modern – the rotating cutter-head. TBMs range widely in dimensions, application and other characteristics, but they all have some form of rotating head. However, the cutter-head is just a small part of the TBM. It combines in one place several processes and is a large moving construction complex that is tens of meters in length. The TBM shield provides a secure environment for workers and contains within it the equipment needed for the construction of the tunnel lining and muck disposal.

TBMs are very expensive machines to design and build and are therefore economically justified when used for longer tunnels or multiple shorter ones. Because of this TBMs are only manufactured when ordered and the design of each machine is consistent with the requirements of the client. Those requirements usually determine the diameter and the type of the cutter-head, the muck removal method and other factors. They are constructed in factories, then disassembled and transported to the location of the project where they are reassembled. After the completion of the project if the TBM is in good condition it can be used for another project where a machine with similar characteristics is needed. New developments in the field make every new model slightly more effective and the growing demand for TBMs means that manufacturers can invest more resources to produce better machines.

### 5.2.1. Types of tunnel boring machines

The different types of tunnel boring machines are determined by what they are designed to excavate. The two main categories are "Hard rock TBMs" and "Soft ground TBMs" but in practice each machine is categorized more precisely using the specific technology the cutter-head utilizes.

#### 5.2.1.1. Slurry Machine

Slurry machines are typically used for soils with different hardness. For the excavation process a mixture of soil and slurry is created to produce a positive face pressure required for the soil removal to be maintained. In this "closed circuit" type machine the excavation of the soil is done by pumping the mixture of soil and slurry through pipes that lead it out of the tunnel. There a facility is constructed to filter the mixture and extract the slurry so it can be pumped back to the face and reused.[37]

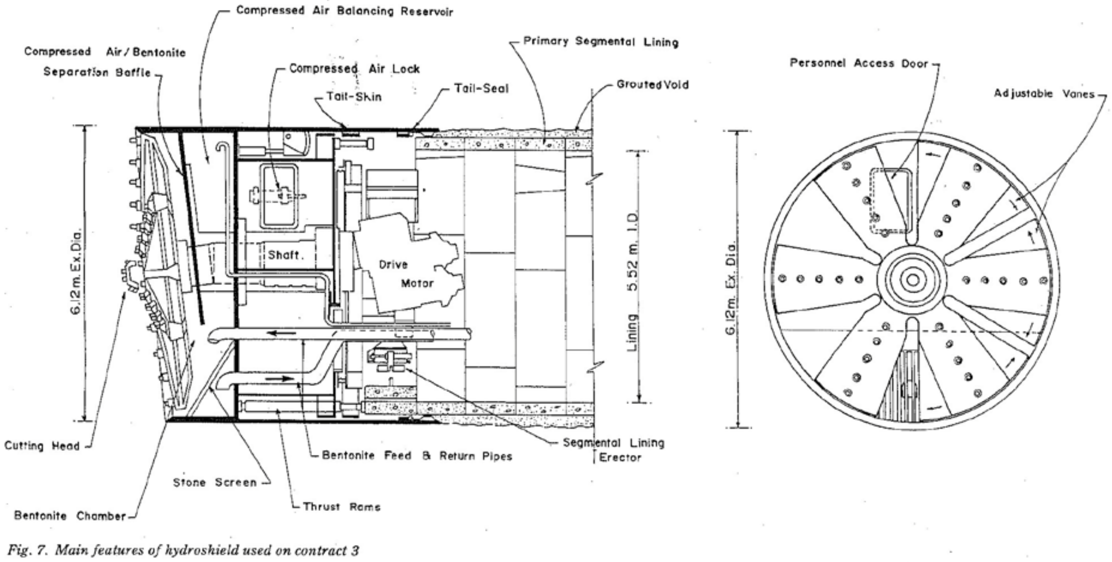


Figure 14 Slurry TBM cross-section[38]

### 5.2.1.2. Earth pressure balance machine

Another type of closed type TBM is the Earth Pressure Balance machine, with application in mainly soft and cohesive types of soil. As the name states, the pressure at the face of the machine is maintained using the excavated earth masses. The pace with which earth is removed is controlled by the speed of the rotating screw conveyor. The extracted volume is small enough to keep the broken soil in front of the machine under pressure. The screw conveyor deposits the soil onto the means for transportation out of the tunnel, either conveyor belt or skips.[39]

[37] See SPENCER, STOLFA, BENTZ: Tunnel Boring Machines, http://www.imia.com/downloads/imia_papers/WGP60_2009.pdf, 29.07.2012
[38] SPENCER, STOLFA, BENTZ: Tunnel Boring Machines, http://www.imia.com/downloads/imia_papers/WGP60_2009.pdf, 29.07.2012
[39] See SPENCER, STOLFA, BENTZ: Tunnel Boring Machines, http://www.imia.com/downloads/imia_papers/WGP60_2009.pdf, 29.07.2012

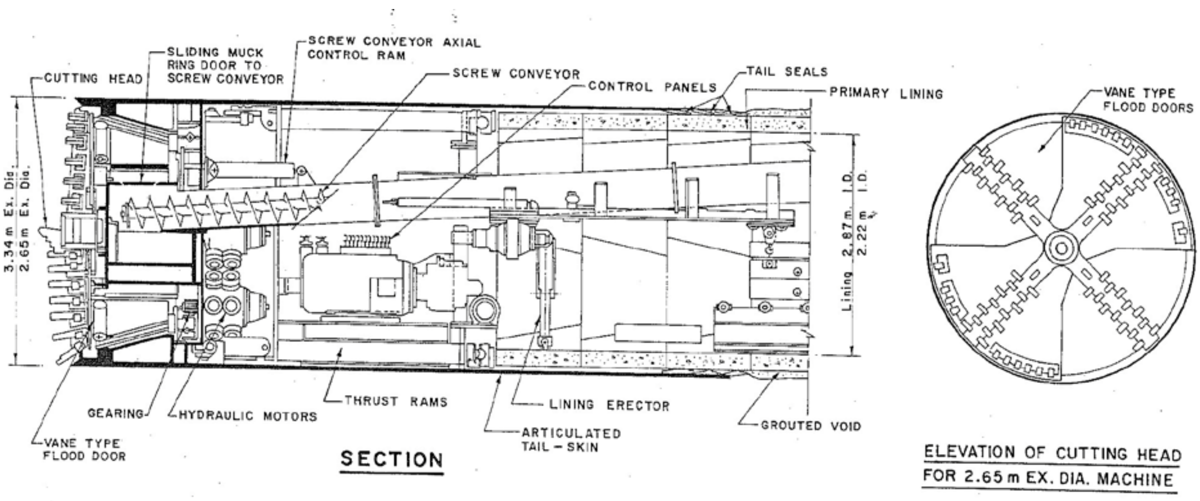


Figure 15 Earth pressure balance TBM cross-section[40]

### 5.2.1.3. Rock Machine

The rock TBM removes rock by first crushing it with the cutters mounted on the rotating head of the machine. The cutters usually consist of rotating discs manufactured to be very durable and resist the abrasiveness of hard rocks. The broken rocks are collected and transported on conveyors or trolleys outside of the tunnel.[41]

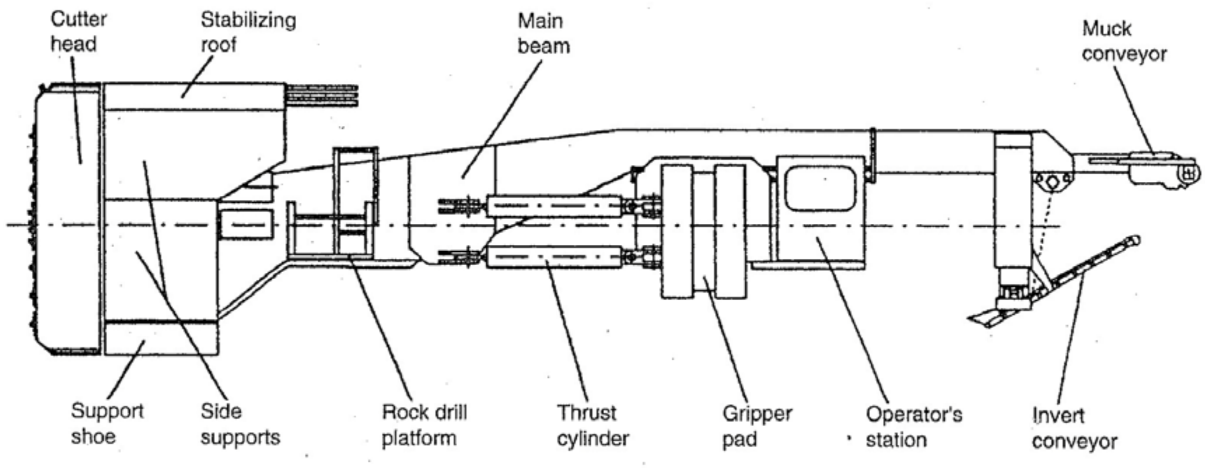


Figure 16 Rock TBM cross-section[42]

[40] SPENCER, STOLFA, BENTZ: Tunnel Boring Machines, http://www.imia.com/downloads/imia_papers/WGP60_2009.pdf, 29.07.2012
[41] See SPENCER, STOLFA, BENTZ: Tunnel Boring Machines, http://www.imia.com/downloads/imia_papers/WGP60_2009.pdf, 29.07.2012
[42] SPENCER, STOLFA, BENTZ: Tunnel Boring Machines, http://www.imia.com/downloads/imia_papers/WGP60_2009.pdf, 29.07.2012

### 5.2.2. General structure of a TBM

A typical TBM has several main parts and secondary mechanisms that vary according to the specific type. TBM's have one or two metal cylinders in the front part that are called "shields", their purpose is to protect machinery and workers before the exposed rock is secured. At the front of every TBM is the cutter head. It is a rotating wheel which has the cutting discs and/or teeth and has openings that let the broken material into a chamber that is located directly behind the cutter head. The "open" or "closed" type of TBM depends on the pressure inside the chamber. If the pressure is higher than the external it is considered a "closed" type and if it is equal to the external it is "open".

The movement of the machine is provided by hydraulic jacks. The jacks use the completed part of the tunnel behind the machine to push it forward. After the jacks have reached their maximum extension, the front part of the TBM is secured in place and the rear part is shifted forward using the same hydraulic jacks. When the jacks are retracted a new ring of segments are constructed before the next advance begins. Of course, there are variations of this technique in the different types of TBMs. The hydraulic jacks are also used to steer the machine in both horizontal and vertical planes.

Most of the support equipment of the TBM, such as the muck removal systems, operator room, rails used for the delivery of the concrete segments, is located in the completed part of the tunnel.

The cutter head is naturally the most important part of a tunnel boring machine. Its rotation speed usually varies between 1 and 10 rpm depending on the diameter of the head and the type of rock excavated. The composition of the muck consists of either soil or rocks and after it's collected and transported to the rear of the machine there are three main methods for disposal from the tunnel:

- conveyor belt system
- skips
- mixed with slurry and pumped through pipes

Securing of the tunnel depends on the geological conditions and the engineering design. Apart from concrete segment lining a tunnel can be secured only with shotcrete or even left unlined when the rock is strong enough. However, tunnels for transportation needs are almost exclusively lined with precast segments. They are mounted using a mechanic arm which is a part of the TBM and is guided by an operator.[43]

Modern TBMs require relatively small crews to operate, which usually work at three shifts and keep the machine constantly operational. When maintenance or repair works have to be

[43] See SPENCER, STOLFA, BENTZ: Tunnel Boring Machines, http://www.imia.com/downloads/imia_papers/WGP60_2009.pdf, 29.07.2012

done, additional workers are brought to the machine to execute the tasks faster and reduce the downtime.

### 5.2.3. Tunnel boring machine in practice today

Today TBM's are used worldwide and there are manufacturers in Europe, North America and Asia which not only produce but also constantly develop modifications of their models. The implementation of every new technology has to be thoroughly tested so there are few unknowns when they are put into practice.

The biggest TMBs today are all built by Herrenknecht AG, the largest one – 19.25 m in diameter was made for the Orlovski Tunnel in Russia. The company also holds the record for the biggest EPB machine with the "Herrenknecht S-574 Earth Pressure Balance Shield" for Italy's Sparvo highway tunnel which has a diameter of 15.62 m[44] (Figure 20).

Figure 17 The Herrenknecht S-574 Earth Pressure Balance Shield[45]

Different types of TBM's can achieve various speeds depending on factors like their type, dimensions, geological conditions etc. A "closed" type TBM usually operates at slower speed than an "open" one. Some of the main factors involving the machine are the thrust that is put out from the hydraulic jacks and the RPM of the cutter-head. The rock conditions present

[44] http://www.herrenknecht.com/, 27.06.2012

[45] http://www.tunneltalk.com/Discussion-Forum-Mega-TBMs.php, 27.06.2012

more variables and unknowns even when probes are taken in advance. The compressive strength and abrasiveness can greatly impact the performance and exploitation costs. The "closed" type TBM's speed varies between 0-1 cm/min with a maximum of 8 cm/min.[46]

The parameters that describe the behavior of the TBM are:

- speed of the shield
- torque of the cutter-head
- thrust of the hydraulic jacks
- pressure inside the cutting chamber
- quantity of the removed muck
- composition of the removed muck

The operator must be experienced and well-trained in order to understand what the changes in each of the parameters means to the geological conditions in front of the machine. That way he can make the appropriate adjustments for optimal performance. The variation of each parameter over time can help the engineers to make an accurate prediction of the conditions further from the cutter-head. Pressure within the chamber is controlled automatically but the analysis of the changes that the computer makes has to be taken into account from the operator. For slurry type TBMs the loss of bentonite during excavation is a sign that the soil has become more permeable and the bentonite input has to be increased or its rheology can be changed.[47]

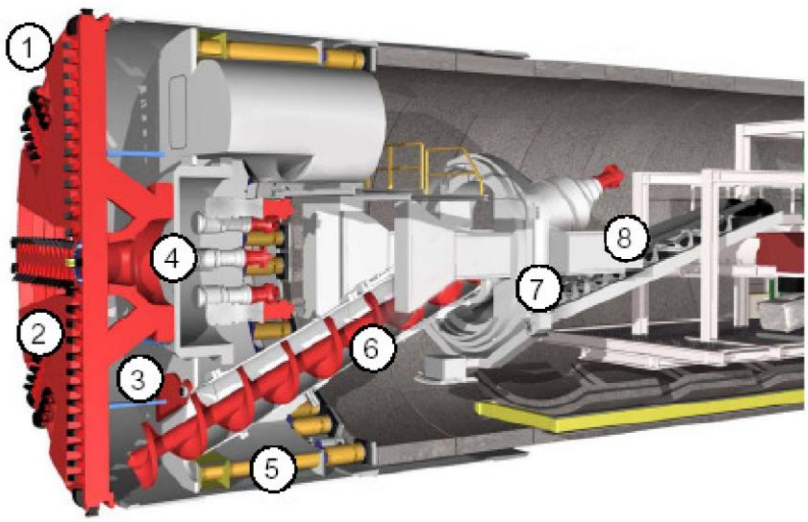


Figure 18 EPB TBM structure: 1. Face; 2. Cutter-head; 3. Working chamber; 4. Bulkhead; 5. Thrust cylinder; 6. Screw conveyor; 7. Erector; 8. Belt conveyor;[48]

[46] See SPENCER, STOLFA, BENTZ: Tunnel Boring Machines, http://www.imia.com/downloads/imia_papers/WGP60_2009.pdf, p. 9, 29.07.2012

[47] See SPENCER, STOLFA, BENTZ: Tunnel Boring Machines, http://www.imia.com/downloads/imia_papers/WGP60_2009.pdf, 29.07.2012

[48] http://www.tunnelseis.de/tunnelling.html, 30.07.2012

In EPB TBMs usually when the machine reaches a water-pressured sand lens the muck's viscosity changes and that lowers the pressure in the screw conveyor. There are critical low-pressure levels that can force the discontinuing of muck removal and sealing of the cutting chamber to avoid face loss. The danger of too much muck removal is that it can cause a sinkhole which can stop the advance of the machine. Muck must be extracted proportionally to the TMB's advance to avoid loss of face. The quantity of the muck is easily controlled either by visually observing the screw conveyor or belt conveyor or by the number of skips used per meter advance. Changes in the color or water content can be easily recognized by the operator as well as size and color of the rock pieces. Operators are the first to encounter the changes in the muck and they have to be able to respond adequately if there are any abnormalities. They go through extensive trainings and must be very familiar with the construction, operating systems and procedures of the particular machine. The operating staff must be knowledgeable in geology and rock mechanics in addition to the standard engineering education. The performance of every TBM depends highly not just from the mechanical capabilities of the machine but also from the crew that operates and maintains it.[49]

Though the construction process is highly automated, the human factor must not be underestimated and contractors must invest in personnel as much as they do in equipment.

### 5.2.4. Evaluation

At the moment TBMs are the state-of-the-art solution for long tunnels and urban areas. They provide great results for the most important requirements: safety, performance, cost per meter and environmental friendliness. Their versatility makes them usable in almost any geological conditions with excellent results. They have great potential for improvements, and the expanding tunneling industry can make them the dominant rock removal method in the future.

[49] SPENCER, STOLFA, BENTZ: Tunnel Boring Machines, http://www.imia.com/downloads/imia_papers/WGP60_2009.pdf, 29.07.2012

## 6. Alternative rock removal methods

For Alternative rock removal methods we can consider all methods except the ones mentioned in the previous part of this paper. The term “alternative” is used because these methods are rarely used and most of the time it is due to some specific circumstances that make the use of the common methods inefficient, uneconomical or just plain unpractical. Some of the methods examined below are not used at all in practice today due to various reasons, some administrative, other technological. Today’s competitive economic climate both pushes and holds back technological advancements in almost every sector, including underground construction. Large corporations, involved in the development and manufacturing of tunneling and mining equipment, spend vast resources for research in order to stay ahead of their competitors.[50] This leads to higher efficiency of the machines, lower production costs, improved safety etc.

Other methods include technologies that are mainly used in other sectors of the industry, but have the potential to be incorporated in rock removal. Before this can be done a large number of tests and experiments must be made so enough data could be collected and studied. Once the data is examined a solid conclusion can be made, if the principles that the method relies on can be used on different types of rock. It is not uncommon for a technology from one field to be transferred into another with some adjustments.

[50] http://www.diavik.ca/documents/dialogue_Volume_10_Q3_2007.pdf, 27.11.2012

### 6.1. Water jet cutting

Water jet cutting is a technology widely used today for precise cutting of many different materials. The method uses a jet of water at high velocity and pressure. In some cases water is mixed with an abrasive substance to enhance the penetration power of the water jet. The method is very versatile, because the water jet can be easily modified which is essential for cutting different types of materials. Today modern jet cutters work with all sorts of materials, including rubber, foam, plastics, leather, composites, stone, tile, metals and much more (Figure 22).

Figure 19 Modern abrasive CNC waterjet[51]

Another advantage is that the water used during the cutting process can be collected, recycled and used repeatedly in a closed-loop system. Water jets also eliminate airborne dust particles, smoke, fumes, and contaminants from cutting materials such as asbestos and fiberglass. In case of cutting rock underground, however, the water loses would probably be larger since the construction site cannot be sealed as well as an indoor machine. This can prove to be a problem since water removal during tunnel construction is a problem with every method used today.

This technique, however, has its disadvantages. Probably the biggest one is its speed. Because one machine can work on only one element at a time the production speed is too slow for mass production. Therefore most water jet cutters are used for production of parts for other machines or elements of prototypes. They are also very popular for the manufacturing of custom design peaces for a large variety of businesses. The other main

[51] http://totesystems.com/waterjet.htm, 23.11.2011

reason this technology is not further spread is the cost. Because the machine needs very high accuracy, it also has to be made from very precise parts and needs a highly complicated guidance software for the nozzle. Manufacturing such a machine is a slow and expensive process which leads to even higher selling prices.

In the field of underground construction, water jet cutters have much more development to be done before being incorporated in this field, and used as equally as other current techniques. Tests and experiments on the matter give promising results, some of which will be examined later in this paper. This technique has a great potential and has the characteristics every modern system needs – efficiency, effectiveness and low exploitation costs.[52]

### 6.1.1. Structure and necessary water pressure of the water jet cutters

In this part of the paper the structure of the two most common water jet cutters will be examined. There are two main non-traditional machining processes – Water Jet Machining (WJM) and Abrasive Water Jet Machining (AWJM). These processes can remove material or machine elements using a combination of water and abrasive phases under very high speeds. These processes are categorized depending on the type of water jet or propulsion method.

Depending on the contents of the water jet:

- WJM – Pure
- WJM - with stabilizer
- AWJM – entrained – three phase – abrasive, water and air
- AWJM – suspended – two phase – abrasive and water

Depending on the type of pumping:

- Direct pumping
- Indirect pumping
- Bypass pumping

Although there are variations depending on the category, the overall principle of the process is the same. Water is pumped through a small nozzle under very high pressures – between 200 and 400 MPa. The machine amplifies the pressure using hydraulic cylinders that have different diameters. The speed further increases when the water reaches the small opening of the nozzle, which is usually around 0.2 – 0.4 mm in diameter. The end result is a water jet

[52] See KHARAGPUR, Ilt: Water Jet and Abrasive Water Jet Machining, http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, 23.11.2011

that has a speed of around 1000m/s. A stream of water with such speeds can cut through a wide range of materials, even hard metals and minerals.[53]

The pure WJM is the simplest type of these machines, but it also has the lowest performance. Because it uses plain tap water, a lot of the energy of the stream is lost before the jet reaches the material being cut. This is why most of the commercially used machines are AWJM. As their name states, abrasives are added to the water to increase performance. Such abrasives can be sand or glass beads. Abrasives improve the performance of WJM drastically, more than 5 times. The AWJM are so much more effective, that they can cut almost any material even at speeds 20% slower than the WJM, about 800 m/s.

Figure 23 shows a commercial CNC water jet machining system and a close-up view of the cutting head.


Figure 20 Commercial CNC water jet machining system and cutting heads[54]

An entrained AWJM is composed of a number of different modules listed below:

• LP booster pump
• Orifice
• Hydraulic unit
• Mixing Chamber
• Additive Mixer
• Focusing tube or inserts
• Catcher
• CNC table
• Abrasive metering device
•Catcher
• Intensifier
• Accumulator
• Flexible high pressure transmission line
• On-off valve

[53] See KHARAGPUR, Ilt: Water Jet and Abrasive Water Jet Machining, http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, 23.11.2011

[54] http://www.oceanmachinery.com/omax-waterjet-cutting-table-omax-waterjet.htm, 25.11.2011

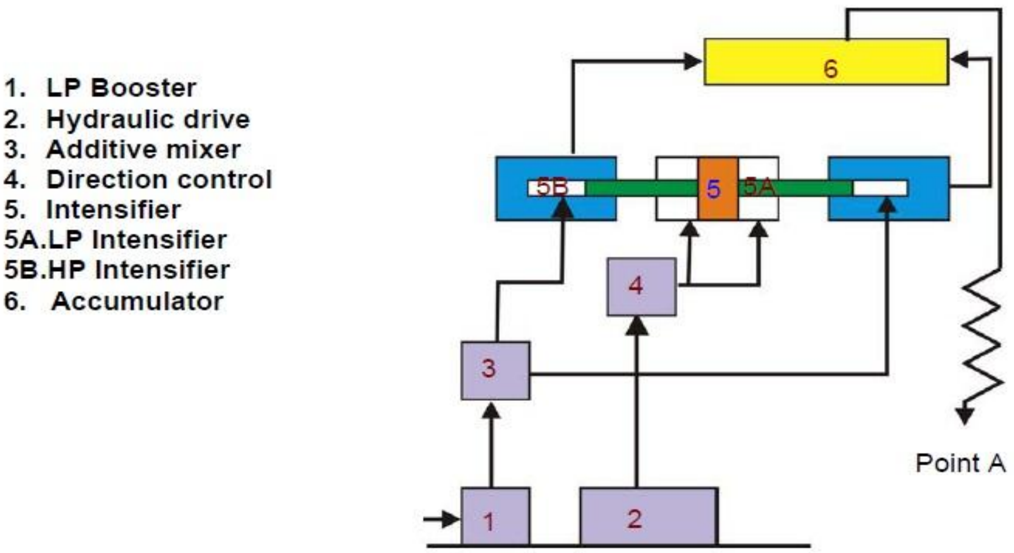


Figure 21 Schematic set-up of AWJM[55]

A hydraulic power pack drives the machine's intensifier (Figure 25). In the middle there is a positive displacement hydraulic pump that is controlled by a computer to ensure the best possible performance and the exact pressure output needed.[56]

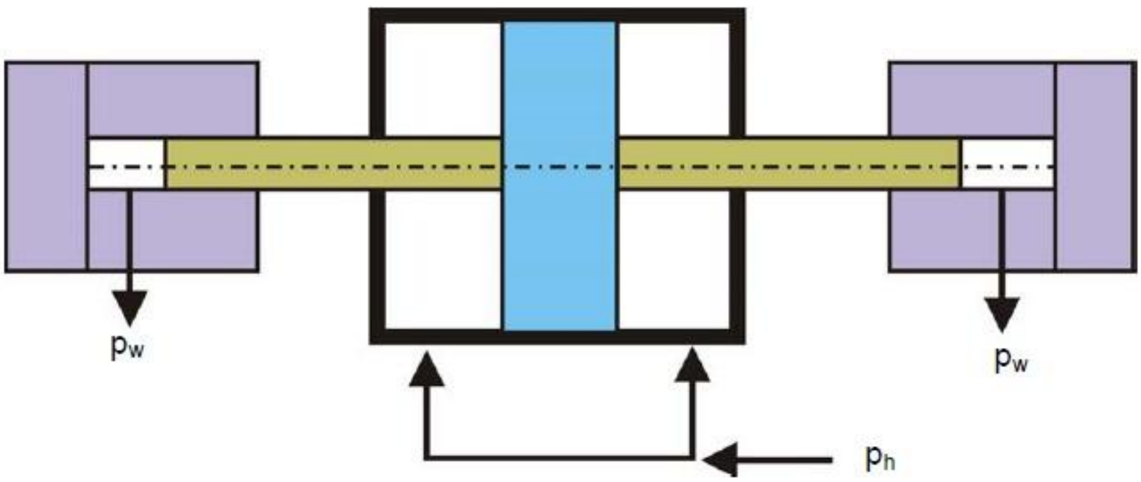


Figure 22 Intensifier – Schematic[57]

The hydraulic unit of the AWJM controls a valve that directs the water flow either straight to the small cylinder of the intensifier or it can be redirected to another device – the booster pump. The booster pump pressurizes the water to 11 bar and then feeds it to the intensifier.

[55] KHARAGPUR, Ilt: Water Jet and Abrasive Water Jet Machining, http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, 23.11.2011
[56] See KHARAGPUR, Ilt: Water Jet and Abrasive Water Jet Machining, http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, 23.11.2011
[57] KHARAGPUR, Ilt: Water Jet and Abrasive Water Jet Machining, http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, 23.11.2011

If the qualities of the water aren’t satisfactory it can be treated with softener or long chain polymers, for this purpose is the so called “additive unit”. The intensifier is connected to the cutting head using flexible stainless steel pipes. They must be strong enough to resist the water pressure which is about 4000 bar (400 MPa) and at the same time allow the cutting head to move easily across the working surface. The structure of the cutting head is explained in Figure 26.

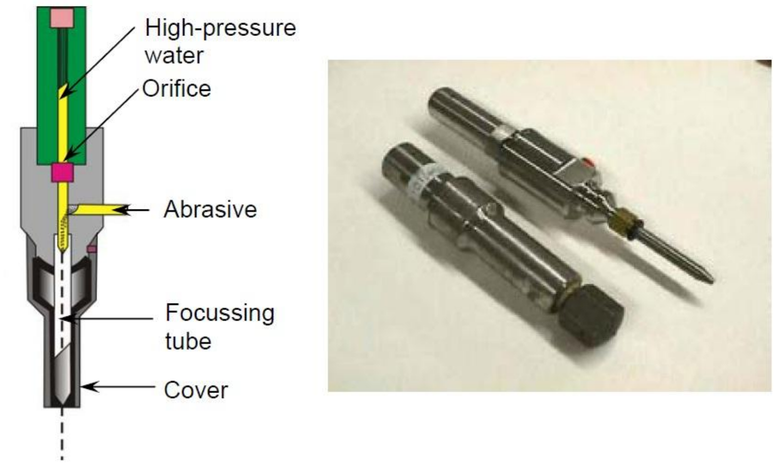


Figure 23 Schematic and photographic view of the cutting head[58]

The small nozzle diameter converts the water’s pressure head into velocity head. In order to withstand the enormous pressures the nozzle is usually made of sapphire and even then its exploitation period is 150 hours at best. The difference between WJM and AWJM is that the AWJM has a mixing chamber where the abrasive particles are added right before the stream exits the cutting head.[59]

### 6.1.2. Experimental data

People have used water to cut rock since Roman times, and from 1962 laboratory research has been carried out at jet pressures above 10,000 psi. Rocks with a wide range of strength, from shale to quartzite have been cut at pressures of less than 30,000 psi. Very high cutting speeds have been achieved some of them of up to 1,000 ft/min (5.08m/s).
Despite good testing results, there is still no widespread acceptance of the method.
It is a common misconception that water jet rock cutting requires very high pressures, but the experiments made by David A. Simmers and his team from the “Rock Mechanics &

[58] KHARAGPUR, Ilt: Water Jet and Abrasive Water Jet Machining, http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, 23.11.2011
[59] See KHARAGPUR, Ilt: Water Jet and Abrasive Water Jet Machining, http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, 23.11.2011

Explosives Research Center" of the University of Missouri at Rolla were made using standard commercially available water pump show that it is possible to cut rocks effectively without ultra-high water pressures. Their results were published in the paper "Water Jet Cutting Related to Jet & Rock Properties" and some of them will be examined in this part of the paper.

When rock breaking is concerned, scientists focus mainly on two different ways water jets can be used. One of them is to use the AWJM to create cuts close enough to each other that the remaining rock can be broken mechanically. The other uses strong water pulses to break the rock in a wider diameter. Both methods have their advantages and disadvantages but recent researches are more focused on the second method because there is less information about it.

The tests made provide data about the connection between the properties of the water jet and the rock and their influence on the performance of the method.

The tests were conducted using 6 different rock types and for each one 9 properties were measured.

The general conclusion from the research was that the cutting effectiveness is directly proportional to the nozzle diameter and the jet pressure. This is until the water jet pressure reaches a magnitude of 35 times the compressive strength of the rock.[60]

### 6.1.2.1. Experimental design

Due to the diverse structures of rock, every experiment has been performed multiple times to reduce fluctuations in the results due to differences in the material.

The results from older experiments are definitive, in that cutting slots and breaking the material in between is more effective than breaking using jet pulses when using equal pressure. Although Figure 27 shows that the penetration with pulsation is deeper than that of a continuous jet, the mechanical braking of the slots made from the continuous jet makes this technique preferable.

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[60] See SUMMERS, David: Water Jet Cutting Related to Jet & Rock Properties, http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, 10.11.2011

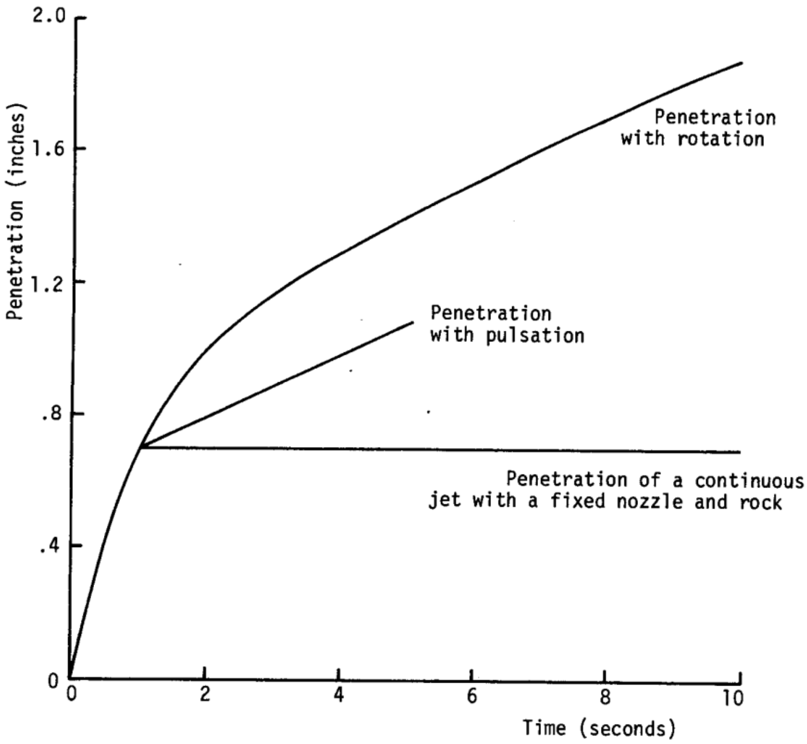



Figure 24 Penetration of a jet into red Woolton sandstone at a pressure of 8,000 psi. and a standoff distance of 2 inches[61]

The goal of the experiment is to separate the parameters that influence the performance of the water jet and the depth of the cut. Older tests executed at the University of Missouri at Rolla showed that the most accurate results are obtained when the jet passes only once over the rock sample.[62]

### 6.1.2.2. Experimental Procedure

The experiments were performed on seven different rocks, four sandstones and one from each of the following: limestone; marble; granite. The samples were cubes with a 6 inch (15.24 cm) side. Each sample was placed in the machine and five circular cuts were made separated by half an inch (1.27 cm). This separation was determined sufficient to avoid interference in the performance of the jet. The nozzle of the machine was placed at a distance of 2 inches (5.08 cm) from the sample for all tests.

[61] SUMMERS, David: Water Jet Cutting Related to Jet & Rock Properties, http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, 10.11.2011
[62] See SUMMERS, David: Water Jet Cutting Related to Jet & Rock Properties, http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, 10.11.2011

| Properties | CS* (psi) | YM ($10^6$ psi) | SHOR | SCHH | RIHN | FT |
|---|---|---|---|---|---|---|
| Berea Sandstone(l) | 5,480 | 3.37 | 26.8 | 35.1 | 3.85 | 147 |
| Indiana Limestone(2) | 7,990 | 4.15 | 20.8 | 37.5 | 14.3 | 428 |
| Barre Granite(3) | 24,550 | 4.76 | 47.5 | 77.6 | 32.6 | 672 |
| Georgia Marble(4) | 23,100 | 8.30 | 32.9 | 38.6 | 12.9 | 327 |
| Buff Sandstone(5) | 5,220 | 2.26 | 20.5 | 30.0 | 1.87 | 101 |
| Pink Sandstone(6) | 6,750 | 2.55 | 22.6 | 29.5 | 1.40 | 131 |
| Red Sandstone(7) | 8,640 | 2.79 | 25.9 | 25.2 | 16.75 | 828 |

Table 4 Properties of Rocks Tested in the Experiment[63]

*Abbreviations:

CS - Compressive Strength

YM - Young's Modulus

SHOR - Shore Hardness

SCHH - Schmidt Hardness

RIHN - Rock Impact Hardness Number

FT - Facture Toughness

The end results of each test were 5 concentric cuts around the center of the sample (Figure 28). Several depth measurements were made within the slots and the average depth of the cuts was calculated. The data from each experiment was evaluated using specialized software: the SPSS computer program. It was used to calculate statistical coefficients between the two types of variables: dependent and independent.

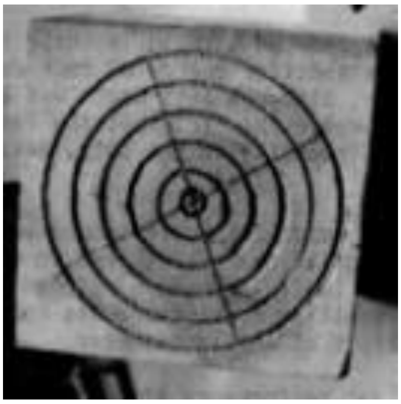


Figure 25 Specimen of Buff Sandstone after cutting[64]

[63] SUMMERS, David: Water Jet Cutting Related to Jet & Rock Properties, http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, 10.11.2011

[64] SUMMERS, David: Water Jet Cutting Related to Jet & Rock Properties, http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, 10.11.2011

The dependent variables included in the calculations of the coefficients were:

- depth of the slot cut;
- specific energy of rock breakage;
- specific energy ratio.

The second one describes the energy required to remove one volume unit of rock, and the third one describes the ratio between the specific energy of breakage and the specific fracture energy of the rock.

The energy used in the calculations is the kinetic energy of the water jet.

The conclusion of the results was that the water jet cuts were actually 3.5 times wider than the diameter of the nozzle. The difference in the width is a result from the lateral velocity of the jet which is high enough to cause additional rock breakage[65].

### 6.1.2.3. Water Jet Properties

Four water jet properties were taken into account when analyzing the test results:

- jet pressure
- jet velocity
- nozzle traverse sped
- nozzle diameter

The water pump used in the tests had to be used at its maximum output which meant that the change of the nozzle diameter meant that the water pressure will change as well. The tests were conducted using three different diameters with the pressure increasing with the decrease of the diameter.

For every test result with a specific jet characteristics the Pearson product-moment correlation coefficients were calculated (Table 5).[66]

In order to retrieve the coefficients between jet performance and jet properties a set of correlations were calculated as shown in Table 6.

The method used in the calculations is as follows:

"*A step-wise regression was performed and only properties which increased the square of the multiple regression coefficient by more than 0.1 were considered in the regression. By this means multiple regression coefficients of greater than 0.9 could be realized*."[67]

[65] See SUMMERS, David: Water Jet Cutting Related to Jet & Rock Properties, http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, 10.11.2011

[66] See SUMMERS, David: Water Jet Cutting Related to Jet & Rock Properties, http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, 10.11.2011

[67] SUMMERS, David: Water Jet Cutting Related to Jet & Rock Properties, http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, 10.11.2011

| Rock* | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
|---|---|---|---|---|---|---|---|
| Jet Pressure | .557 | .574 | .273 | .403 | .483 | .537 | .601 |
| Nozzle Diameter | .027 | -.251 | -0.005 | -0.066 | 0.030 | .095 | - |
| No. of Passes | .258 | .591 | - | - | - | - | - |
| Traverse Speed | -.465 | -.423 | .583 | -.464 | .432 | -.467 | -.394 |
| Velocity Ratio | .686 | .673 | .719 | .757 | .528 | .670 | .694 |
| Jet Energy | .598 | .499 | .281 | .523 | .66 | .692 | .607 |

a) Correlation with Slot Depth

| Rock* | (1) | (2) | (3) | (4) | (5) | (6) | (7) |
|---|---|---|---|---|---|---|---|
| Jet Pressure | .139 | .160 | -.504 | .368 | .240 | .232 | .268 |
| Nozzle Diameter | -.354 | -.246 | .216 | 0.123 | -.123 | -.287 | - |
| No. of Passes | .653 | .618 | - | - | - | - | - |
| Traverse Speed | -.398 | -.474 | .172 | -.130 | -.382 | .592 | .469 |
| Velocity Ratio | .572 | .654 | .063 | .021 | .605 | .835 | .518 |
| Jet Energy | -.036 | .040 | -.428 | -.346 | .096 | .093 | -.259 |

b) Correlation with Specific Energy

Table 5 Pearson Cross-Moment Correlations Between Jet Performance & Properties[68]

*The numbers correspond to the rock types given in Table 4.

| Rock | Depth | Correl. Coef. | Specific Energy | Correl. Coef . |
|---|---|---|---|---|
| Berea Sst. | Velrto*, Press, Pasno | 0.85 | Vertlo, Diam, Pasno | 0.84 |
| Indiana Llst. | Velrto, Press, Pasno | 0.90 | Vertlo, Diam, Pasno | 0.84 |
| Red Sst. | Velrto, Press, Tips | 0.91 | Velrto, Depth, Tips | 0.82 |
| Pink Sst. | Velrto, Press, Diam | 0.86 | Velrto, Depth, Diam | 0.92 |
| Buff Sst. | Velrto, Press, Diam | 0.85 | Ins, Tips, Depth | 0.78 |
| Georgia Mbl. | Velrto, Diam | 0.91 | Press, Depth | 0.40 |
| Barre Gnt. | Velrto | 0.71 | Press, Depth | 0.61 |

Table 6 Multiple Regression Correlation Coefficcients for the Most Influential Independent Variables[69]

Velrto = Jet velocity/nozzle traverse speed Diam = Nozzle diameter (ins)
Press = Jet pressure (psi) Tips = $(1/\text{traverse speed})^2$ $(\text{min/ft})^2$

[68] SUMMERS, David: Water Jet Cutting Related to Jet & Rock Properties, http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, 10.11.2011
[69] SUMMERS, David: Water Jet Cutting Related to Jet & Rock Properties, http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, 10.11.2011

Pasno = Number of passes made Ins = 1/traverse speed (min/ft)
Depth = depth of hole (ins)

After analyzing the data it became clear that the highest correlation is achieved between the jet velocity ratio and the depth of the slot for all rock specimens (Table 5 a)).
When the results from the correlation with the specific energy were evaluated, they showed that the jet velocity ratio has the highest coefficient for the Pink Sandstone (a sedimentary rock) marked with blue in Table 5 b). The highest coefficient between the specific energy and the jet pressure was for the Barre Granite (marked with red in Table 5 b), which has a crystalline structure.
This lead to the conclusion, that the rock structure has an impact on the cutting mechanism of the jet. Rocks with granular structure were eroded by the water without breaking the individual particles while the crystalline structure was destroyed from the jet.
These results were verified with more specific tests using Missouri Granite and Georgia Granite. Some adjustments were made to improve the test, nozzle speed was increased (Figure 29) but sloth depth as well as the specific energy of rock removal were decreased (Figure 30). These changes gave some unusual results. Despite the reduction of the depth the increase of the nozzle speed compensated that loss and even showed improvement in the volume of removed rock. This was due to increased fracturing at the base of the slot. [70]

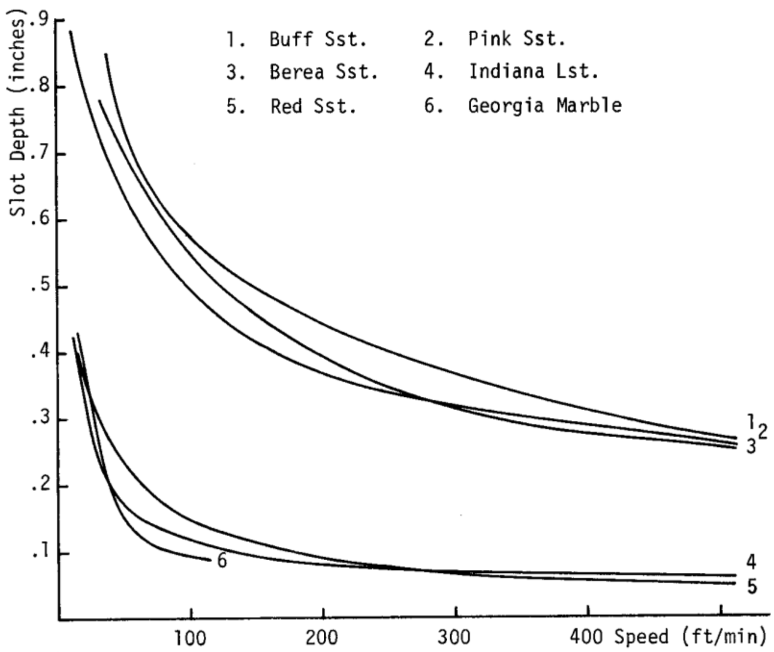



Figure 26 Depth of slot cut versus nozzle speed[71]

[70] See SUMMERS, David: Water Jet Cutting Related to Jet & Rock Properties, http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, 10.11.2011
[71] SUMMERS, David: Water Jet Cutting Related to Jet & Rock Properties,

After the three diameters were compared using the maximum pump output (Figures 31 and 32) it was concluded that a larger nozzle is more beneficial when cutting sedimentary rock regarding the volume of rock removed. Despite the reduced pressure output when using the 0.03 inch (0.076 cm) diameter nozzle – 18 000 psi, compared to the 0.023 inch (0.058 cm) one, when 25 000 psi was reached, the tests showed that it provided the best overall results.[72]

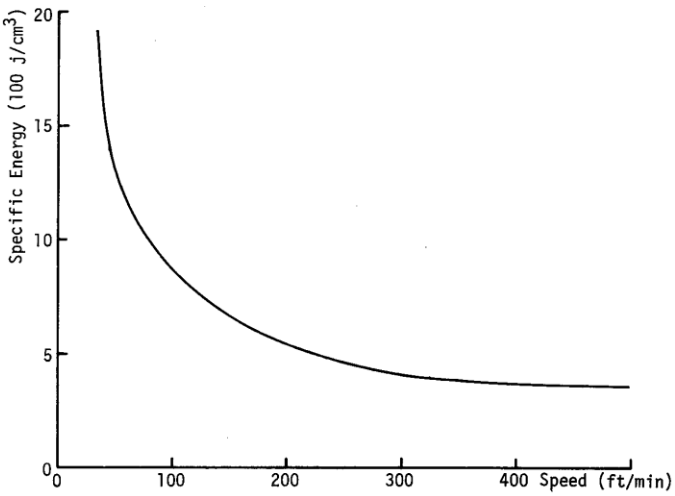



Figure 27 Specific Energy of breakage versus nozzle traverse speed. (Buff sandstone)[73]

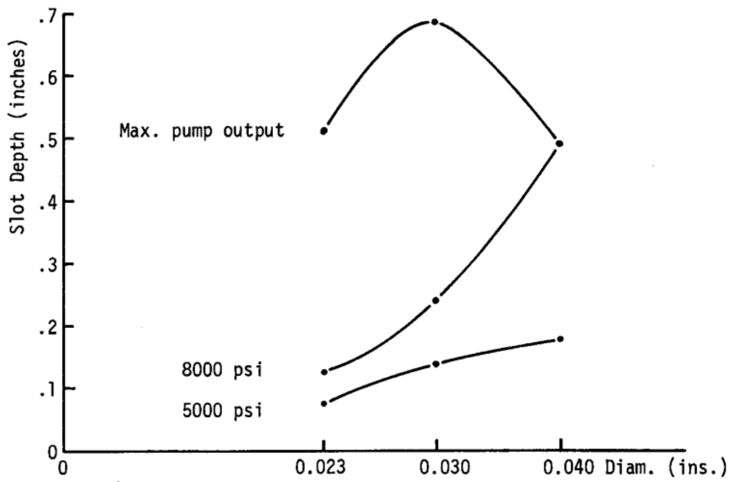



Figure 28 Depth of slot cut versus nozzle diameter (Pink sandstone)[74]

http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, 10.11.2011

[72] See SUMMERS, David: Water Jet Cutting Related to Jet & Rock Properties, http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, 10.11.2011

[73] SUMMERS, David: Water Jet Cutting Related to Jet & Rock Properties, http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, 10.11.2011

[74] SUMMERS, David: Water Jet Cutting Related to Jet & Rock Properties, http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, 10.11.2011

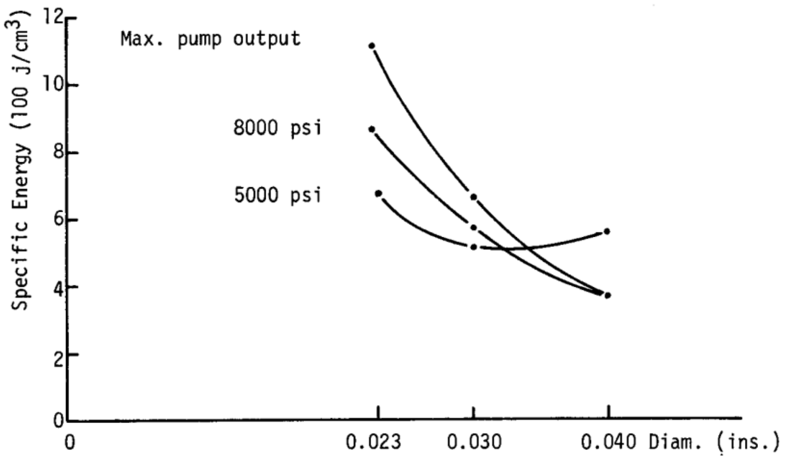



Figure 29 Specific energy of breakage versus nozzle diameter (Pink sandstone)[75]

### 6.1.2.4. Rock Properties

Measurements were taken for six different rock properties of the tested rocks (Table 4):

- Compressive Strength
- Young's Modulus
- Shore Hardness
- Schmidt Hardness
- Rock Impact Hardness Number
- Facture Toughness

During some of the tests on the granite samples there were a few cases in which the rib between two cuts were removed by the water jet and in others there was spallation. This was observed in the Missouri granite when the depth of the cut was more than 1/3 of an inch (0.85 cm). However, spallation was not taken into account when the results of the tests were analyzed because the exact causes for this phenomenon couldn't have been determined with enough precision to be added into the calculations.
The correlation between the rock properties and the properties of the water jet is showed in Table 7. Table 8 shows the different rock properties and how they correlate with each other.
Highest correlation coefficient was observed between the depth of the slot and the inverse of the rock compressive strength.
Other properties that showed a strong connection were the Specific Energy and Rock Impact Hardness Number and the Specific Energy Ratio and Young's modulus[76].

[75] SUMMERS, David: Water Jet Cutting Related to Jet & Rock Properties, http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, 10.11.2011
[76] See SUMMERS, David: Water Jet Cutting Related to Jet & Rock Properties, http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, 10.11.2011

| Rock Property Correlation Coefficient with | Depth | Specific Energy | Specific Energy Ratio |
|---|---|---|---|
| Compressive Strength (CS) | -.249 | .470 | .030 |
| Young's Modulus (YM) | -.066 | .479 | .519 |
| Shore Hardness (SHOR) | -.013 | .286 | -.060 |
| Schmidt Hardness (SCHH) | -.079 | .434 | .081 |
| Rock Impact Hardness Number (RIHN) | -.279 | .597 | .278 |
| Fracture Toughness (FT) | -.312 | .494 | .242 |
| Specific Fracture Energy (SFE) | -.223 | .379 | -.099 |
| Inverse Compressive Strength | .352 | -.547 | -.223 |
| Inverse Young's Modulus | -.004 | -.496 | -.495 |
| Inverse Shore Hardness | -.078 | -.193 | .063 |
| Inverse Schmidt Hardness | -.028 | -.412 | -.221 |
| Inverse RIHN | .052 | -.505 | -.446 |

Table 7 Pearson Correlation Coefficients between Water Jet Cutting Parameters and Rock Properties[77]

| Properties* | CS | YM | SHOR | SCHH | RIHN | FT | SFE |
|---|---|---|---|---|---|---|---|
| CS | 1 | .45 | .82 | .90 | .85 | .61 | .98 |
| YM | .45 | 1 | .43 | .55 | .62 | .39 | .28 |
| SHOR | .82 | .43 | 1 | .82 | .59 | .36 | .84 |
| SCHH | .90 | .55 | .82 | 1 | .73 | .34 | .87 |
| RIHN | .85 | .62 | .59 | .73 | 1 | .88 | .75 |
| FT | .61 | .39 | .36 | .34 | .88 | 1 | .51 |
| SFE | .98 | .28 | .84 | .87 | .75 | .51 | 1 |

Table 8 Correlation Matrix between Rock Properties[78]

*Properties are symbolized by the abbreviations given in Table 7

### 6.1.3. Regression Analysis

***"**The calculation of the Pearson product-moment correlation coefficients provided a measure of the accuracy of prediction of the penetration parameters based on individual independent variables. However, although the properties for the various rocks were initially considered as independent of each other, this is not necessarily the case (Table 8).**"**[79]*

[77] SUMMERS, David: Water Jet Cutting Related to Jet & Rock Properties, http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, 10.11.2011
[78] SUMMERS, David: Water Jet Cutting Related to Jet & Rock Properties, http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, 10.11.2011
[79] SUMMERS, David: Water Jet Cutting Related to Jet & Rock Properties, http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, p. 10, 10.11.2011

The high correlations in some cases required the use of a step-wise regression. It was used for the three dependent variables in order to find which of the jet and rock property combinations results in the highest correlation with the chosen dependent variable.

*"In a step-wise regression, a linear regression equation is calculated between the dependent variable and the independent variable which is found to be the best predictor. The correlation coefficients are then recalculated to determine which independent variable gives the best prediction when combined in the equation with the first variable. This variable is added to the regression equation and the procedure is repeated, adding a single independent variable in each step of the regression. The program used also gives a value of the tolerance. A low value for tolerance indicates that the variable considered is a linear combination of variables already present in the regression, and should therefore be disregarded."*[80]

The progression was executed until no improvement was present. This is why only four of the independent variables are used for i) and ii). Adding more terms to the regression gave insignificant results and therefore only six variables are combined in iii).

"*The equations obtained were:*
i) DEPTH = $5.72 + 24.8 \times 10^{-4} (VR)^2 + 16 \times 10^3 (CS)^{-1} + 3 \times 10^{-5} (P) - 7.4 \times 10^{-2} (SHOR)$
*The regression coefficient units should be chosen to give depth values in inches.*
ii) SPECIFIC ENERGY = $-99.4 \times 10^3 + 8.19 \times 10^3 (RIHN) + 84.3 \times 10^7 (CS)^{-1} + 1.97P - 38.2 (SFE)^{-1}$
*The regression coefficient units should be chosen to give specific energy values in joules/cm*$^3$
iii) SPECIFIC ENERGY RATIO = $-1228 - 1.56(VR) + 7.4 \times 10^6 (YM)^{-1} - 0.248(CS) + 177(RIHN) + 6.1 \times 10^{-4} (YM) - 2.0(FT) - 42.4 \times 10^3 (SHOR)^{-1}$

*The regression coefficient units should be chosen to give dimensionless units. (…)*
*The equations are empirical descriptions based on the test results obtained and should not be considered as absolute equations, but rather as a guide. The statistical data for the equations are:"*[81]

| | Multiple Regression Coefficient | Standard Error of Estimate | F Value |
|---|---|---|---|
| Depth | .72 | .35 ins. | 413 |
| Specific Energy | .89 | 4978 joules/cm$^3$ | 1531 |
| Specific Energy Ratio | .91 | 122 | 1133 |

[80] SUMMERS, David: Water Jet Cutting Related to Jet & Rock Properties, http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, p. 11, 10.11.2011
[81] SUMMERS, David: Water Jet Cutting Related to Jet & Rock Properties, http://www.onepetro.org/mslib/servlet/onepetropreview?id=ARMA-72-0569, p. 11, 10.11.2011

### 6.1.4. Evaluation

As mentioned above the best use for water jet cutting is to cut slots in the rock. Removing the whole face of the tunnel by water jet would be slow and inefficient, due to the small radius of the nozzle. However, using the jet, rock removal can be greatly enhanced. Without its natural structural integrity and support, the rock between the slots will be weakened and easy to break mechanically.

This could reduce the wear and tear of the machine elements. The water jet head could be mounted on a specially designed TBM shield. After the slots are made, the shield will mechanically break the rock in between and remove the debris.

This process can be executed either in two steps or in a continuous excavation in which the shield is rotating and the rock is removed directly after the water jets make the slots. The results from the examined tests are promising and this technique may find its place in tunnel construction in the future.

# Fact sheet 6.1.

| **Name of the method** | Water jet cutting |
|---|---|
| **Year of origin** | 1950 – cutting wood<br>1970-80 – addition of abrasives to the water; cutting metal, plastic, foam, rubber, stone etc. |
| **Tests conducted** | Laboratory experiments on a wide range of cubic rock samples; different water pressures; nozzle sizes; |
| **Area of application (types of rock)** | limestone; sandstone; granite; marble |
| **Performance (m²/h)** | ≈ 30 m²/h [1]; |
| **Costs (€/m²)** | ≈ 12 €/h => 0.40 €/m² [1] |
| **Energy consumption** | For a 20 kW pump:<br>Electrical power use: 22-35 kW [2]<br>Water: 10 l/h [2]<br>Abrasive: 36 kg/h [2] |
| **Necessary Equipment** | High pressure pump;<br>Cutting head;<br>Mechanical guidance system; |

[1] http://www.waterjetcorp.com/resources.php#, under FAQs, 12.11.2011

[2] http://www.teskolaser.com/waterjet_cutting.html, 12.11.2011

## 6.2. Disc cutting

Discs are widely used today in tunneling equipment and have proven to be very effective for rock breaking. They are usually mounted on a TBM shield and are moving perpendicular to the rock face. The force originating from the TBM and transferred to the rock via the discs breaks the rock surface in a circular pattern. In this part of the paper, different uses of the discs will be examined. These other types of disc cutting are used today in the tunneling and mining industry with different success, but they are proven to be an advancement from the standard use in terms of productivity, efficiency and costs. As with every other method, disc cutting has its flaws. Because it's a relatively new approach, there are research and tests being conducted every year, and some of those flaws have already been removed. And as the performance increases the wider use of this technique is imminent.
In 2010 the "International Journal of Mining & Environmental Issues" published "A state-of-the-art review of mechanical rock excavation technologies" by A. Ramezanzadeh and M. Hood, focuses on the newer and more practical uses of discs in rock excavation. Parts of the paper are examined and discussed below.

### 6.2.1. Undercutting disc

Disc cutting is usually a straightforward process but in recent years there have been some new developments in the field. For instance, the disc cutters used on tunnel boring machines have been slightly modified and are used to break rocks via undercutting (Figure 33). Using this principle the discs require less force because it causes tensile stresses more directly. This means that the overall process is much more efficient and cost-effective.[82]
The undercutting technology has been just recently implemented successfully as a part of a TBM. This was done for the construction of the Uetliberg Tunnel in Switzerland. This tunnel is part of Zurich's new Western Bypass Expressway. The bypass consists of two 4.4 km-long tunnels. The undercutting technique was chosen because of the wide diameter needed to accommodate the motorway's three lanes in each tunnel. The method has been utilized before in other industries.

[82] See RAMEZANZADEH; HOOD: A state-of-the-art review of mechanical rock excavation technologies, http://tinyurl.com/9xpg5lt , 23.02.10

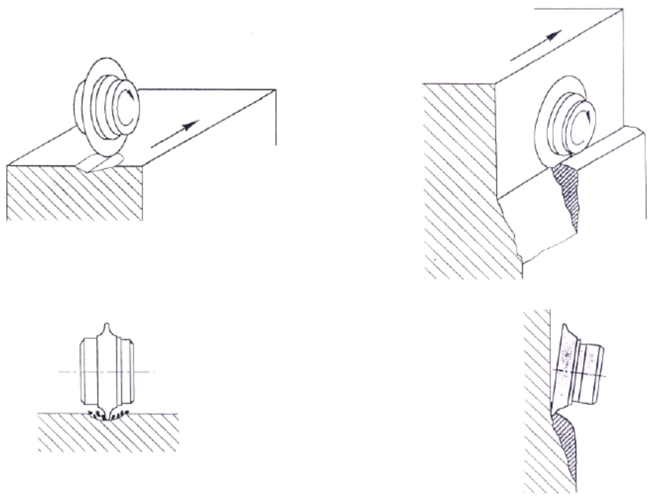


Figure 30 Conventional disc cutter (left) versus undercutting disc (right)[83]

The advantages of this method have been proven in the CRC Mining's research laboratories in Brisbane, Australia, where numerous tests were performed on a large number of rocks. One type of rocks tested was sandstone. In Table 5 are shown the results of a test performed on a sandstone sample with compression resistance of 36 MPa. The tests were conducted using a 50 mm diameter disc cutter and their goal was to make several grooves that had a depth of 10 mm and were separated 30 mm from one another. The results show that the reduction of the force is significant when using undercutting. Compared to the conventional method undercutting required about 2.5 times lower forces.[84]

| | Conventional Disc | Undercutting Disc |
|---|---|---|
| Normal (thrust) force (kN) | 18 | 6.8 |
| Cutting (rolling) force (kN) | 4.5 | 1.8 |

Table 9 Comparison of disc cutter forces – conventional (indentation) cutting and undercutting[85]

It should be noted that the discs are not mechanically rotated and their rotation is caused solely by the contact of the discs and the rock. The rotation is important because it helps to reduce the stresses upon a single part of the disc and the heat generated from the friction is

[83] RAMEZANZADEH; HOOD: A state-of-the-art review of mechanical rock excavation technologies, http://tinyurl.com/9xpg5lt , 23.02.10
[84] See RAMEZANZADEH; HOOD: A state-of-the-art review of mechanical rock excavation technologies, http://tinyurl.com/9xpg5lt , 23.02.10
[85] RAMEZANZADEH; HOOD: A state-of-the-art review of mechanical rock excavation technologies, http://tinyurl.com/9xpg5lt , 23.02.10

spread across the cutter. This reduces wear and tear and lengthens its work life. This method has enough potential and two of the major equipment manufacturers - Wirth and Voest Alpine (now Sandvik Mining) are independently developing machines that use the undercutting principle. Some of the machines have even been put into practice in underground construction.[86]

### 6.2.1.1. Wirth Machines

**CMM-MTM**

Wirth is a German equipment manufacturer that started their research and development on a machine that utilizes the undercutting principle in the late 1980s in collaboration with the Canadian consortium HDRK. The goal was to create a continuous mining machine that is capable of breaking hard rock. The first tests were performed with an existing machine – the Atlas Copco mini full facer, which was modified to work with undercutting discs. The machine was trialed in a sandstone quarry and performed so well that the manufacturers began work on a machine specially designed for using undercutting discs. The machine that was created was named CCM (continuous mining machine) and had four arms at the front, each equipped with a disc cutter that had a diameter of 560 mm (Figure 34)[87].


Figure 31 Wirth Continuous Mining Machine (CMM)[88]

[86] See RAMEZANZADEH; HOOD: A state-of-the-art review of mechanical rock excavation technologies, http://tinyurl.com/9xpg5lt , 23.02.10
[87] See RAMEZANZADEH; HOOD: A state-of-the-art review of mechanical rock excavation technologies, http://tinyurl.com/9xpg5lt , 23.02.10
[88] See RAMEZANZADEH; HOOD: A state-of-the-art review of mechanical rock excavation technologies, http://tinyurl.com/9xpg5lt , 23.02.10

Each arm was mounted on a movable joint which allowed the machine to cut different forms of cross-sections with a maximum diameter of 4.25 m. Each cutter was capable to withstand a thrust force of 1 MN but for normal operation the force used was 250 kN. The CMM power was 700 kW of which 525 kW were provided to the cutting head. It weighed 150 t.

As with the first machine, the tests were conducted in the sandstone quarry. In order to gain enough information about the performance of the machine and to tests its durability in a work environment the tests continued for four months. The sandstone in the quarry had the following characteristics:

- Uniaxial compressive strength (UCS) – 120 – 140 MPa
- Uniaxial tensile strength (UTS) – 10 – 13 MPa

Under those conditions the machine's performance was between 8 and 16 $m^3$/h/cutter, which was a very good result[89].

After the trials were completed the machine was transported to Canada, where it was used to excavate rocks with UCS – 250 MPa and UTS – 16 MPa within a nickel mine. The performance in the new conditions wasn't nearly as good as the ones during the tests and the machine was removed from exploitation after excavating about 200 $m^3$ of rock. With this ended the collaboration between the two companies.

Although the development of the machine didn't continue as planned, Wirth was confident with the qualities of this method and produced a redesigned version of the CMM that was called MTM 550H (Mobile Tunneling Machine). It had some minor improvements from the first model: Power was increased to 800 kW; Weight was reduced to 135 t; Excavation diameter was increased to 5.6 m.

There were some notable advantages that a machine using undercutting discs had compared to a conventional TBM:

- The forces under which the thrust and the gripper operated were significantly lower;
- The power consumption and the weight were about half of that of a TBM;
- The transportation and on-site assembly costs were significantly lower due to the smaller size;[90]

**Voest-Alpine Sandvik Reef Miner ARM-1100**

Voest-Alpine Sandvik is an Austrian manufacturer that produced three machines that used the undercutting principle. Unlike Wirth's machine, these were designed for work in a

[89] See RAMEZANZADEH; HOOD: A state-of-the-art review of mechanical rock excavation technologies, http://tinyurl.com/9xpg5lt , 23.02.10

[90] See RAMEZANZADEH; HOOD: A state-of-the-art review of mechanical rock excavation technologies, http://tinyurl.com/9xpg5lt , 23.02.10

platinum mine located in South Africa. For the mining purposes short and wide slots needed to be excavated. The three machines that were constructed were of two different types. The initial model was called ARM-1000 and excavated slots with a height of 1 m. From the improved model – ARM 1100 (Figure 35) two were manufactured and they were capable of cutting slots with a height of 1.15 m.

Figure 32 Voest-Alpine Sandvik ARM1100[91]

The machines were used in two different platinum reefs. One of them was called Merensky and consisted of a strong rock with UCS in the range of 150-200 MPa. The other was called UG2 and had weaker rocks with UCS at around 40-120 MPa. The rock on both locations was very abrasive but on the second one significantly more than on the first site.

The ARM-1000 was initially used at the reefs and its performance met the requirements of the two companies that operated the mine which convinced each of them to invest in the upgraded version – the ARM-1100.

One of the ARM-1100 machines was successfully used in the UG2 with a good performance but high operation costs which forced the company to relocate it to the other location. Although the rock was harder there, the machine performed better reaching the required excavation speed of 1m/h which meant a total rock volume of 4.89 $m^3$/h (4.25m/h 1.15m x 1m = 4.89$m^3$/h). However, this performance wasn't consistent and over the course of 1 month a total volume of 625 $m^3$ (or 2500 t) was reached. The company that operated the mine had a requirement of 10,000 t/month excavated per machine which was four times more than the actual performance of the ARM-1100.

Adding to the insufficient performance the companies also complained of the high cutter costs the cause of which was probably the abrasiveness of the platinum reefs. The other machine faced similar difficulties in the Merensky reef which forced the company to remove

[91] RAMEZANZADEH; HOOD: A state-of-the-art review of mechanical rock excavation technologies, http://tinyurl.com/9xpg5lt , 23.02.10

its ARM-1100 from the excavation operations. The wearing problem of the cutters was so severe that the operation costs of the machines added up to about 20-30 Euro per tonne of ore. This was as much as it would cost the companies to excavate the rocks using the drill-and-blast methods. For this type of machine to have a competitive advantage over other methods the costs had to be reduced four to six times in order to reach a price of around 5 Euro per tonne. This shows that serious improvements must be made before the machines reach a desirable performance/costs ratio. The initial results are not surprising considering the short history of this type of machines.

Because the companies had already made the investment in these machines they continued to operate them with different success and a total of about 6,000 $m^3$ of rock have been excavated. The manufacturer Sandvic-Tamrock continues to work on improvements in the machines with the help of one of the companies that owns the ARM-1100. They have seen potential in this technology and with their combined effort are hoping to create a superior version of the machine that meets the needs of the mining companies.[92]

### 6.2.2. Activated/Oscillating Disc Cutting

During the last few years some companies are trying to further improve the performance of the undercutting discs by creating a mechanism that oscillates during the cutting process (Figure 36).

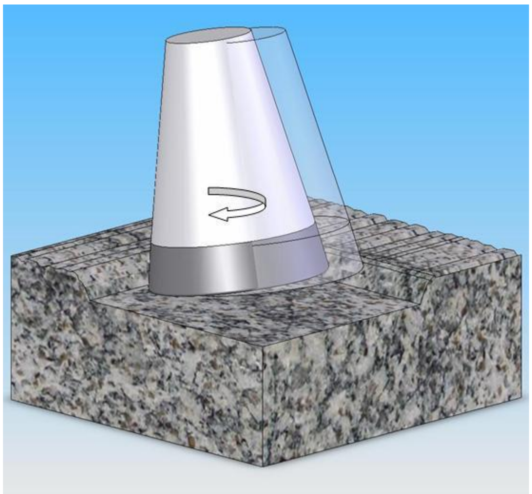


Figure 33 Undercutting and oscillating (activated) disc cutter[93]

[92] See RAMEZANZADEH; HOOD: A state-of-the-art review of mechanical rock excavation technologies, http://tinyurl.com/9xpg5lt , 23.02.10

[93] RAMEZANZADEH; HOOD: A state-of-the-art review of mechanical rock excavation technologies, http://tinyurl.com/9xpg5lt , 23.02.10

Although this complicates the process, the purpose of the oscillation is to weaken the rock with many small load cycles over a short period of time that cause fatigue and small cracks on the surface of the rock.

The added oscillation had a significant effect during the test cuts made in a sandstone sample. The results of this test are shown in Table 6. In order to gain data for comparison, cuts were made with a conventional disc, an undercutting disc and an oscillating undercutting disc with oscillating frequency of 35 Hz. The numbers in the table clearly show the improvement that the oscillation adds to the undercutting. The thrust force is reduced ten times compared to the conventional disc cutting and 3.8 times compared to normal undercutting. The reduction of the cutting force was also quite significant, 3.75 times less than that of the conventional and 1.5 times less than that of the undercutting disc[94].

| Oscillating Frequency | 0 Hz Conventional Disc | 0 Hz Undercutting Disc | 35 Hz Undercutting Disc |
|---|---|---|---|
| Normal (thrust) force (kN) | 18 | 6.8 | 1.8 |
| Cutting (rolling) force (kN) | 4.5 | 1.8 | 1.2 |

Table 10 Comparison of disc cutter forces – conventional (indentation) cutting, undercutting with no oscillation, undercutting whilst oscillating at 35 Hz[95]

This simple test was enough to convince researchers to further investigate the oscillating undercutting technique. New tests were using marble with a UCS of 90 MPa, the goal was to make a groove in the stone using each method and measure the forces needed to accomplish that task. The results are shown in Figure 37.

The blue curve in the top graphic of Figure 37 shows the changes in the forces during the test without oscillation. On average, the cutting force was around 30 kN peaking at 50 kN. The undercutting technique used for this test was like the one that was used on the machines made by Wirth and Voest-Alpine.

The pink curve in the same graphic shows the forces during the oscillating disc run. The reduction in the forces is quite obvious: using oscillating the force averaged at around 7 kN and peaked only at around 15 kN. The force is more than 4 times less than the one without oscillating. It should be noted that all parameters except the oscillation were equal for both tests. Both cuts reached the same depth and were made with equal speed.[96]

[94] See RAMEZANZADEH; HOOD: A state-of-the-art review of mechanical rock excavation technologies, http://tinyurl.com/9xpg5lt , 23.02.10

[95] RAMEZANZADEH; HOOD: A state-of-the-art review of mechanical rock excavation technologies, http://tinyurl.com/9xpg5lt , 23.02.10

[96] See RAMEZANZADEH; HOOD: A state-of-the-art review of mechanical rock excavation technologies, http://tinyurl.com/9xpg5lt , 23.02.10

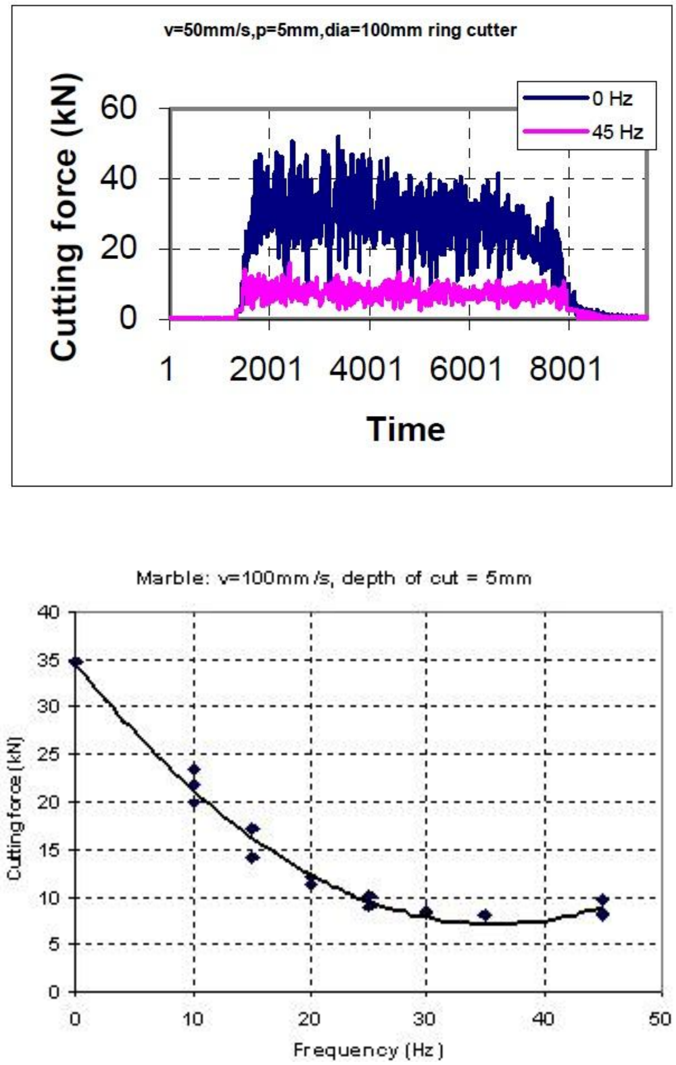



Figure 34 Measured disc cutting forces in marble showing the influence of cutter oscillation[97]

The benefits of oscillation were discovered as early as 1988 by a German called Ulrich Bechem who has several patents regarding a method using "activated" undercutting discs. His work didn't stay unnoticed and Mr. Bechem collaborated with different companies trying to find a commercial use for his invention.

A decade later, there were some companies that develop equipment using oscillating or "active" discs. The German company DBT is a mining equipment manufacturer that produced such machines for the Anglo Platinum company that operates the same UG2 reef. Starting in 1999 the companies began using the machine with oscillating discs. After years of exploitation the results were discouraging. The combined length of the excavation was only 30 m and 1 m or less in height. There were two main problems that cause the poor performance. The first one was mentioned earlier in this part, the cutter discs quality

[97] RAMEZANZADEH; HOOD: A state-of-the-art review of mechanical rock excavation technologies, http://tinyurl.com/9xpg5lt , 23.02.10

deteriorated very rapidly. The other problem was more specific to the nature of this technique. The added oscillation was achieved using an eccentric shaft that was connected to a gearbox which controlled the frequency. That gearbox was the main cause of the problems, it required frequent repairs and maintenances that increased the already high exploitation costs.

The engineers at DBT have since redesigned the gearbox and in 2007 it was installed in the machine along with other improvements in the mechanisms. The disc cutters were also reworked to reduce the rates at which they wear. No information has been released from the companies since the implementation of the improvements.[98]

Although the terms activated and oscillating discs are interchangeable there is a significant difference between the two techniques. ACD was the one patented by Bechem which had the gearbox and eccentric drive shaft. The OCD system provides a more simple method for oscillation and it also includes an inertial mass that is located on the cutter arm. This further reduces the forces that reach the machine by dampening the vibration. Another key feature of the OCD method was the implementation of water jets. High-pressure jets fractured the rock reducing the needed force from the cutter head even more and at the same time cooled the cutter discs which retains their hardness and makes them last longer.

The OCD technology having undisputable advantages has been further developed today by some companies which plan to use it for machines for the platinum mines where their predecessors operated mostly unsuccessfully. Hopefully, the technological challenges that plagued the development of these machines will be resolved, and their use will become more common.[99]

### 6.2.3. Minidiscs

In the field of conventional disc cutting, the force required and the disc's contact area have a directly proportional correlation between them. In short, smaller discs require lower force to reach a certain penetration depth. From this comes the conclusion that if the force isn't lowered the penetration depth must be increased, or, if both force and depth are unchanged the cutter disc can be reduced. In practice, this meant that it may be possible to reduce the

[98] RAMEZANZADEH; HOOD: A state-of-the-art review of mechanical rock excavation technologies, http://tinyurl.com/9xpg5lt , 23.02.10

[99] See RAMEZANZADEH; HOOD: A state-of-the-art review of mechanical rock excavation technologies, http://tinyurl.com/9xpg5lt , 23.02.10

power of the machine and increase the depth of the cuts by changing the size of the disc cutters that were used.

This was tested by the Colorado School of Mines in 1990 with their first minidisc cutter that had a diameter of 5 inches (12.7 cm) and a pedestal mounting system (Figure 38). These discs were tested thoroughly on different types of rock. The tests showed some serious problems with this method. One of them was the mounting system which wasn't strong enough for the forces involved. Another one came from the discs. Because of their small diameter their cutting edge was very small and wore off very quickly reducing the cutting capabilities of the discs drastically. Those two problems were enough to end the development of mini discs using this type of mounting system.[100]

Mini discs are used today with the saddle mount system and bigger diameter 6-10 inches (15.24-25.4 cm) in the field of microtunneling machines.

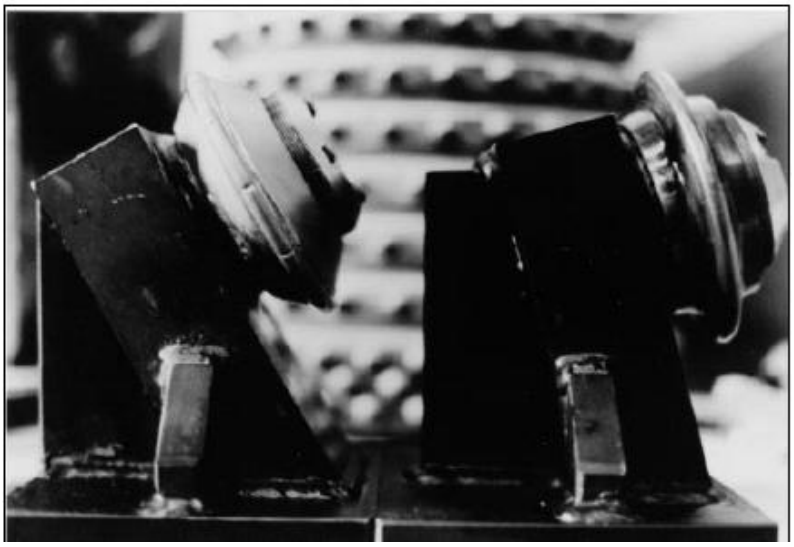


Figure 35 Prototype of 5 inches mini disc[101]

### 6.2.4. Evaluation

Disc cutting is a very effective rock removal method and conventional disc cutting is widely used today in tunnel boring machines. Its qualities have been proven successfully in practice all over the world and are well known within the industry. Undercutting is also starting to make its way into the tunneling industry, and its first use in a major project (the Uetliberg

[100] RAMEZANZADEH; HOOD: A state-of-the-art review of mechanical rock excavation technologies, http://tinyurl.com/9xpg5lt , 23.02.10

[101] RAMEZANZADEH; HOOD: A state-of-the-art review of mechanical rock excavation technologies, http://tinyurl.com/9xpg5lt , 23.02.10

Tunnel) has been very successful, but the benefits of this method come with few disadvantages.

The same cannot be said with certainty for the oscillating disc cutting. The results outside of the laboratories have so far been unsatisfactory, yet the results from the laboratory tests confirm the potential of the technology. It seems that a lot more effort, time and investment is needed before that potential can be harvested.

# Fact sheet 6.2.

| | |
|---|---|
| **Name of the method** | Disc cutting |
| **Year of origin** | 1956 |
| **Tests conducted** | Laboratory tests with different sizes of discs, angles and frequencies(for oscillating discs) |
| **Area of application (types of rock)** | Limestone; sandstone; |
| **Performance with undercutting discs ($m^3$/h)** | maximum 4.89 $m^3$/h* [1] |
| **Costs (€/$m^3$)** | ≈ 86-126 €/$m^3$ *[1] |
| **Energy consumption** | 350kW [2] |
| **Necessary Equipment** | Cutting discs;<br>Mechanical arms;<br>Drive unit; |

*4.89 $m^3$/h = 20 t/h=> 1 $m^3$ =4.09 t;

cost: 21-31 Euro/t => 86-126 Euro/$m^3$

[1] RAMEZANZADEH; HOOD: A state-of-the-art review of mechanical rock excavation technologies, http://tinyurl.com/9xpg5lt, p. 35, 23.02.10

[2] http://www.miningandconstruction.sandvik.com/sandvik/9082/Internet/S002630.nsf/Alldocs/Products*5CContinuous*2Dmining*and*tunneling*machines*5CContinuous*reef*miners*2AAlpine*Reef*Miner*ARM*1100/$FILE/ARM_1100.pdf, 27.11.2012

## 6.3. Wire cutting

Wire cutting is a technology mostly used today in open quarries when the excavated material must preserve its integrity as much as possible without wasting too much of the material. Most commonly this method is used in marble and granite mines. Wire cutting includes a wide variety of wires, that can be used, which differentiate in thickness, structure and abrasiveness.

In this part of the paper the different types of wires and ropes will be examined as well as their productivity for different rock types, wire speed and oscillating. This technique offers high performance with relatively cheap and easy to maintain equipment. This method is not by itself sufficient to cut and remove rocks, even in open mines the process involves drilling before the cutter can be installed.

Overall, the main part of the work is done by the wire and after the initial setup the machine can even work without constant human supervision. It's a relatively simple, but effective technology of which the most important and expensive part is understandingly the wire itself. The wires, also known as ropes when the diameter is bigger, have different properties and structure, allowing cutting of many different types of rock. An advantage of this technology is that a single motor can use a wide range of wires and they can be changed quickly.

Innovations allow this technique to be more widely used today in different industries. Thin diamond coated wires are used today for cutting a wide variety of materials like wood, ceramics and even foam. Modern wire cutting machines are equipped with instruments that monitor the cutting process, different parameters, so that they may be adjusted accordingly to maximize performance. Operators can change the wire speed, the down feed rate and the wire bow angle to get the cleanest and fastest cut possible for every material. The different uses and approaches to diamond wire saws will be overviewed below.

### 6.3.1. Diamond wire saws

Wire sawing is and old cutting method but diamond wire saws weren't popular until the production of synthetic diamonds with sufficient quality became cheap enough for them to be used for cutting purposes. The alternative to wire cutting has always been circular saws but their limited cut depth was a big drawback for mining companies which quickly embraced the wire cutting technique.

The origins of the diamond wire cutting can be followed back to England were the method was invented. The original wire consisted of a steel cable with diamond beads that were electroplated around it. The first commercial use of a diamond wire saw came 30 years later when the method has been improved drastically from its original design. These first practical diamond saws used just one strand of diamond wire.

In 1994 a Japanese company called Yamana Co. began work on a new type of wire cutting machine that had 10 wires, each with a diameter of 10 mm. It was called a multi diamond wire (MDW) machine, but the manufacturer never took the concept past the prototype phase. MDW machines were produced by other companies and some models had as much as 30 wires. These models were used primarily for cutting multiple thin granite slabs, the position of the wires being parallel to one another.[102]

### 6.3.2. Wire types

The wires used in rock cutting differ in diameter and composition depending on the types of rock that are being cut. There is no single standard for diamond wires, most manufacturers of wire-cutting equipment produce different patented types of wire with their own specifications which are usually suitable for a certain type of rock. The composition of the wires is developed continuously and each version is tested thoroughly before being put into practice. Maximum strength and cutting efficiency is the goal of every manufacturer, as the materials used are expensive, and recycling and reuse of wires which snap during cutting is almost impossible.

A diamond wire saw has to withstand very high tensile forces, which is why its main element is a high strength wire core carrying the cutting elements (Figure 39). The wire is joined together forming a closed loop, the part closing this loop is called, appropriately, a joiner and holds the wire using a swaging/crimping tool. It may be permanent or detachable (Figure 40).

The cutting elements steel rings coated with diamonds, attached using either electroplating or sintering (Figure 41). Between each two carrier rings there is a compression spring which keeps the wire straight and prevents tangling. The springs and the core wire are encased in an elastomeric material (Figure 43) which provides additional protection from corrosion that can be caused by the liquid coolants used while cutting. Only the rings with the diamond coating are left exposed so they can grind through the rock. The rings are the thickest element of the wire and define its diameter which is usually around 10 mm for wires of this type.[103]

[102] See McCARTHY, Shane: Diamond wire cutting, http://www.tmr.qld.gov.au/~/media/495496ae-ab76-4cdd-a2b1-84ea893d8bff/page2939diamondcutred2.pdf, 17.02.2012

[103] See McCARTHY, Shane: Diamond wire cutting, http://www.tmr.qld.gov.au/~/media/495496ae-ab76-4cdd-a2b1-84ea893d8bff/page2939diamondcutred2.pdf, 17.02.2012

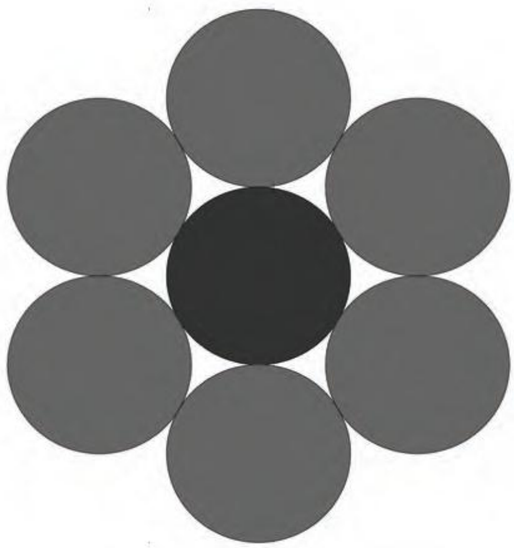


Figure 36 Section through a tension element/carrier wire[104]

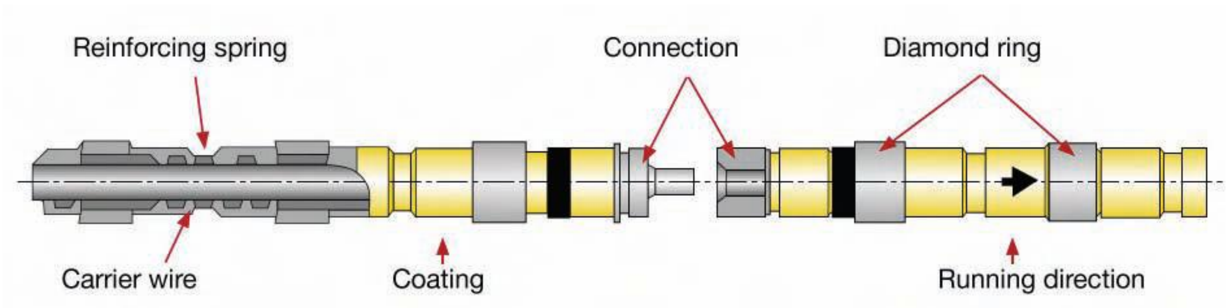



Figure 37 Screwed wire joiner[105]

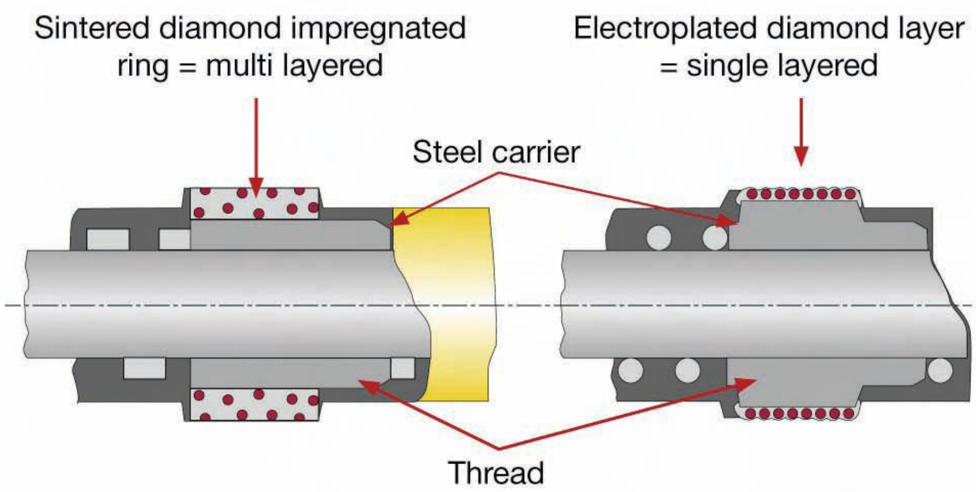
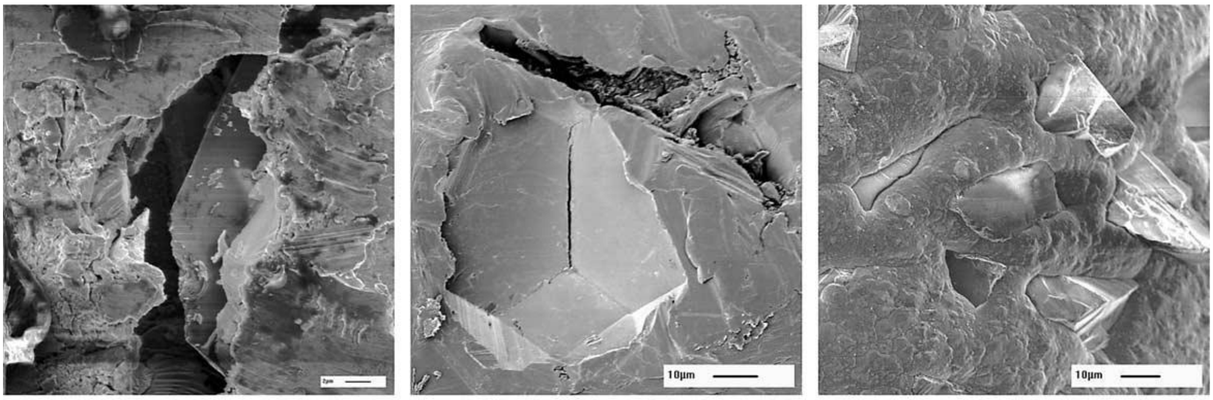



Figure 38 Mounting of diamonds[106]

[104] McCARTHY, Shane: Diamond wire cutting, http://www.tmr.qld.gov.au/~/media/495496ae-ab76-4cdd-a2b1-84ea893d8bff/page2939diamondcutred2.pdf, 17.02.2012

[105] McCARTHY, Shane: Diamond wire cutting, http://www.tmr.qld.gov.au/~/media/495496ae-ab76-4cdd-a2b1-84ea893d8bff/page2939diamondcutred2.pdf, 17.02.2012



(a) (b) (c)

Figure 39 Close-up view of the diamond grit on new wires. (a) Supplier 1; (b) Supplier 2; (c) Supplier 3.[107]

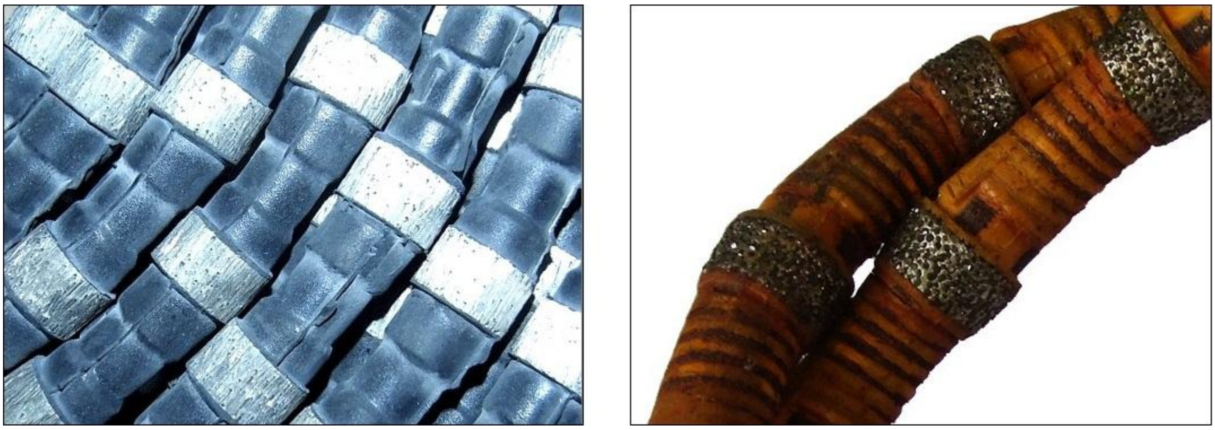
With the advancement of this technology diamonds have been fixed to the wires using different methods. Some examples of newer methods are shown in Figure 43 Picture (a) shows a wire using the sintering method, bond with increased diamond retention achieved after laser treatment. A second layer of metal bond is added to increase the bond strength of the diamond wire. In picture (b) the diamond grits are mechanically rolled into a steel wire. The close-up picture shows the exposed diamond grits which provide a better cutting action. The supplier of the wire on picture (c) uses smaller grit size diamonds. The advantage of smaller sized grits is the reduced damage on the cut surface. The rapid evolution of diamond wire technologies in the last few years results in new, more durable diamond wires which ensures the increased application of this technology in the future[108].

**a)** **b)**

[106] McCARTHY, Shane: Diamond wire cutting, http://www.tmr.qld.gov.au/~/media/495496ae-ab76-4cdd-a2b1-84ea893d8bff/page2939diamondcutred2.pdf, 17.02.2012

[107] HARDIN, Craig: Fixed Abrasive Diamond Wire Saw Slicing of Single Crystal SiC Wafers and Wood, http://repository.lib.ncsu.edu/ir/handle/1840.16/420, 08.04.2003

[108] See http://www.chinawiresaw.com/, 19.02.2012



c) d)

Figure 40 Examples of diamond wire: a) Spring Fixing with Sintered Diamond Beads b) Plastic Coating with Sintered Diamond Beads c) Rubber + Spring Coating with Sintered Diamond Beads d) Rubber + Spring Coating with Electroplated Diamond Beads[109]

### 6.3.3. Cutting techniques

The use of wires provides a wide range of cutting techniques which may be used, depending on the individual situation, with just a few changes in the setup of the machines. It is mostly used for cutting very large blocks of marble, granite, etc, but due to the abrasiveness of the diamond wire it can also cut through reinforced concrete and other materials if needed. The cutting depth of an average diamond circular saw is usually limited to about one third of the diameter of the saw blade which makes it impractical for deep cuts. The diamond wire saw solves this problem. The basic cutting principal is shown in Figure 44 illustrating the cutting of a concrete slab.[110]

[109] http://www.chinawiresaw.com/, 19.02.2012

[110] See McCARTHY, Shane: Diamond wire cutting, http://www.tmr.qld.gov.au/~/media/495496ae-ab76-4cdd-a2b1-84ea893d8bff/page2939diamondcutred2.pdf, 17.02.2012

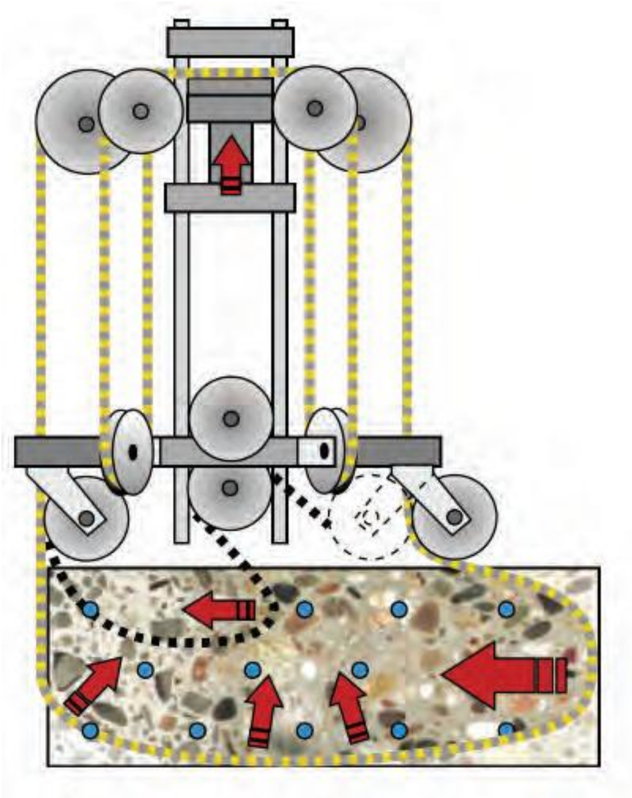


Figure 41 Diamond wire cutting a reinforced concrete slab[111]

A diamond cutting wire typically has a joiner piece used for easier mounting. The joiner disconnects the wire loop so it can be wrapped around the slap to be cut. If there is no access, a drill must be used to make an access hole through which the wire is threaded. The wire is looped around the slab and reeved through a system of pulleys designed not only to guide the wire during the cutting but also to amplify the power of the motor and hydraulic system. Water is used during the cutting process to cool and lubricate the wire as well as a mean to remove the cut concrete and steel particles. As the cutting continues the excess slack wire is stored using the pulley system. Tension and cutting speed are controlled at all times and are adjusted according to the material and its hardness. The tractive effort in the system is achieved by a drive pulley on which the wire is wrapped in order to create a simple capstan drive.

The safety around the wire is highest priority because of the speed of the wire and the tensile forces a whiplash caused from a break during cutting can lead to fatal injuries.

Some of the materials more commonly cut using the diamond wire method include:

- Concrete
- Rock

[111] McCARTHY, Shane: Diamond wire cutting, http://www.tmr.qld.gov.au/~/media/495496ae-ab76-4cdd-a2b1-84ea893d8bff/page2939diamondcutred2.pdf, 17.02.2012

- Reinforcing steel
- Stressing strand
- Steel sections
- Steel plate

Among the other advantages of this process is that it is relatively quiet compared to circular saws. The hard rock surroundings can amplify the noise significantly and make the environment even more exhausting for the workers.[112]

Figure 42 Deep cutting of marble using diamond wire[113]

The wire cutting technique's main advantage is its great versatility. The wires may be set up to cut vertically or horizontally but if needed any angle can be arranged. The size of the piece being cut depends almost entirely from the length of the wire which means large pieces of rock can be cut at a time thus increasing productivity. Figures 46-48 show a few of the many possible cutting configurations[114].

[112] See McCARTHY, Shane: Diamond wire cutting, http://www.tmr.qld.gov.au/~/media/495496ae-ab76-4cdd-a2b1-84ea893d8bff/page2939diamondcutred2.pdf, 17.02.2012
[113] McCARTHY, Shane: Diamond wire cutting, http://www.tmr.qld.gov.au/~/media/495496ae-ab76-4cdd-a2b1-84ea893d8bff/page2939diamondcutred2.pdf, 17.02.2012
[114] See McCARTHY, Shane: Diamond wire cutting, http://www.tmr.qld.gov.au/~/media/495496ae-ab76-4cdd-a2b1-84ea893d8bff/page2939diamondcutred2.pdf, 17.02.2012

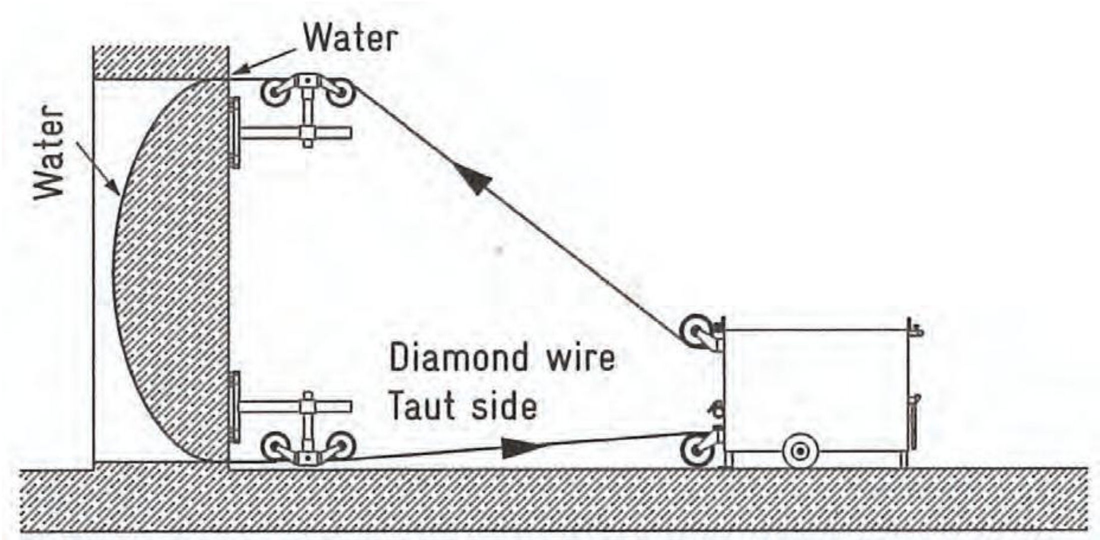



Figure 43 Vertical cut – standard method[115]

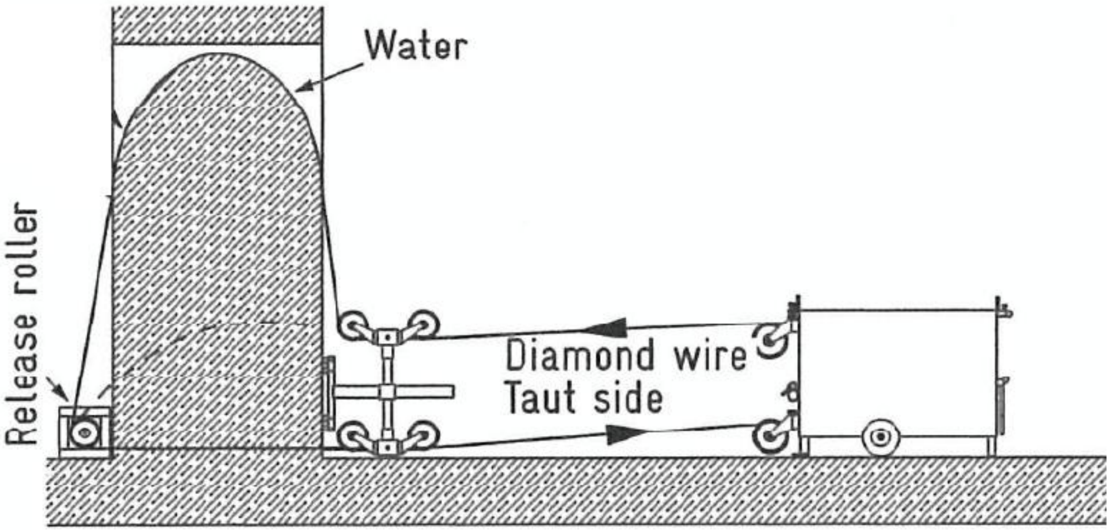



Figure 44 Vertical cut – with release roller[116]

115 McCARTHY, Shane: Diamond wire cutting, http://www.tmr.qld.gov.au/~/media/495496ae-ab76-4cdd-a2b1-84ea893d8bff/page2939diamondcutred2.pdf, 17.02.2012
116 McCARTHY, Shane: Diamond wire cutting, http://www.tmr.qld.gov.au/~/media/495496ae-ab76-4cdd-a2b1-84ea893d8bff/page2939diamondcutred2.pdf, 17.02.2012

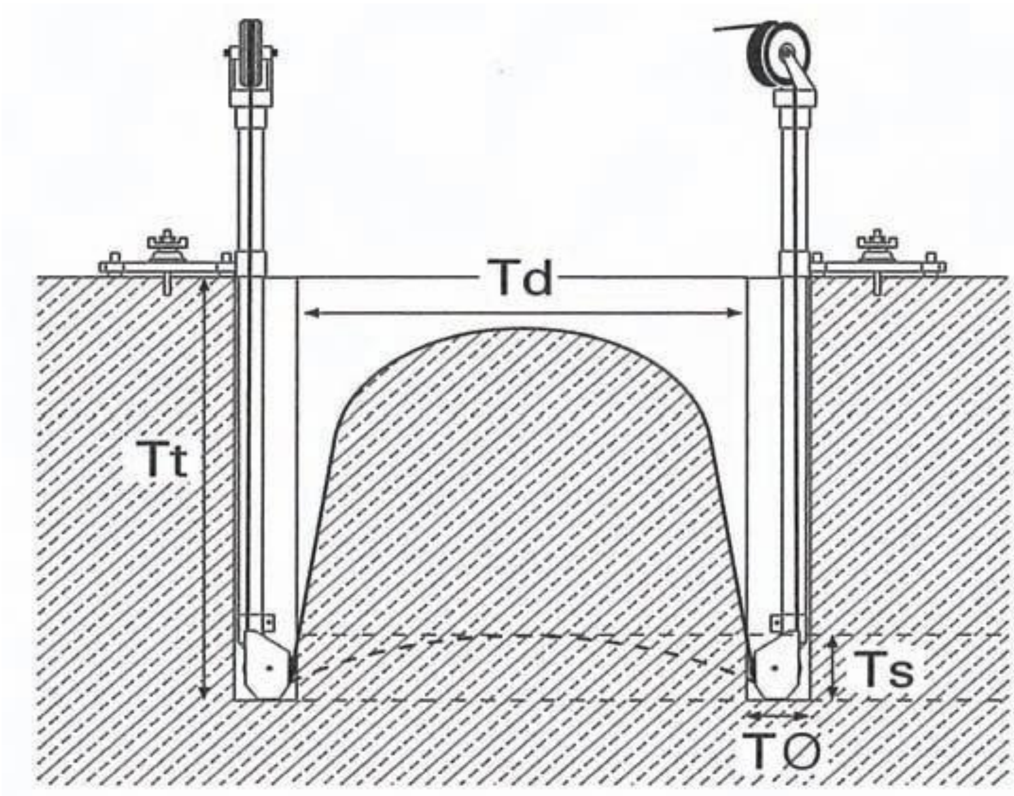



Figure 45 Plunge roller cutting[117]

### 6.3.4. Evaluation

Diamond wire cutting is a technology that provides great productivity at relatively low exploitation costs and inexpensive equipment in terms of overall construction machinery. The method is fairly simple and straightforward to use and maintain which further reduces the costs. Although the costs are low for rock cutting when it is important for the cut pieces to remain whole, in terms of rock removal for tunnel construction these costs are more than two times higher than using the drill-and-blast method.[118] However, due to safety reasons rock blasting is forbidden or very restricted in certain areas, which makes wire cutting a viable alternative despite the higher costs. Overall, it is unlikely that this technology can be used as a main rock removal method without developments that can make it economically comparable to the alternatives.

The improvements and further developments of the wire will ensure the ever widening use of this technology in construction and deconstruction.

[117] McCARTHY, Shane: Diamond wire cutting, http://www.tmr.qld.gov.au/~/media/495496ae-ab76-4cdd-a2b1-84ea893d8bff/page2939diamondcutred2.pdf, 17.02.2012

[118] GUSTAFSSON, Nils: Wire cutting as a complement to drill and blast in vibration sensitive environments, http://publications.lib.chalmers.se/records/fulltext/147788.pdf, p. 33, 10.08.2012

# Fact sheet 6.3.

| | |
|---|---|
| **Name of the method** | Wire cutting |
| **Year of origin** | 1970s: Synthesis of high-quality 'saw' diamond was developed for demanding stone working applications such as sawing granite.<br>1980s: Coated 'saw' grits were introduced into broader application. |
| **Tests conducted** | extensive trials in open quarries and laboratory tests using different types of diamond wires, wire speeds and angles |
| **Area of application (types of rock)** | all types of solid rock |
| **Performance (m/h)** | ≈ 1-4 m/h*[1] |
| **Costs (€/m²)** | ≈ 7.2 €/m²[2] |
| **Energy consumption** | ≈55kW[3] |
| **Necessary Equipment** | Diamond wire; motor; pulley system; |

* vertical progress of the wire/depth of the cut

[1] Mancini, R.; Cardu, M.; Fomaro, M.: Technological and Economic Evolution of Diamond Wire Use in Granite or Similar Stone Quarries, http://www.maden.org.tr/resimler/ekler/01627aa14e37bd1_ek.pdf, 17.02.2012

[2] http://www.graniteland.com/infos/production/gang-saw-diamond-wire-saw, 17.02.2012

[3] http://www.diastar.co.za/p/114990/dia-star-diamond-wire-saw-dns-55ax, 17.02.2012

## 6.4. Circular saw cutting

Circular saws are relatively old technology compared to the others mentioned in this part of the paper. The exact invention of the circular saw is unclear but there is information dating it back to the end of the 18th century.[119] Originally, circular saws were used only for wood cutting and were powered using wind or water since they were placed in specially constructed mills that housed them. The circular saws use the same cutting principles as the regular ones but instead of the forth and back motion they use a single rotating disc. The disc has sharp teeth and with each rotation takes away a small portion of the material leaving a narrow kerf and smooth surface finish.

### 6.4.1. Circular diamond saw characteristics

The diamond blades do not actually cut. The process they use for the removal of material is grinding. The blades usually have rectangular teeth, also called segments, which have diamond particles embedded in their structure so that during usage there are always exposed crystals which grind from the material being cut.

The diamond segments of the saw are held in place by powdered metals. The powdered metal part of the blade is called “bond” because it binds the diamond crystals together. The bond’s hardness differentiates depending on the blade type. During the grinding process the bond allows new layers of crystals to become exposed ensuring a “sharp” edge of the blade at all times. That is why it is very important to choose the right blade for the specific materials. The connection between the hardness of the bond and that of the material is somewhat counter-intuitive. The harder a material, the softer bond it needs. This is because harder materials need constant exposure to fresh, sharp diamond crystals in order to be cut, which as stated above, means softer bond. Otherwise the blade will grind only with the bond and worn diamond facets, making little progress. A harder bond is used for softer, more abrasive materials, like asphalt or freshly poured concrete. As such materials lead to increased wear, harder segments to resist such wear are required.

Other important characteristics of the diamond blades which have to be considered are the diamonds’ size, or grit, as well as their toughness and concentration. In terms of size, smaller diamonds are used for hard materials since they cut more easily into them and vice versa, bigger diamonds are more effective for cutting softer materials.[120]

There are many other factors that must be considered as when deciding for one diamond saw over another. For instance, whether or not will water be used for lubrication and cooling

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[119] http://inventors.about.com/library/inventors/bltools.htm, under “Saws”, 18.06.2012

[120] See http://www.diamondtecblades.com/safebladeoperation.pdf, 18.06.2012

during the process? In open mines or at construction sites within cities water is easy to access, but in terms of underground construction accessing a water supply is more difficult.
As with all modern tools, power is relevant when considering different diamond saws. The horsepower of the saw motor has a strong connection with the other characteristics of the composition. A more powerful motor requires either higher diamond concentration or harder bond. This is because a high-powered machine will cause the diamonds to receive larger forces. Higher concentration of diamonds will result in less wear on each individual crystal currently grinding. A harder bond is needed to resist the stronger forces involved that will otherwise separate the crystals from the blade resulting in a loss of productivity.[121]


**A**

**B**

[121] See http://www.diamondbladeselect.com/tips/how-to-select-suitable-diamond-blades/, 18.06.2012


**C**

**D**

Figure 46 Application of circular diamond saws in practice: A[122], B Usage in open quarries[123]; C usage for deconstruction[124]; D underground usage in an existing tunnel[125]

Diamond tools reach highest performance when cutting wet. Water aids the cutting process in several ways, listed below:

- It cools the blade, preventing overheating and structural deformities;
- It collects most of the tiny dust particles that are released in the air and are dangerous if inhaled;

[122] http://www.rocktoolsinc.com/, 19.06.2012
[123] http://www.andersonstone.com/home/and/smartlist_12/about_us.html, 19.06.2012
[124] http://aardvarkrocktools.weebly.com/rock-saws-diamond---jcb-robot-skid-steer-mounted.html, 19.06.2012
[125] http://www.suhire.com.au/categories/specialised-attachments/excavator-mounted-diamond--saws.aspx, 19.06.2012

- It removes the slurry during cutting ensuring the blade makes contact with a clean surface;

The diamond crystals are unable to withstand the increased temperatures that are reached during the cutting of some of the more abrasive materials. If left uncooled the blade will wear rapidly and even fail. Wet cutting greatly extends the blade’s life. When dry cutting, the blade must be periodically allowed to cool off. This can be easily done by removing the blade from the cut and allowing it to spin freely, allowing air to cool the segments.
Many blades are capable of operating both dry and wet, but in principle, dry cutting is to be avoided when there is water available and there are no factors against its use.[126]
When such factors are present, measures must be taken to ensure the safety of the operator and other workers on site. The inhalation of dust created by dry cutting poses a serious health risk. If silica dust reaches the lungs it may cause a disease know as Silicosis. Because of those risks, dry cutting using diamond saws is under strict regulation. Everyone involved in the process must be familiar with the risks and must use the necessary safety equipment.[127]

### 6.4.2. Diamond blade types by manufacturing

The blade type is another important aspect when choosing the right cutting tool for your needs. It depends on the manufacturing method. There is a variaty of methods for attaching diamonds to the blade's base. A commonly used method is sintering. Sintering combines a mixture of diamonds and metal powders to form the saw blade's cutting segments. This and other methods like vacuum brazing, electroplating, extruding and so on, will be explained further in this part of the paper.

#### 6.4.2.1. Electroplated diamond blade

The exact techniques used by manufacturers for those types of blades are a closely guarded secret. Diamonds are electroplated with nickel in thin layers over a metal base. Due to the thin layers of coating that can be achieved, this method is mostly used for precise cutting tools and is generally not suitable for the heavy industry. However, some manufacturers have developed technology that can electroplate multiple layers on one blade which allow longer work life.[128]

[126] http://www.diamondbladeinfo.com/About/about_diamond_blades.htm, 19.06.2012
[127] http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=INTERPRETATIONS&p_id=22737, 19.06.2012
[128] http://www.duracut-tools.com/electroplated-diamond-cutting-discs.htm, 19.06.2012

Figure 47 Electroplated diamond blade[129]

### 6.4.2.2. Vacuum Brazed diamond blade

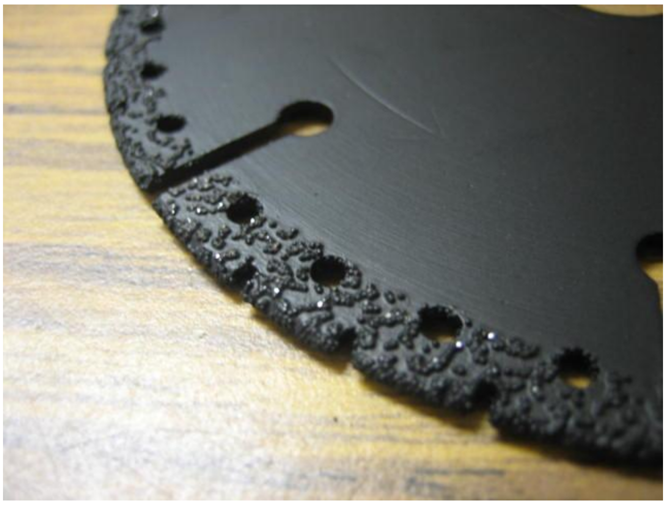

Figure 48 Close-up of a vacuum brazed diamond blade[130]

With this method, the synthetic diamond crystals are attached to the cutting edge of the saw blade using a vacuum brazing furnace. This way, all diamond particles are welded to the outside edge of the blade, without any metal-diamond mixture. An advantage of this method is the fact that removes the need to match the materials being cut with specific types of blades. Vacuum brazed blades cover a wide range of materials, including: stone, concrete, masonry, wood, glass, tile etc.[131]

[129] http://www.cccme.org.cn/shop/wp2008/offerinfo-3095243.aspx, 19.06.2012
[130] http://pic.stonecontact.com/picture/20098/13523/V-B-diamond-saw-blades-P26173B.jpg, 19.06.2012
[131] See http://www.desertdiamondindustries.com/faq.php, 20.06.2012

### 6.4.2.3. Sintered Metal-bonded diamond blade

This is the most common type of diamond blades. Sintered metal-bonded blades are composed of a steel plate, serving as a rigid base for the diamond segments. They are a combination of synthetic diamond crystals and powder metal. Those two components are sintered together to form the grinding segments on the edge of the steel plate, better known as the "cutting teeth" of the saw.


Figure 49 Sintered diamond blade[132]

As with all types of blades, these too vary a lot depending on the manufacturer. There are two main types of steel core designs. The first one alternates grinding teeth and spaces, to help with slurry removal and provide better cooling, as previously mentioned. The second one consists of a continuous flat rim edge. This design is preferred, for example, in marble quarries, where the cut segments are used for decorative purposes and need to have a smoother finish, without visible imperfections.[133]

Metal-bonded diamond blades are separated into three types, depending on the manufacturing technique. These are:

- Wholly sintered diamond blades
- Silver brazed diamond blades
- Laser welded diamond blades

[132] http://www.zydon6.ecvv.com, 20.06.2012

[133] See http://www.desertdiamondindustries.com/faq.php, 20.06.2012

### 6.4.2.3.1. Wholly sintered diamond blade

This type of diamond blades are made by combining the diamonds, metal bond materials and the steel core into a mold, which is placed into a sintering machine. Because of the mold, wholly sintered blades are generally not very large, the diameter rarely exceeding 400 millimeters. One of the disadvantages of the mold sintering process is that as the steel core is also included in the mold, it cannot be quenched (heat treated), so, strength and hardness are not very high. The softer core leads to deformities when subjected to high-load and intensity during cutting. If such cases are avoided, the wholly sinter diamond blade has a very high cutting efficiency[134].

### 6.4.2.3.2. Silver brazed and laser welded diamond blade

Unlike wholly sintered blades, silver brazed diamond blades as well as laser welded diamond blades avoid this problem by treating the steal core and diamond segments separately. Because the steel core needs much higher strength and hardness, it is treated using different methods from those used for the segments. The segments and steel core are brazed together using a silver solder. The result of this is a blade that retains high cutting efficiency even during high-load and intensity cuts. However, silver brazed diamond blades must always be used with liquid cooler. Otherwise the high temperatures that are generated during the cutting process may lead to melting of the silver solder. This can result in detachment of diamond segments from the blade during its high-speed rotation, which is very dangerous for the equipment operators[135].

Figure 50 Close-up of silver brazed diamond blade segments[136]

[134] See http://www.diamondbladeselect.com/knowledge/wholly-sintered-silver-brazed-and-laser-welded-diamond-saw-blades/, 20.06.2012

[135] See http://www.diamondbladeselect.com/knowledge/wholly-sintered-silver-brazed-and-laser-welded-diamond-saw-blades/, 20.06.2012

[136] http://diaproblades.blogspot.com, 20.06.2012

### 6.4.3. Evaluation

Circular diamond saws have outstanding short-term performance but aren’t effective for longer use since the diamond layers of the blade wear relatively quickly and they have to be resintered. They are also not suitable for deep cuts and their overall capabilities are greatly limited by the diameter of the saw. However, there are enough situations and jobs that benefit from the characteristics of circular saws which makes them a valuable tool in the engineers arsenal.

# Fact sheet 6.4.

| | |
|---|---|
| **Name of the method** | Circular Saw Cutting |
| **Year of origin** | 1935-1939 |
| **Tests conducted** | wide use in practice in open mines and cutting of materials in various industries; |
| **Area of application (types of rock)** | limestone; sandstone; granite; marble; basalt; slate; flagstone and many more |
| **Performance ($m^2/h$)** | up to 3.5 $m^2/h$ [1] |
| **Costs (€/$m^2$)** | 12.92 – 78.8 €/$m^2$ *[2] |
| **Energy consumption** | Power depends on blade size, from 30kW up to 190 kW [1] |
| **Necessary Equipment** | Diamond blade; Motor; Mechanical guidance system; |

[1] http://www.antraquip.net/, 21.06.2012

[2] http://www.allcostdata.info/browse.html/021124700/Saw-Cutting

*Price listed is for linear foot with depth of 1 inch or 0.00774 $m^2$ with all extra costs. For 1 $m^2$ of cutting only the price for the saw is multiplied by 129.2 and converted in Euro by multiplying by 0.76

Lowest price taken is 0.10 / LF for asphalt sawing (see details).

Highest price taken is 0.61 / LF for rod enforced concrete wall (see details).

## 6.5. Tunnel bore extender

The TBE is a rather unique machine since it was the first of this kind to be put in operation. In its entirety it is about 180 m long and weighs about 1000 tonnes (Figure 56).

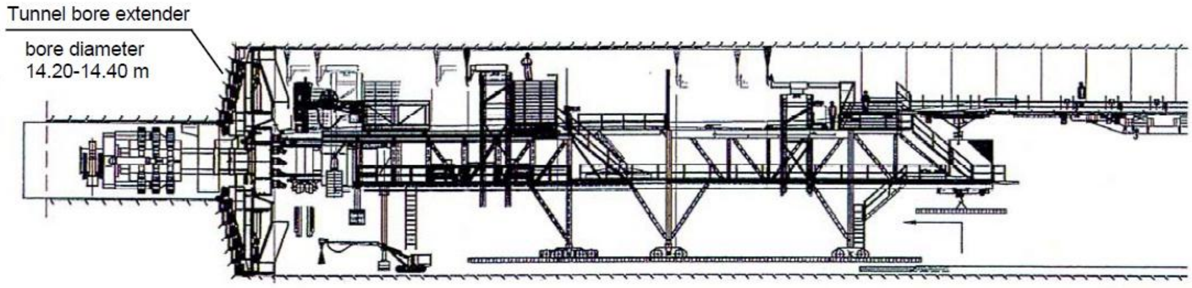


Figure 51 TBE: with bracing arrangement in the pilot tunnel[137]

The unique part of the machine is its boring head. Its design includes a two-piece cutterhead body and six cutter arms (Figure 57)[138].

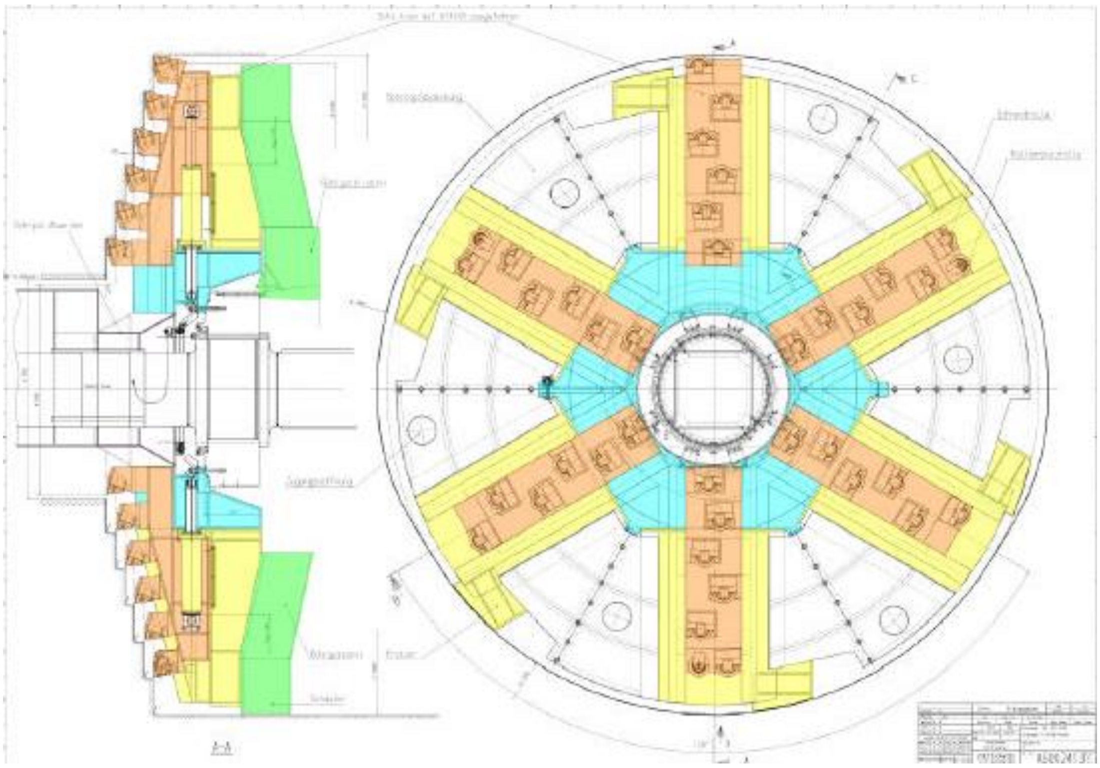

Figure 52 Front view and cross-section of the cutter arms[139]

[137] Amberg Engineering AG: N4.1.5. Uetliberg Tunnel – TBE Information, http://www.uetlibergtunnel.ch/downloads/TBE%20Information%20E-DM.pdf , 11.04.03

[138] See Amberg Engineering AG: N4.1.5. Uetliberg Tunnel – TBE Information, http://www.uetlibergtunnel.ch/downloads/TBE%20Information%20E-DM.pdf , 11.04.03

[139] Amberg Engineering AG: N4.1.5. Uetliberg Tunnel – TBE Information, http://www.uetlibergtunnel.ch/downloads/TBE%20Information%20E-DM.pdf , 11.04.03

The six arms of the main boring head rotate around bracing front part of the TBE along the axis of the pilot tunnel. The undercutting discs are mounted on the cutter arms and are offset in both radial and axial direction from the tunnel axis. The rollers are mounted in groups on slides, which move radially along each arm. The position of each roller and the movement of the individual slides are adjusted to form a spiral pattern. That way each of the outermost cutters leads the rest, forming a stair-step profile on the face area in which every cutter shears away the rock against a free surface using the undercutting principle. Each "step" formed by the cutters depends on the axial displacement of the rollers and has a maximum width of 20 cm. Shorter "steps" are made when the rock is harder. In order to make an advance of the full face the boring head needs to make between eight and ten rotations (Figure 58). This process extends the tunnel's diameter from the original 5 m to the final 14.4 m. During the course of the construction the TBE reached a maximum advance of 16.5 m per day and an average advance of 45-55 m per week. Although that is significantly slower compared to the for-mentioned peak of the pilot TBM, the diameter of the extended tunnel is the crucial factor to be considered. At 14.4 m that was the biggest TBM at the time, 2.4 meters wider than any other available TBM. This was a big part of the decision-making process for the engineers responsible for the project's execution. There were also other reasons why this particular method was selected[140].

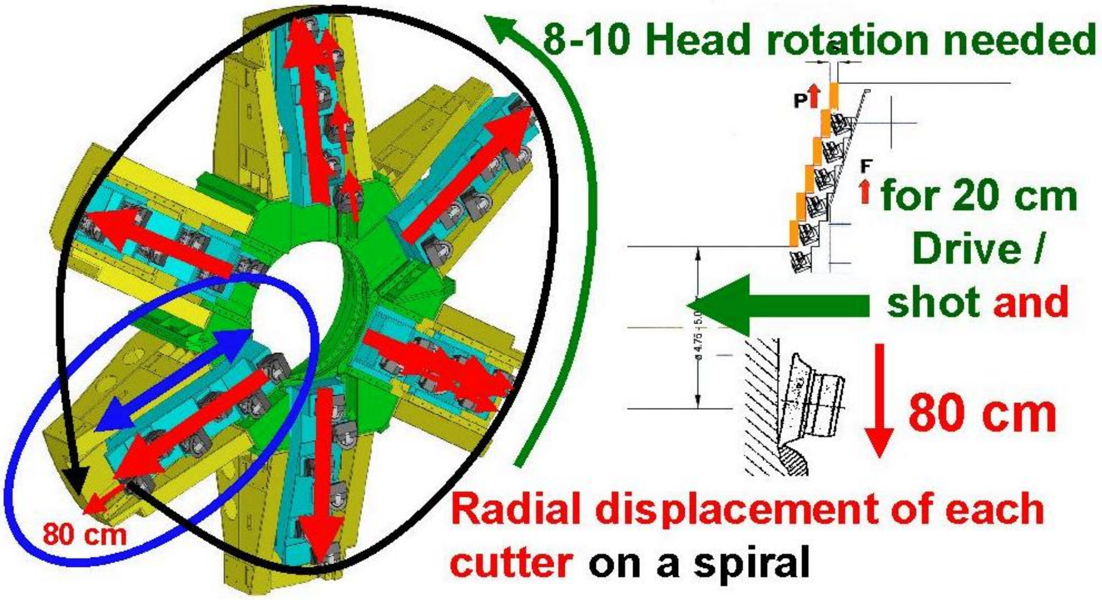


Figure 53 Operating principle of the boring head[141]

[140] See Amberg Engineering AG: N4.1.5. Uetliberg Tunnel – TBE Information, http://www.uetlibergtunnel.ch/downloads/TBE%20Information%20E-DM.pdf , 11.04.03

[141] Amberg Engineering AG: N4.1.5. Uetliberg Tunnel – TBE Information,

### 6.5.1. Advantages and disadvantages of the TBE with undercutting discs

During the exploitation period of the TBE it became apparent that its advantages are more than designer's calculations and hypotheses. Naturally, as with every method, there were some disadvantages as well. However, they were far fewer which meant the undercutting technique has a great foundation for future improvements and wider implementation for underground construction. The most notable examples of the two categories are listed below[142]:

Advantages:

- Weaker forces acting on the TBM parts, which mean lower exploitation and maintenance costs;
- Lower energy consumption for rock breaking;
- Shorter construction of the bore head, which allows the rock surface to be secured faster and closer to the face and makes the tunnel safer for the construction workers.
- The face profile can be inspected because there is space between the extender's arms.
- Optimizes rock breaking adapting the cutter's movement to the desired profile, thus lowering excavation costs.
- The face can be secured between the arms while the machine is stopped;
- Lower amount of dust particles produced when undercutting compared to crushing;
- Easier rock breaking around the pilot tunnel because the breaking force isn't parallel to the pilot tunnel axis;

Disadvantages:

- The overall advance speed is limited by the classic securing measures;
- The size of the rock debris depends from the rock structure;
- The cutting discs can be changed only in front of the cutting arms where the rock isn't secured;
- The shield doesn't provide protection for the workers before the securing of the surface[143];

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http://www.uetlibergtunnel.ch/downloads/TBE%20Information%20E-DM.pdf , 11.04.03
[142] See BOLLINGER, Josef: Auswetings-TBE mit Hinterscheindtechnik, http://www.uetlibergtunnel.ch/downloads/Vortrag-Bolliger-HSt.pdf , 22.02.02
[143] See BOLLINGER, Josef: Auswetings-TBE mit Hinterscheindtechnik,

### 6.5.2. Evaluation

The TBE with undercutting discs proves that there is much potential for improvements in terms of rock removal technology. Using a different approach this new type of machine provides great performance at reasonable costs and most importantly – for large scale works. Larger scale not only in terms of tunnel length, but also in diameter of the cross-section.

http://www.uetlibergtunnel.ch/downloads/Vortrag-Bolliger-HSt.pdf , 22.02.02

# Fact sheet 6.5.

| | |
|---|---|
| **Name of the method** | TBE with undercutting discs |
| **Year of origin** | 2002 first use for tunnel construction |
| **Tests conducted** | Exploitation of machines using the undercutting principle on other projects |
| **Area of application (types of rock)** | Molasse |
| **Performance ($m^3$/h)** | around 110 $m^3$/h [1] |
| **Costs (€/$m^3$)** | N/A |
| **Energy consumption** | 1500 kW [2] |
| **Necessary Equipment** | TBM with TBE attachment |

[1] Average progress of 16.5 m per day times the surface of the face - 160 $m^2$ divided by 24 hours, BOLLINGER, Josef: Auswetings-TBE mit Hinterscheindtechnik, http://www.uetlibergtunnel.ch/downloads/Vortrag-Bolliger-HSt.pdf , 22.02.02

[2] BOLLINGER, Josef: Auswetings-TBE mit Hinterscheindtechnik, http://www.uetlibergtunnel.ch/downloads/Vortrag-Bolliger-HSt.pdf , 22.02.02

## 6.6. Subterrene

During the 1970's a group of inventors working at the Los Alamos National Laboratory for the United States Atomic Energy Commission has filed several patents for underground tunneling equipment that relies on rock melting. One of these patents: № 3,693,731 from September 26, 1972 is for "Method and apparatus for tunneling by melting" and its abstract states:

"*A machine and method for drilling bore holes and tunnels by melting in which housing is provided for supporting a heat source and a heated end portion in which the necessary melting heat is delivered to the walls of the end portion at a rate sufficient to melt rock and during operation of which the molten material may be disposed adjacent the boring zone in cracks in the rock and as a vitreous wall lining of the tunnel so formed. The heat source can be electrical or nuclear but for deep drilling is preferably a nuclear reactor*"[144] - United States Patent № 3,693,731 Sept. 26, 1972

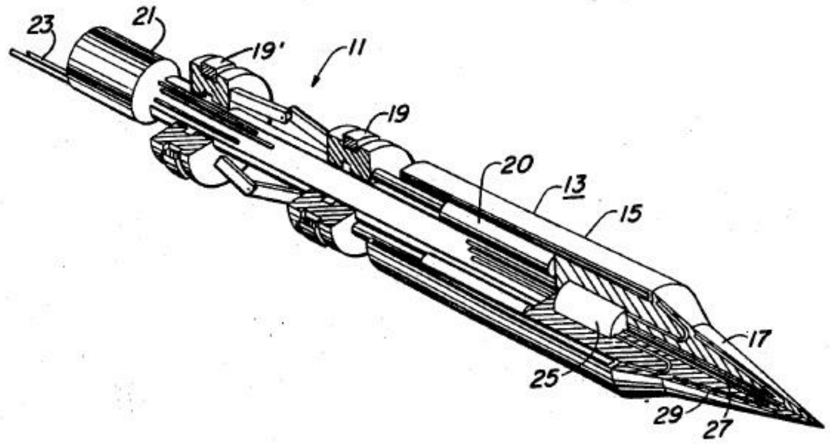



Figure 54 A drawing showing the main structure parts of the patented machine[145]

This machine, commonly known as a "Subterrene", melts the rock instead of crushing it and forces the molten mass around its body where it cools down and forms a solid glass lining around the tunnels perimeter.

[144] ARMSTRONG, McINTEER, MILLS: Method and apparatus for tunneling my melting, http://www.boomslanger.com/images/us3693731a1.pdf , 26.09.72
[145] ARMSTRONG, McINTEER, MILLS: Method and apparatus for tunneling my melting, http://www.boomslanger.com/images/us3693731a1.pdf , 26.09.72

The heat for the melting process is supplied either by a compact nuclear reactor within the machine or using electricity from another source outside from the tunnel delivered to the machine.

### 6.6.1. Laboratory tests and results

Laboratory tests showed that lithium is an appropriate working liquid for the heat exchange. The lithium is circulated through a system of heat pipes, it is heated to about 1300 °C and pumped to the tip of the penetrator and then along the exterior of the machine. As the heat melts the rock around the machine, the lithium is cooled and it circulates back to the reactor/heat source where it is reheated and the process starts over.
According to the patent, the machine using the heat pipe melting technique is easily capable of reaching tunneling speed of about a 100 m per day. This would be significantly faster than modern TBMs 40 years later.
The Subterrene's biggest advantage, besides the speed, is that unlike its rock-crushing counterparts it leaves no excess rock material that must be disposed of during the construction. This not only makes the whole process a lot simpler. With increasing lengths and diameters of modern tunnels the debris become a serious problem. They not only have to be removed from the tunnel, but in some cases have to be further transported to a depot location, which adds even more to the costs. The way this problem is solved with the Subterrene is as stated in the patent:

"... *(D)ebris may be disposed of as melted rock both as a lining for the hole and as a dispersal in cracks produced in the surrounding rock. The rock-melting drill is of a shape and is propelled under sufficient pressure to produce and extend cracks in solid rock radially around the bore by means of hydrostatic pressure developed in the molten rock ahead of the advancing rock drill penetrator. All melt not used in glass-lining the bore is forced into the cracks where it freezes and remains (...) Such a (vitreous) lining eliminates, in most cases, the expensive and cumbersome problem of debris elimination and at the same time achieves the advantage of a casing type of bore hole liner*."[146]
The patent also explains in detail the process of crack forming which is a combination of the thermal stress induced on the rocks by the heaters and the hydraulic pressure from the molten mass forced radially by penetrator. The cracks extend in all directions around the machine and simultaneously filled with molten rock, which then solidifies. The solid lining

[146] ARMSTRONG, McINTEER, MILLS: Method and apparatus for tunneling my melting, http://www.boomslanger.com/images/us3693731a1.pdf , 26.09.72

around the tunnel is connected naturally with the material in the cracks and as a whole resembles the securing structure of modern tunnels using anchors and sprayed concrete. According to the scientist, the glass lining left behind the machine has enough structural integrity to be used for initial securing of the tunnel but for exploitation a stronger lining must be constructed.

In 1973 the Los Alamos National Laboratory released with the title "Systems and Cost Analysis for a Nuclear Subterrene Tunneling Machine: A Preliminary Study" which revealed that the nuclear subterrene tunneling machines (NSTMs) are more cost effective than the existing TBMs. According to the study the costs between the two methods are close if the conditions are favorable for the TBMs operation. In any other conditions the NSTMs are proven to be more effective by a large margin.

Two years later, in 1975 the National Science Foundation released its analysis of the NSTMs cost effectiveness. The analysis was done by the A.A. Mathews Construction and Engineering Company of Rockville, Maryland and consisted of two parts with combined volume of over 500 pages[147].

In the report the costs for three different tunnel diameters were compared:

a) 3.05 meters
b) 4.73 meters
c) 6.25 meters

Again, the comparison was done between the mechanical TBMs and the NSTMs. The conclusion of the A.A. Mathews' analysis was the following:

For the smallest, 3.05 meters tunnel, the mechanical TBM was 30 percent more effective. However, for the 4.73 and 6.25 meter tunnels the advantage was in favor of the NSTM with savings of 12 and 6 percent respectively. The explanation for these results is that the NSTM method is more capital than labor intensive system and the fact that, as mentioned above, the initial support for the tunnel is completed during the excavation process. This leads to another advantage of the NSTMs. Due to their design, they can operate with very little or none at all human supervision on site, and can be navigated and operated from a command center outside of the tunnel. This is convenient especially for longer tunnels, which are what the NSTMs were designed to construct.[148]

In another study by the Los Alamos laboratory made for the application of this method for drilling and exploration on the moon it is stated:

[147] See ROWLEY, J.; NEUDECKER, J.: In Situ Rock Melting Applied to Lunar Base Construction and for Exploration Drilling and Coring on the Moon,http://adsabs.harvard.edu/full/1985lbsa.conf..465R , 03.07.2012

[148] ROWLEY, J.; NEUDECKER, J.: In Situ Rock Melting Applied to Lunar Base Construction and for Exploration Drilling and Coring on the Moon, http://adsabs.harvard.edu/full/1985lbsa.conf..465R , 03.07.2012

"*The most basic conclusions reached from the laboratory research efforts were these. (1) Formed-in-place glass linings could be practically formed through proper handling, forming, and thermal processing (chilling) of the soil and rock melts (Lundberg, 1975; Stanton, 1974), and because these methods applied to all soils and rocks tested, a single Penetrator design could be effectively used for virtually all natural terrestrial materials. (2) The melting process is quite insensitive to rapid variations in rock or soil types, void space, water content, or competence of the rocks or soils, and it is especially effective in Consolidating "mixed ground' (i.e., gravels or soils with rocks and cobbles). (3) A very uniform and precisely dimensioned borehole could be produced. (4) A high-temperature electric heater technology was perfected that used efficient low-voltage direct current resistance heaters (Armstrong, 1974; Krupka, 1972; Stark and Krupka, 1973). (5) Heat losses to the surrounding rocks or soils were low and predictable (Murphy and Gido, 1973; Cort, 1973; McFarland, 1974). (6) Low mass loss from the refractory metal penetrator would lead to long equipment life (Stark and Krupka, 1975). Lastly, (7) materials, design methods, fabrication techniques, and analytical procedures were available to systematically construct and predict penetrator performance that scaled with size*."[149]

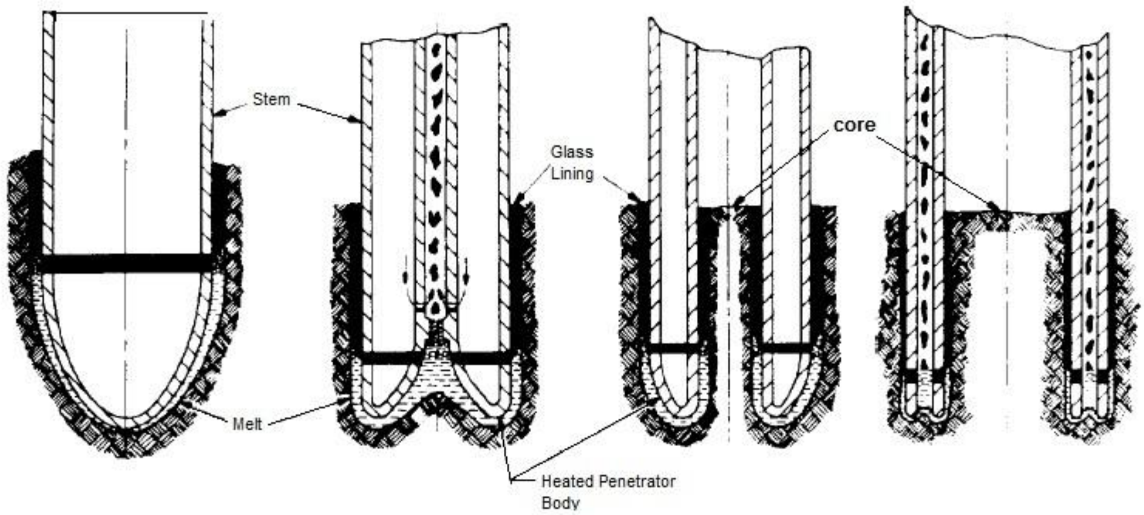

Figure 55 Typical glass-lined hole: Cross section of glass-lined hole (51-mm-diameter) melted in tuff rock[150]

The versatility is a function of both shape of the tunnel and specific mechanics of the melting process that different Subterrenes provide, as explained below:

[149] ROWLEY, J.; NEUDECKER, J.: In Situ Rock Melting Applied to Lunar Base Construction and for Exploration Drilling and Coring on the Moon,http://adsabs.harvard.edu/full/1985lbsa.conf..465R , 03.07.2012
[150] ROWLEY, J.; NEUDECKER, J.: In Situ Rock Melting Applied to Lunar Base Construction and for Exploration Drilling and Coring on the Moon,http://adsabs.harvard.edu/full/1985lbsa.conf..465R , 03.07.2012

"*The subterrene project included a wide range of penetrator configurations (Figure. 61*[151]*). The depicted shapes include nearly all concepts of hole making by melting. Figure. 61a illustrates a "consolidating" penetrator used in higher porosity materials all the rock melted during formation of the hole will be densified, forming the glass lining. No debris removal is required. An alternate configuration for a melting penetrator, shown in Figure 61b, is termed an "extruder" , Pass-through port(s) allow the melt to flow back through the penetrator head into a device that chills the melt and forms "debris" (or "cuttings" or "muck," depending upon whether drilling or tunneling are considered). These solids can easily be formed as glass pellets, rods, or a glass woollike material . The core-consolidating mode of operation is shown in Figure. 61c, and cores with a glass encasement are possible (Murphy et al., 1976). The final configuration in Figure 61d was not fabricated, but the knowledge and methods are all in hand to design and construct a kerf melting, coring extruding penetrator. This configuration might be the conceptual design for a large size tunneler. The cross section of the hole (tunnel) could be any (non-circular) geometry*."[152]

The custom geometry of the cross-section further increases the method's cost effectiveness by optimizing the usable are of the tunnel and also ensuring the best shape for structural integrity. The study also suggest that larger tunnels can be constructed using this principle without a drastic increase of the costs due to the large variation of suitable designs.




a) b) c) d)

Figure 56 Schematic cross sections of different rock melting penetrators. a) Consolidation of porous rock and soils no debris produced. b) Extruding of glass fiber or pellets to remove

[151] "Fig. 2." in the original text was replaced with "Figure 61" for the purposes of this paper

[152] ROWLEY, J.; NEUDECKER, J.: In Situ Rock Melting Applied to Lunar Base Construction and for Exploration Drilling and Coring on the Moon,http://adsabs.harvard.edu/full/1985lbsa.conf..465R , 03.07.2012

material in more dense materials c) A coring-consolidating configuration with glass-lined hole and core. d) An extruding-coring combination mode of hole formation[153]

### 6.6.2. Evaluation

Although the Subterrene has advantages, as mentioned above, there are two major problems with it. The first one, obviously, is the fact that there is no proof for the existence of this type of machine.

Despite not proven in practice, the laboratory tests conducted clearly show that rock melting is not only a possible solution for rock removal but that it can theoretically be more practical and cheaper than classical methods.

[153] ROWLEY, J.; NEUDECKER, J.: In Situ Rock Melting Applied to Lunar Base Construction and for Exploration Drilling and Coring on the Moon,http://adsabs.harvard.edu/full/1985lbsa.conf..465R , 03.07.2012

## 7. Conclusion

Rock removal is an important process for many different industries and during the years each of them has developed the equipment that suits their needs in the best way possible. These technologies are in a constant improvement process and each of them benefits from the innovations of other fields – computer sciences, hydraulics, chemistry etc.

In the last decade there has been a tremendous improvement in almost all forms of rock removal - performance has increased - safety has been improved - costs have been reduced. Technology has enabled engineers to develop new machines that would not have existed before like precise water jet machining. The global need for more resources, cheaper construction materials and shorter transportation routes pushes everyone involved in the field to search for better solutions for their problems. That may include improvements in their existing methods or investing in the research of new, alternative technologies enabled by the 21$^{st}$ century.

Rock removal at present is an essential part of the modern world, and the fact that the demand for its products is a lot higher than the supply ensures a steady progress.

The methods examined in this paper are the proof of this statement. No matter what disadvantages they have or the purposes they are used for, every method shows a significant improvement over the past few years. Equipment manufacturers are constantly working on the next versions of their products that will improve the good qualities and reduce the negative ones. And although most of them are not used for infrastructure construction today, their future successors will most likely find their niche in tunneling.

| **Name of the method** | **Area of application (types of rock)** | **Performance** | **Cost** | **Energy consumption** |
|---|---|---|---|---|
| Water jet cutting | limestone; sandstone; granite; marble | ≈ 30 $m^2$/h | ≈ 12 €/h => 0.40 €/$m^2$ | ≈ 22-35 kW |
| Disc cutting | limestone; sandstone; | ≈ 4.89 $m^3$/h | ≈ 86-126 €/$m^3$ | 300-700 kW |
| Wire cutting | all types of solid rock | ≈ 1-4 m/h | ≈ 7.2 €/$m^2$ | ≈55kW |
| Circular saw cutting | limestone; sandstone; granite; marble; and more | up to 3.5 $m^2$/h | ≈ 12.92 – 78.8 €/$m^2$ | 30kW - 190 kW |
| TBE with undercutting discs | molasse | ≈ 110 $m^3$/h | N/A | 1500 kW |

Comparison of some of the parameters of the reviewed rock removal methods.

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