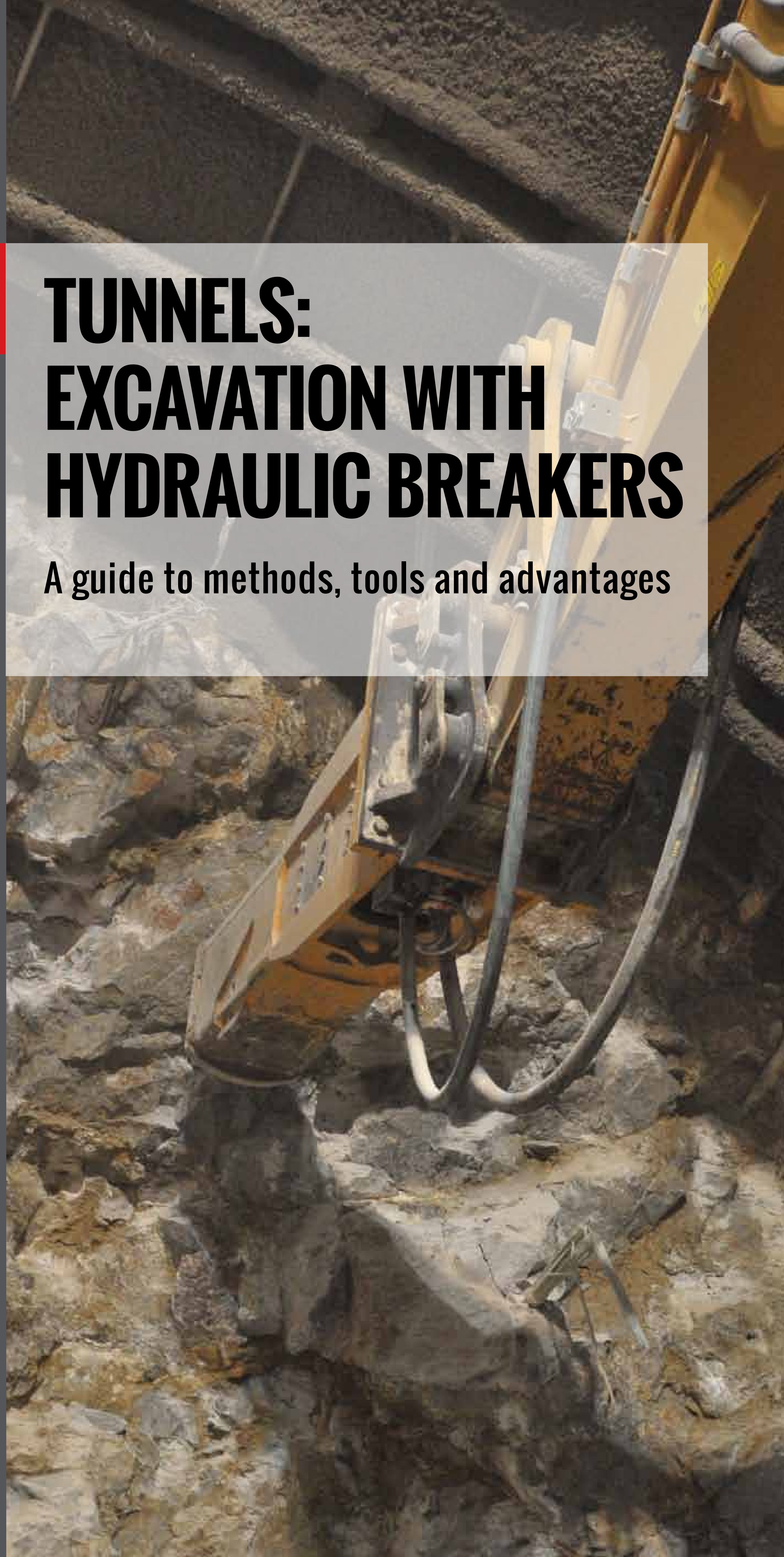
FOCUS ON

TUNNELS: EXCAVATION WITH HYDRAULIC BREAKERS

A guide to methods, tools and advantages



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A guide to methods, tools and advantages

FOCUS ON
is a series of technical publications by Indeco Ind. Spa

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OUR EXPERIENCE USING BREAKERS FOR TUNNEL EXCAVATION

For a long time we had been contemplating the idea of organizing, condensing and sharing Indeco's experience in the industry over a period of almost two decades in the form of reference guides. Companies, in their pursuit of goals, seldom find the time for a structured analysis of the knowledge acquired from the daily use of their products on the field in applications such as excavation, demolition and recycling, construction and earthmoving, specific applications like trenching, or primary and secondary demolition in quarries and mines, and tunnelling.

This prompted the idea of devoting handbooks or guides to the specific sectors where our equipment is used which would serve as tools for industry professionals, including principals, engineers, contractors or site managers.

The spark, or the "casus belli", that elicited, particularly in me, the motivation to realize our idea and draft this publication came about during an annual meeting of the CECE (Committee for European Construction Equipment) in Berlin a few years ago. During the meeting, coinciding with a global crisis in the industry, the audience of anxious managers and equipment makers heard several talks, one a rather overstated, self-referential presentation by a German company, leader in the production of tunnel boring machines (TBM), praising the utilization and performance of these machines around the world.

While nothing could be said about the speaker's remarks, much could be called into question, especially from a technical standpoint, regarding the idea that full-face tunnel boring machines are always the most efficient system for tunnelling.

That concept, expressed in such absolute terms, clashed with the reality of the many tunnels that Indeco has helped to excavate thanks to a reliable and effective technology refined over years of constant investment in research and technology.

Italy, after all, owing to its territory and complex geological formations, claims many civil engineering companies recognized internationally for their tunnelling expertise. It is no coincidence that our engineers and technicians have had to face challenges rarely encountered in other countries, and that they have often met them by adopting new solutions, such as the hydraulic breaker for tunnel excavation. This is a method that can be implemented thanks also to the development of new systems of reinforcement in problematical rock masses and is today "exported" around the world.

What's more, all this came about despite the limitations and risks associated with the drill-and-blast method used for tunnel excavation, which continued to represent a necessary and advantageous option. Our experience on the market, which has embraced the entire globe for the past several decades, has taught us that in many countries there lacks a full grasp of the experience, techniques of execution, design decisions, economic advantages and the "flexibility" afforded by tunnel excavation using hydraulic breakers as either an alternative or complement to blasting.

In no other activity in the construction industry like tunnelling do the uncertainty, the unexpected and the "clash" with nature demand a flexible approach, now more than ever. This is even more important in light of the many problems (even as we prepare for the publication of this guide) that have been associated with the nearly "devout" use of the TBM over the years, difficulties incomparable to the successes in numerical terms no doubt, yet of consequence when it comes to work delays and the economic impact on project costs.

More evident, however, is that the risk of an incorrect geognostic evaluation or one that corresponds only in part to reality is so great that it may nullify, in itinere, infrastructure projects of enormous scope. The idea of elevating a single system of excavation and advancement as the best in all cases is not only intrinsically mistaken, but could even seem ludicrous.

Later in this guide we will illustrate the most frequent variables that can influence the choice of one excavation method over another to construct tunnels. Essentially, our view is that when conditions of uncertainty exist, only a "flexible" approach, such as that offered by the breaker (in certain cases in combination with blasting) enables a solution through the implementation of "Plan B".

In conclusion, I would like to announce that this is the first of a series of publications devoted to specific sectors and fields of applications for the hydraulic breaker, including the quarrying of aggregates and primary and secondary volume reduction, special demolition and demolition of structures in different materials using hydraulic breakers and silent demolition tools, and so on. The series does not claim to be a compendium of exhaustive studies, but rather a compilation of solutions based on techniques and experiences consolidated over time and, where possible, on the development of new approaches to a range of problems. Our project will be a work in progress that takes full advantage of multimedia tools and the internet, enabling us to update the guides on a continuing basis with examples, case studies, job reports and other contributions to make these publications a working tool for users of our breakers, as well as those who are not yet customers.

This general concept is fully reflected in this first publication, which intends neither to be a comprehensive discussion of excavation methods, nor has the pretence of being epoch-making innovation; rather it seeks to be guide that prompts thought and provides direction. That said, what this publication definitely sets out to be is a recognition of the hydraulic breaker as a product, of the contractors who have long used this equipment to excavate tunnels around the world, of the criteria of cost-effectiveness, efficiency and flexibility of this technique, as well as the constant efforts that Indeco has made over the years in an effort to meet the needs of their customers around the world.

Michele Vitulano
Marketing and Commercial Manager
Indeco Ind. SpA

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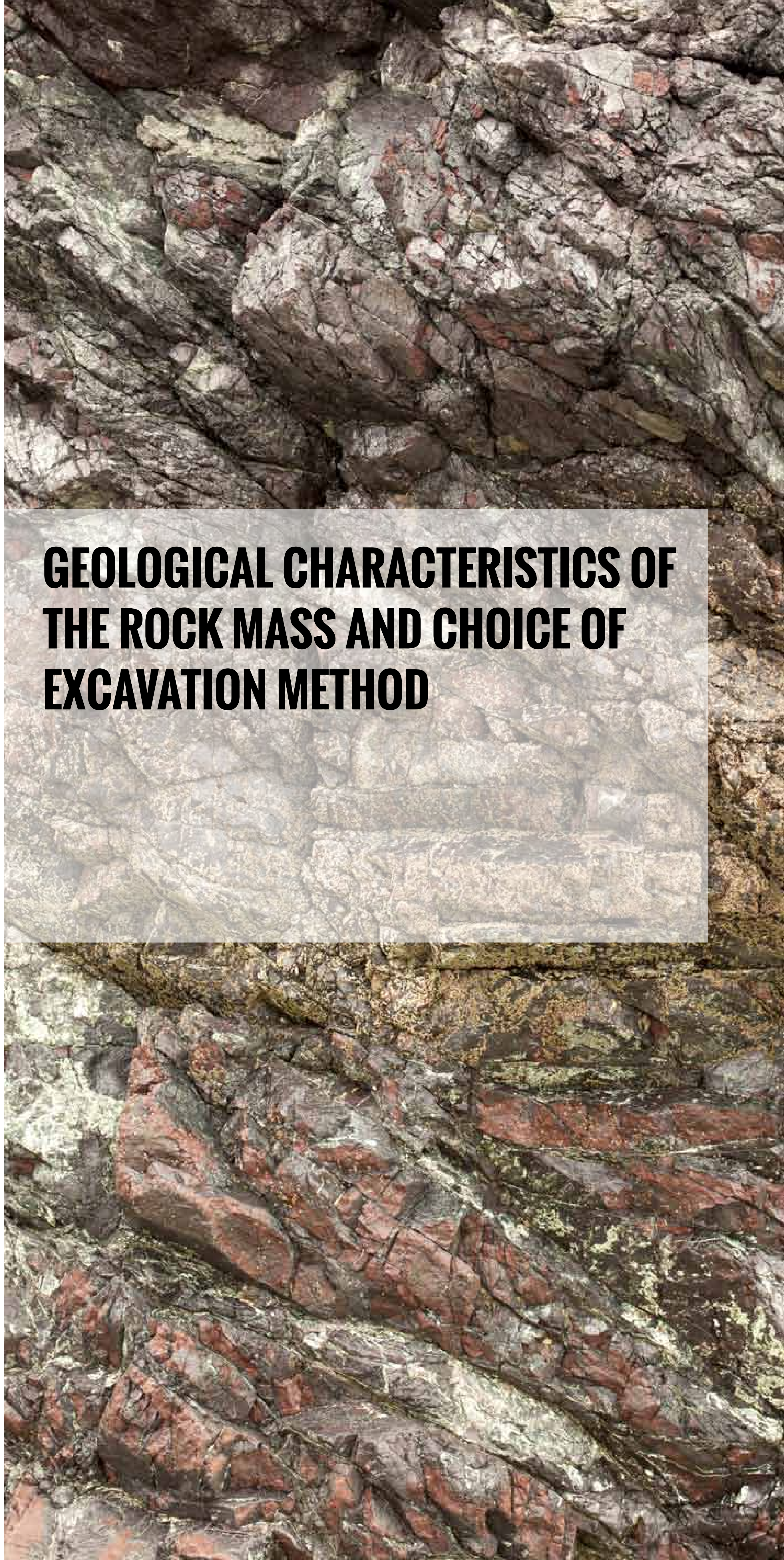
FOCUS ON

- Introduction
- The geomechanical model and its importance in the choice of excavation method
- The importance of RQD
- The choice of excavation method



GEOLOGICAL CHARACTERISTICS OF THE ROCK MASS AND CHOICE OF EXCAVATION METHOD

GEOLOGICAL CHARACTERISTICS OF THE ROCK MASS AND CHOICE OF EXCAVATION METHOD

Introduction


(Rinina25 & Twice25_CC BY-SA)

From a construction standpoint, tunnels are undeniably among the most complex works to execute due to the intrinsic risks imposed by the geology (in certain conditions recognized in tunnelling specifications under the heading "geological uncertainty") and the logistical difficulties related to excavation, reinforcement and muck removal.

So it is not unusual that tunnels are almost always longer and more costly to build compared to other projects to construct road and railways. Right from the project design phase the construction of these underground works places principals, engineers and contractors before choices that, if not corresponding with the actual conditions verified in situ, can lead to delays, heavy economic losses and in the worst cases hazards for the operators working on the construction site.

The route and its geology, the final design, the geometry of the various type sections, the geographic conditions, as well as conditions of accessibility to the site are basic factors for the contractor, who must define and estimate a priori the requirements in order to execute the project. Nevertheless, the factors of greatest significance, that is, those that play a pivotal role in the success of the construction site and the profitability, are clearly the correctness and reliability of data provided by the geognostic surveys. If, during project execution there is, as often occurs, a total or partial deviation of the geomechanical behaviour of the rock masses versus what is presumed, this has inevitable consequences, in some cases severe, on the progression of the works, especially as concerns the efficacy and productivity of pre-selected systems of excavation and reinforcement.


Collapse at Ganzhou, eastern China (www.xinhuanet.com)

Indeed, this is a condition that encapsulates the difficulties and risks associated with the construction of tunnels, but that in part can be responded to by adopting excavation and reinforcement systems that allow a rapid, less onerous way of adapting to the altering characteristics of the rock mass.

THE GEOMECHANICAL MODEL AND ITS IMPORTANCE IN THE CHOICE OF EXCAVATION METHOD

As mentioned, in an operating framework that strictly depends on the geomechanical characteristics of the rock masses to be traversed, the geognostic survey is obviously essential to estimating working conditions and the actual production. However, it must be made clear that the data resulting from the surveys, presuming they accurately reflect or acceptably approximate the real situation, are not aimed, at least not initially, at establishing the excavation methods.

The characterization of the model, and thus of the various types of rock mass, provided by the various geognostic surveys that result in the definition of RMR, RQD, RMC, GSI etc. is necessary in order to define:

1) The geomechanical characteristics of the various rock masses and their stress state
2) Underground hydrogeological structure and verification of the presence of gas
3) The geological-structural characteristics that may have an impact on the distribution of the stresses around the tunnel, during and after the excavation of the rock mass

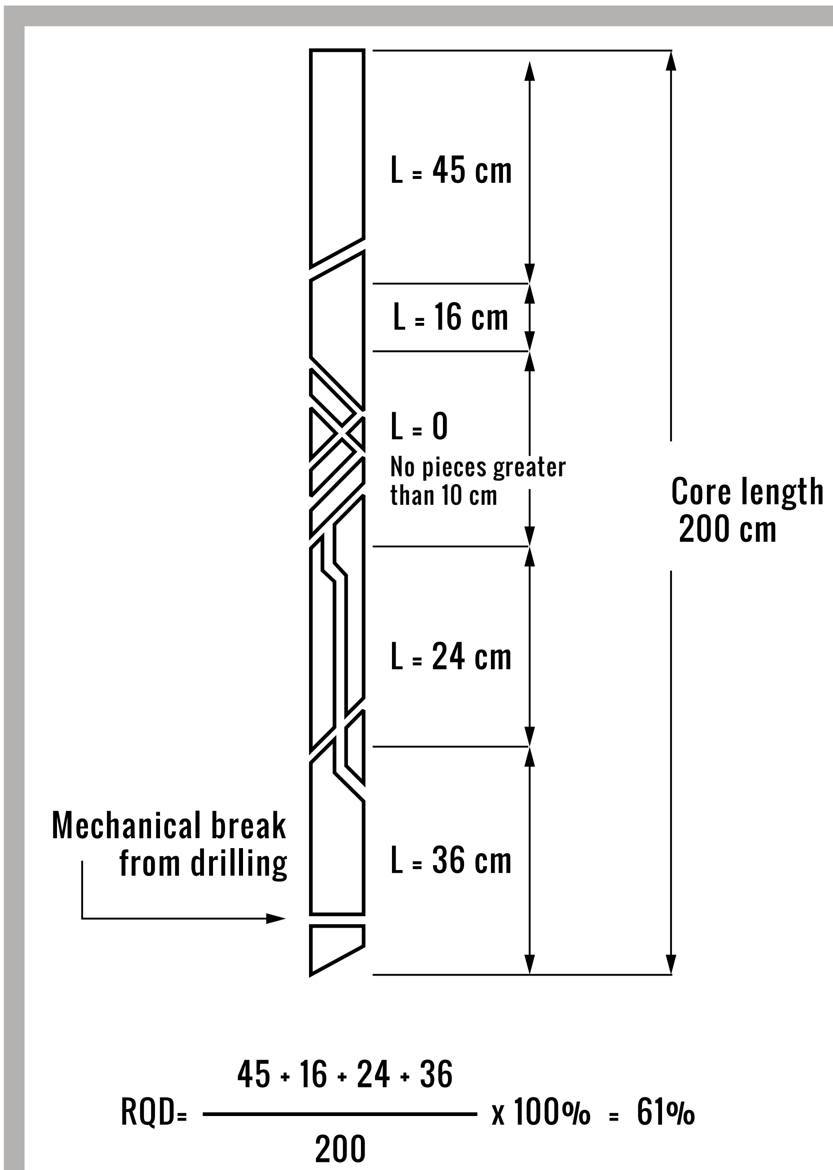
Geognostic surveys do not have as their primary goal to emphasize the best excavation method (which is a result of their conclusions), but rather to define with precision the conditions of rock masses for the purposes of the project and especially to identify the most efficient method of reinforcement to utilize during advancement.

Among the evaluation methods utilized and commonly included on geomechanical models used on the construction site, there are the quantitative and qualitative criteria articulated by Beniawski in 1974 and condensed in the RMR (Rock Mass Rating) values, and the qualitative criteria resulting from the studies by Ladislaus Von Rabcewicz and Franz Pacher between 1957 and 1965 in Austria that produced the NATM (New Austrian Tunnelling Method).

An important contribution to the evaluation for the qualitative method was also provided by the Q-system developed by Barton, Liene, and Lunde from the Norwegian Geotechnical Institute in 1974. Basing itself on the evaluation of data of over 200 tunnels, the Q-system takes into consideration different parameters (RQD, level of alteration, number of joints, roughness of the surface, discontinuities, degree of alteration of the discontinuities, presence of water and the stress reduction factor) that can determine a factor that represents the structure of the rock mass and size of the blocks, the shear strength that they develop and the condition of stress in the rock mass.

THE IMPORTANCE OF RQD

RQD or Rock Quality Designation was developed in 1964 by D.U Deere specifically for tunnel excavation and is a parameter that was incorporated into other rock quality rating systems such as RMR by Beniawski and the Q-system



Core sample for calculating RQD

by Barton. The index is based on the percentage evaluation of fragments longer than 10 cm taken from every borehole and thus provides a general indication of the degree of fracturing of the rock mass. The RQD classification is expressed in a percentage from 0 to 100% and is highly important for indicating the quality of the rock masses, especially if the quality is low. Taken alone, it is not sufficient to fully define all geomechanical aspects of the rock mass as do the most complex parameters provided by Beniawski (of which the RQD values are only an element) or by the NATM, but it is undoubtedly an immediate criterion of evaluation for sole purposes of the excavation and can therefore orient the choice for the most efficient method. The higher the value of RQD (in percentage), the more the rock mass will be considered compact and with low fracturing; on the contrary, the high number of "small" core sample segments indicate heavy fracturing of the rock mass.

The **Beniawski classification (RMR or Rock Mass Rating)** basically considers and assigns values to:

1) Uniaxial compressive strength
2) Rock Quality Designation Index (RQD)
3) Spacing of discontinuities
4) Conditions of discontinuities
5) Hydraulic conditions
6) Orientation of discontinuities

When utilizing the RMR values to determine the excavation method (and specifically the use of the breaker) attention must be paid to the values that indicate discontinuities (fracturing) and the characteristic strength expressed in MPa.

Discontinuity is an important value since it is always an indication of fracturing and "weakness" of the rock mass, consequently which has inferior characteristics (i.e., strength and deformability) compared to the integral rock mass

and such to modify its mechanical behaviour. An analysis of the discontinuities and their characteristic parameters permits an evaluation of the state of fracture of the rock mass and definition of the rock mass classification.
The classes articulated by Beniawski are accompanied by values from 0-100 that also consider the strength in MPa of the rock (always indicated separately in the geomechanical model).
Typically the values assigned to the rock mass and the relative classes are:

RMR (Rock Mass Rating)

Class I	RMR 81-100	Very Good
Class II	RMR 61 - 80	Good
Class III	RMR 41 - 60	Fair
Class IV	RMR 21 - 40	Poor
Class V	RMR < 20	Very Poor

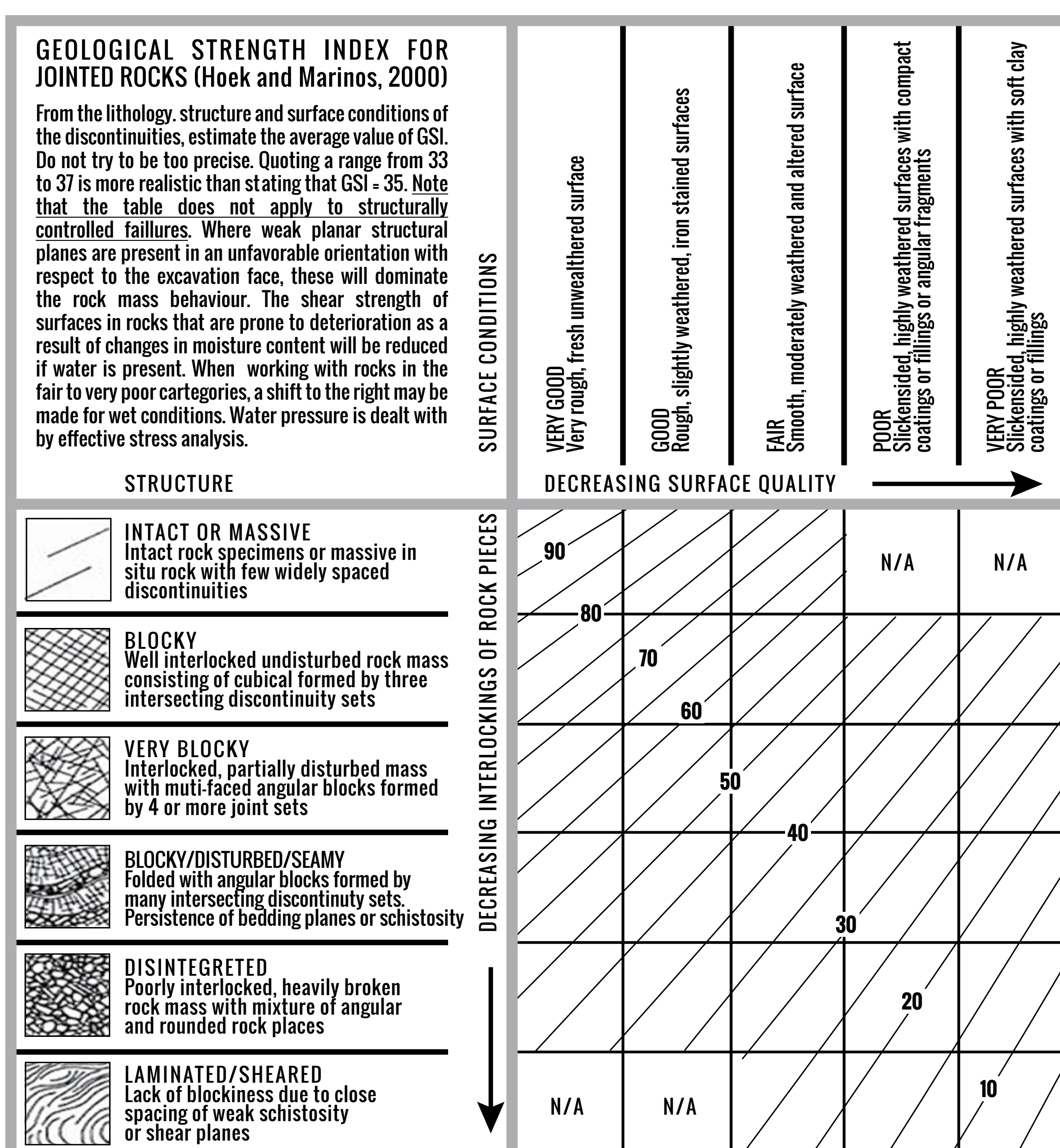
The New Austrian Tunnelling Method (NATM) aims instead to determine the self-standing capacity of the rock mass by means of the control and redistribution of the stresses in the ring. Based on the data, the method indicates the type of reinforcement works that must make up for an insufficient self-standing capacity. Basic principle of the NATM is that the systems to support and reinforce the terrain depend on the measurement of the deformations, and must be constantly adapted to the conditions verified during advancement. To determine the type of rock mass and its self-standing capacity, NATM utilizes the following classes and descriptions:

Class I self-supporting
Non-fractured, massive rock: the excavation is self-supporting and the stresses around the excavation do not exceed the strength of the rock; this allows for a full face excavation with stand-up times of several days in the roof and of unlimited duration at side walls.
Class II slightly fractured
Stratified, slightly fractured rock: possible fall-outs in roof making support works necessary; side walls are stable (excepting local fall-outs) with stand-up times of days in the roof and weeks at side walls; full-face excavation is possible.
Class III fractured and Class III B highly fractured
Rocks from fractured to very fractured, limited squeezing: the limit of strength is reached at side walls and exceeded in the roof resulting in fall-outs; full-face excavation is possible, but with forepoling systems that guarantee the stability of the face.
Class IV squeezing
Altered, schistose, faulted rock: the strength of the rock is exceeded around the whole excavation; special reinforcement works required, i.e., invert and intensive support (forepoles) of excavation face.

Class Va highly squeezing	
Very altered rock completely crushed and sheared (the opening of the excavation sets off strong pressures in all directions; the ring is completely plasticized and in its deformation tends to restrict the section excavated). No stand-up time in roof and a few hours at side walls and face.	
Class Vb loose material	
(loose, unstable soils): excavation cannot be performed by conventional methods and is regulated according to support methods with practically zero stand-up time.	

As for reinforcement works, they vary not only in relation to the class, but also to the position (roof, face and invert). Like the Beniawski classes, those of the NATM indirectly offer important elements for identifying the excavation method, especially concerning the degree of fracturing of the rock and the relative class.

A more recently developed index is the GSI (Geological Strength Index by Hoek, Kaiser and Bawden et al., 1995). Starting with the estimate of the uniaxial compressive strength of the intact rock, the GSI integrates the evaluation of the geomechanical characteristics of the rock mass with those relative to the characteristics of discontinuities.



General diagram to estimate GSI starting from geological observations.

Source: Marinos V., Marinos P., Hoek E.; The geological strength index: applications and limitations; Bell Eng Geol Environ; 2005

THE CHOICE OF EXCAVATION METHOD

The choice of excavation method, while depending on geomechanical considerations (expressed by RMR, RQD, GSI, etc.) appropriately interpreted, also involves logistical and economic evaluations, which have a particular bearing on the profitability of the construction site and adherence to completion times imposed by the principal. Selecting the best excavation method encompasses different factors (purpose of the AHP method described in the next chapter). Its definition results not only from the analysis of the geomechanical models, essential to understanding the actual difficulties of advancement (intended as the cycle of excavation, mucking and reinforcement), but also from evaluations of productivity and profitability that take into account the number of workers, number of machines and equipment, accessibility to the construction site, environmental restraints, etc.
It should be emphasized that when we talk about excavation, we are referring to full-face excavation. Although in some countries excavations are still occasionally partialized, today tunnels are almost always excavated in the full section. A broader application of the principles of the NATM method, the use of a combination of first-stage support systems (ribs, shotcrete, dowels, etc.), techniques to reinforce the face to avoid extrusion according to the ADECO RS method (Analysis of Controlled Deformation in Rocks and Soil developed by Lunardi), and the widespread use of the TBM, have in fact made partialized excavation practically obsolete and applicable to very special cases.
Today two methods are commonly used for full-face excavation:

a) The “traditional” system (blasting and hydraulic breaker for scaling and excavation of the invert)
b) The mechanized system (TBM, roadheader and hydraulic breaker)

The goal of this guide is to highlight the advantages that, under certain conditions, are gained by mechanized excavation with the hydraulic breaker as opposed to the traditional method of blasting.
In this analysis, we deliberately do not make reference to the roadheader (rarely utilized as the single excavation method to perform tunnelling) and only in part (i.e., only in part during evaluation of the AHP method proposed in the next chapter) to the TBM. It is necessary to point out that where there exist geomechanical, design, logistical and economic conditions, the TBM guarantees production rates that are incomparable to any other method or technique in terms of excavation and advancement on a daily basis.
We should also emphasize how the enormous progress made in the productivity and reliability of TBMs has led to their standing (particularly in some markets) as the most advanced and advantageous method attainable without actually considering the disadvantages and limits. This emphasis on the TBM, even when the geomechanical conditions of the rock mass deviated from the actual


Roadheader

conditions, in more than one case caused enormous problems for the contractor and obviously for the principal, who saw the timing and costs of project completion inflate. There have been many examples around the world where the TBM has run into problems or has been blocked, in certain cases unable to be recovered.

The tunnel boring machine cannot be considered a viable alternative in the following cases:

1) When the geognostics and surveys cannot guarantee sufficient data regarding the homogeneity of the rock mass along the entire route.
2) When the rock mass or masses have a high degree of fracturing and hydrogeological conditions are especially critical.
3) In tunnels (especially characterized by the features in point 2) with a length of less than 2 km as the use of the TBM would fail to be economical.
4) When the route involves accentuated radii of curvature.
5) When the project requires a polycentric section (the TBM always operates by forming a perfect circle).
6) When the logistical conditions around the perimeter do not facilitate its assembly/disassembly (lack of space, or existence of bridges, viaducts or other structures from the entry or exit of the tunnel).

In addition, the TBM does not allow for the excavation method to be switched when the rock mass characteristics vary with respect to those determined by the geomechanical model. A "change of mind" during execution would impose prohibitive logistical and economic conditions that would jeopardize timing and probably the successful result of the project. The traditional system or mechanized excavation using the hydraulic breaker, while obviously not guaranteeing daily production output even comparable to the TBM, offer better guarantees of success when cutting through hard rock masses that require the constant adjustment of excavation to meet the changing conditions.
According to the type of rock masses, the two excavation systems ((blasting and breaker) can be alternatives or as often occurs, even complementary. But it should be noted that the hydraulic breaker is always on the construction site in any event, as scaling and invert operations are always performed using this irreplaceable piece of equipment.

The co-existence of the two excavation methods in the same project is especially efficient when:

TBM used for Lesotho Highlands water supply project (Tambo_CC BY-SA)

1)	the geomechanical model evidences high variability of the rock masses to be excavated with a prevalence of highly fractured masses (e.g., characterized by fractured or highly fractured rocks with limited squeezing of Class III and III B of the NATM, of those that fall under Classes III or IV according to RMR parameters, or those that can be associated with the category of blocky, distributed, seamy of the GSI index).
2)	There is a repetitive alternation on short lengths of compact and incoherent rock masses.

Precisely for these reasons the breaker has found wide application in Italy, one of the countries in the world that boasts a high number of tunnels and of different type, and where there is a consolidated design and construction experience with roots in works such as the Frejus rail tunnel (13.6 km, open to traffic in 1871) or the Sempione rail tunnel (19.8 km open to traffic in 1905). Besides a long tradition, the reason for this know-how can be found in the need to build tunnels in a territory which, if in part excluding the Alps, is characterized by rock masses where excavation and reinforcement present complex challenges. Demonstration of these difficulties and of the ability of designers and Italian construction companies to build tunnels in the face of "difficult" rock masses are the Bologna-Florence high-speed rail (Alta Velocità), which with its almost 73 km of tunnels out of a total route of 78 km traverses the "insidious" formations of the Apennines bordering the regions of Tuscany and Emilia.

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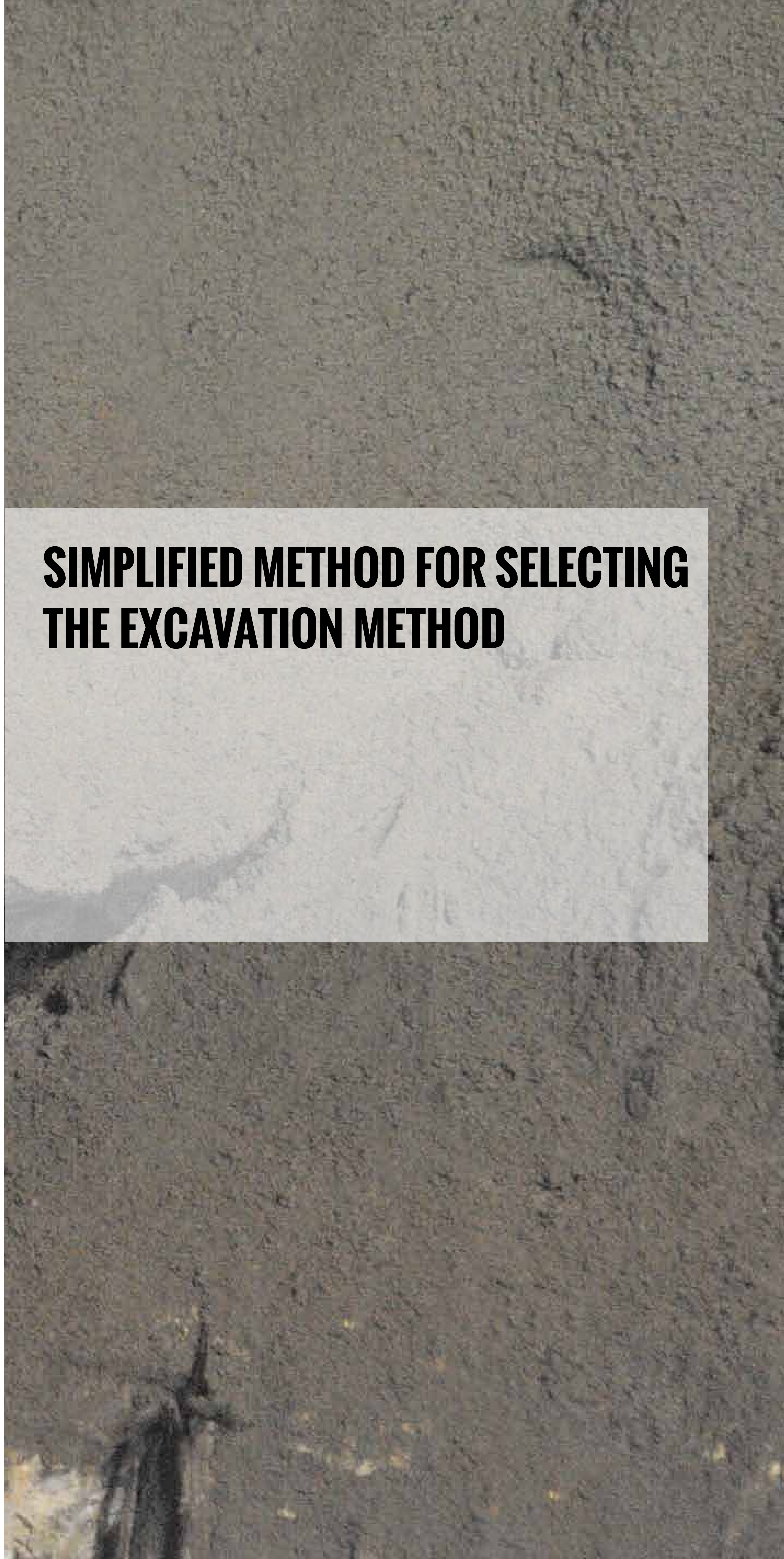
SIMPLIFIED METHOD FOR SELECTING THE EXCAVATION METHOD



SIMPLIFIED METHOD FOR SELECTING THE EXCAVATION METHOD

Introduction

Choosing the machinery and the excavation method for the construction of a tunnel is a complex decision-making process, which, as mentioned earlier, imposes broader considerations compared to those pertaining exclusively to data on the geomechanics of the rock masses to be excavated.
This chapter will outline a "criteria matrix" method of evaluation that takes into consideration all factors entered into the correct evaluation for the choice of the excavation equipment.

The excavation systems analyzed and compared include:

- Excavation using hydraulic breakers
- Excavation using TBM (Tunnel Boring Machine)
- Excavation using blasting method

The parameters considered in the analysis can be subdivided into different sets:

- Parameters characteristic of the rock mass and geometry of the excavation
  - UCS (Unconfined Compressive Strength)
  - RQD (Rock Quality Designation), degree of rock compaction
  - Classification index of rock masses, e.g., RMR (Rock Mass Rating) of Beniawski
  - Rock Mass Cuttability Index (RMCI)
  - Geometry of the excavation (length, section, etc.)

- Parameters characteristic of the excavation system
  - Power required by the machine and/or system
  - Cost of the machine and/or system, hourly cost
  - Hourly production rate in m^3/h calculated by type of excavation system and in relation to RMCI of the rock mass

The complexity of choosing the optimum means of tunnel excavation is due to the multiple parameters involved, both interconnected and not interconnected. For an analysis of this type there already exist multi-objective decision-making methods such as the **Analytic Hierarchy Process (AHP).** Developed in the early 1970s by Dr. L. Saaty of the University of Pittsburgh, AHP makes it possible to correlate properties and characteristics that do not have the same scale of reference and therefore are not comparable with each other.

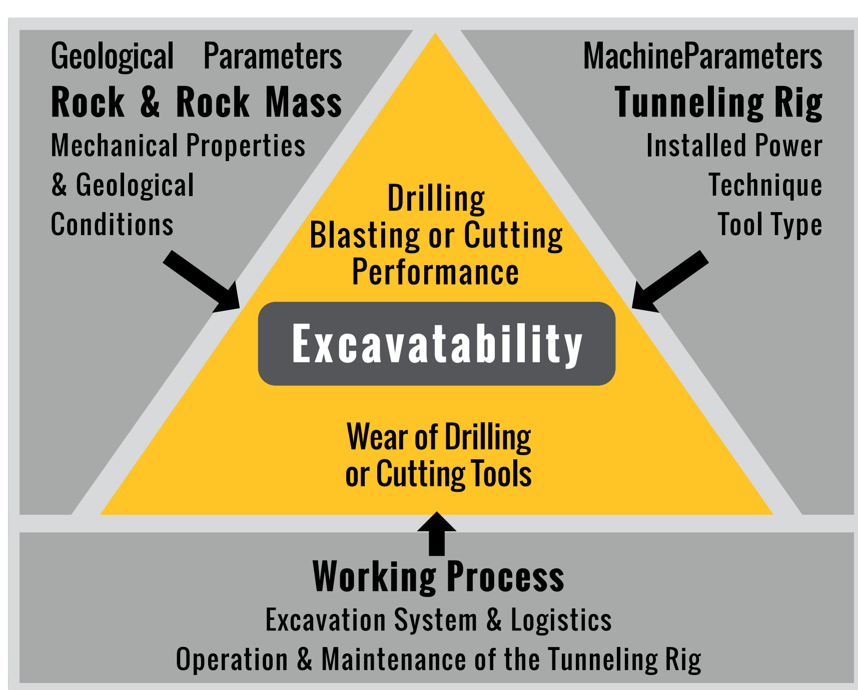
The basic principle guiding this method is problem deconstruction. A definition is made of the project criteria decisive for the choice of the optimum excavation system:
Example: RMR Index, hourly production rate, cost of machinery, etc. Each criterion is assigned a relative weight via the pairwise comparison:

- Example: Hourly production: Cost of machinery 2:1
- Example: Hourly production: RMR Index 1:3
- ...and so on.

In this way we construct the "criteria matrix" which allows the criteria of major importance to be identified based on the assigned weights; the criteria are calculated for each method of excavation (there will be a preferential excavation method for each criterion and it will be possible to define the "preference matrix"). We define the "comparison matrix" which correlates the "criteria matrix" with the "preference matrix", thus providing the best solution to the problem based on the value assigned to each criterion and to the relative values calculated for each single excavation method taken into analysis.
It is clear that the choice of criteria and the definition of the values to assign to project parameters indicate to the designer the best solution to the problem. If, for example, the highest value is assigned to the excavation's speed of execution, not necessarily will the choice fall on the most economical excavation method.
The AHP method is not a sealed box where data are simply input in order to obtain a solution; rather it is an open system that leaves ample space to the capacities and the experience of the designer. Thanks to the AHP method, the designer, upon determining the preferences among the excavation systems under consideration (breaker, blasting and TBM) can employ a procedure much more applicable to the project to be realized and its surrounding conditions.

THE CONCEPT OF EXCAVATABILITY

All underground works require a careful evaluation of the geological aspects (i.e. characterization) of the site where they will be constructed. This is naturally something that takes on further importance when the task is to construct tunnels.
Geognostic surveys also perform an important role not only in understanding the geomechanical behaviour of the rock masses excavated through, but also in determining, though almost always with a variable degree of approximation, the best method for excavation and reinforcement.
When it comes to excavating a tunnel, different types of rock masses can be



CONCEPTUAL DIAGRAM OF THE THREE MAIN PARAMETERS INFLUENCING EXCAVATABILITY

Source: K. Thuro, R.J. Plinninger: Hard rock tunnel boring, cutting, drilling and blasting: rock parameters for excavatability; Technology roadmap for rock mechanics, South African Institute of Mining and Metallurgy; 2003 encountered, or else the same rock mass with different geomechanical characteristics. In addition, the geomechanical model produced by the geognostic surveys can signal continuities and discontinuities that make it difficult, and at times impossible, to adopt a single solution for excavating the entire length of the tunnel. In this sense, the "degree of excavatability" of one or more rock masses that are encountered within the range of a single geomechanical model is thus determined by parameters summarized by the concept of "excavatability".

In short, excavatability can be defined as the element that gathers all parameters that influence the excavation of tunnels, in particular factors that determine the level of performance of the excavation with reference to execution times. The parameters to be taken into analysis define the excavating system (power, excavation technique, type of tool utilized), the production process (mucking and system of advancement, logistics for removing debris and allowing work to continue on the site, reinforcement of the excavated section during advancement phase) and the geomechanical characteristics of the rock mass.

The field of testing and surveying, moreover, is seeing continuous expansion and is often the source of debate among those in the field, but undoubtedly the correct choice of systems to survey and evaluate the rock mass is key to the successful outcome of the design and execution of the project. As discussed in the previous chapter, the surveys and respective indices that have particular importance in the construction of tunnels include: the RQD calculated based on core samples extracted from the rock mass, the RMR index of the Beniawski classification, the Q-System of the Barton classification, the Geological Strength Index (GSI) and the Rabcewicz-Pacher classification at the base of the NATM method. To these are added the values of compressive strength of the rock matrix, the degree of deformability of the rock mass, and the description of the discontinuities that cross it.

Compressive strength

The compressive strength of a rock is its capacity to resist a compression load. It is a maximum stress and is measured in Pa or derivatives. It is rather intuitive to understand how the compressive strength of the rock inside the mass through which the excavation must pass is one of the factors that directly influences excavation operations, since the action of the tools of the excavation machinery is first and foremost a striking action that stresses the rock and puts its strength to a hard test. This parameter is derivable from laboratory tests and on-site tests. The laboratory tests that can be used to evaluate this parameter are:

1) The uniaxial compression test
2) The triaxial compression test
3) The point load test
4) The shear strength test

The uniaxial compression test is performed on cylindrical-shaped samples and consists of submitting the material to a gradual compression load until the breakage of the sample; the load thus reached corresponds to the specific load at failure.

The triaxial compression test consists of submitting the rock sample to an increasing axial load by means of a press and imposing a constant confining stress by means of a hydraulic device that allows us to obtain a stress-strain curve of the material function of τ/σ or of $\sigma 1/\sigma 3$.

The point load test can also be performed on site thank to the small size of the testing apparatus. It determines a

strength index (Point Load Strength Index) that can be correlated with accuracy to the uniaxial strength of the rock.
The shear strength test on the matrix has a function similar to the direct shear test on the ground; it allows us to obtain mechanical parameters of the rock's strength ϕ (internal friction angle) and c (cohesion) and derive the compressive strength value of the material in any load and confining condition using strength criteria. By repeating the test several times, we obtain the values of internal friction angle and cohesion of the rock examined. Studies (Goktan R. M., Gunes N., 2004) have demonstrated how the relation, which ties the cu m/h excavated by the breaker, is linear with the rock's compressive strength. These studies correlate the net cutting rate (NCR) with the results of Schmidt hammer test (RN) (among the most commonly used and easiest to perform on site) and the RQD value of the surveyed vertical.

RQD< 25%: NCR = -0,2RN + 26,1;
25% <RQD< 49%: NCR = -1,05RN + 70,1;
50% <RQD< 75%: NCR = -1,18RN + 76,8.

Therefore, if it is true that with the increase of the RN blows recorded with the Schmidt hammer there is a decrease in the capacity of the tool to break the rock, we must assert that with the increase in RQD, thus the integrity of the rock mass, the inverse proportion gradually becomes more evident. It is immediately clear, in any case, that analyzing only one scale of problems is impossible; the rock is always considered as part of the rock mass system that will be excavated.

Deformability

Understanding the deformability of a rock mass, intended as the inclination of the material to change form or volume, is a basic consideration in the construction of the tunnel. Excavation operations are essentially intrusions to the rock mass in stress and strain terms. This means that a substantial part of the design and construction lies in the planning and implementation of reinforcement techniques, which serve to minimize the effects that the excavation (release of stresses along the edge of the excavated section) has on the rock mass. In addition, the anisotropy of the stress-strain behaviour of the excavated section determines the most appropriate choice of excavation method when we use equipment such as hydraulic breakers and roadheaders. Therefore, predicting how the excavated section will behave means planning for the correct reinforcement operations to carry out (to improve or preserve) and to choose the suitable excavation method.
There are many tests to judge the deformability of a mass: the dilatometer test, the flat jack, the plate load test, the pressurized hydraulic chamber. These tests serve to obtain **Young's modulus "E"** of the rock mass (which differs from that of the intact rock, derivable from laboratory tests) or as an alternative the **Bulk Modulus "K"**, **Poisson's ratio "V"** or the **shear modulus "G"**, always referring to the rock mass plus discontinuity, not only to the rock matrix alone. The dilatometer test consists of measuring pressure, which enables the dilation of a flat probe fixed into the rock; in addition to determining the characteristics of deformability of the rock mass it also provides measurement of the stress state existing on the surface of the rock mass.
The plate load test consists of measuring the movements induced on the rock by a rigid plate. Once the load applied is known and the movements are measured it is easy to identify the parameters of deformability. It is an on-site test on a medium considered (because of how the test develops) elastic and isotropic. To obtain these values the test must be performed using different-sized plates since the induced collapse depends on the area where the load is applied.

The pressurized hydraulic chamber, instead, is carried out on large rock samples by means of special radial multi-base extensometers positioned in the central section of the chamber that measure the induced deformation so as to obtain (through the theory of elasticity) the parameters of deformability of the mass in which measurement is taking place.

The level of fracturing and discontinuity

A rock mass's behaviour is essentially determined by the two components that characterize it: the rock matrix and the discontinuities. This means that, besides the stress-strain behaviour of the rock, it is important to know the behaviour of the discontinuities, determined by characteristics such as orientation, spacing, conditions of the walls of the joint, persistence, termination, opening, filling and roughness. Identifying these specificities of the discontinuities that run through the rock mass enables it to be classified (e.g., through Rock Mass Rating), so that it can be assigned more efficient strength parameters than those given to the rock if it were an isotropic homogeneous medium.

That said, due to the high degree of heterogeneity of the discontinuities inside the mass, it is difficult and laborious to have a complete picture of the rock mass from these classifications. As a first analysis, then, evaluating the degree of spacing (from extremely narrow to extremely wide), persistence (from very low to very wide) and of opening gives an initial useful indication of the response of the rock mass to the action of the excavator and the strength of the walls of the excavated section.

Before proceeding with any classification it is important to know how to recognize the discontinuities and the role that they have in determining the stability of the rock mass. Planes of discontinuity can be divided into three categories: planes of stratification, planes of schistosity and fractures.

The characteristics of planes of stratification, typical of sedimentary rocks, depend on the period of sedimentation and by the events that characterized the mass over the course of its life. These planes can be open (there is a continuous contact between the two consecutive layers), closed (continuous contact without compenetration between the layers), coloured (joints filled with clay), smoothed due to the friction movement of the rocks, or filled with coarse or cemented material. According to their spacing (usually measured in centimetres) the rock mass can have a massive or stratified appearance.

The planes of schistosity are typical of metamorphic rocks and are also planes of weakness for the rock mass. Unlike the planes of sedimentation, they are rough and undulated and their formation depends on the percentage of mica contained in the rock mass. Relaxation in the rock mass or tectonic activity may have opened these planes, which may have in turn been filled with other material (often quartz, or more rarely carbonates).

The fractures are important for obtaining full knowledge of the discontinuities that run through a rock mass, since they are not systematic like the other discontinuities, but in the same manner are weak points of the rock mass. This is even truer if we take into account the anisotropy in their internal development.

Empirical methods also exist that provide by a simple visual inspection specific indications regarding the characteristics of the rock in the zone being observed. One of these is the Manev formula, which obtains the admissible load on a rock mass from the strength of the rock matrix under uniaxial load (σ_r) and the number of discontinuities per linear metre (i): $\sigma_c = \sigma_r \, 0.114 \, e^{-0.48(i-2)} + 0.02$

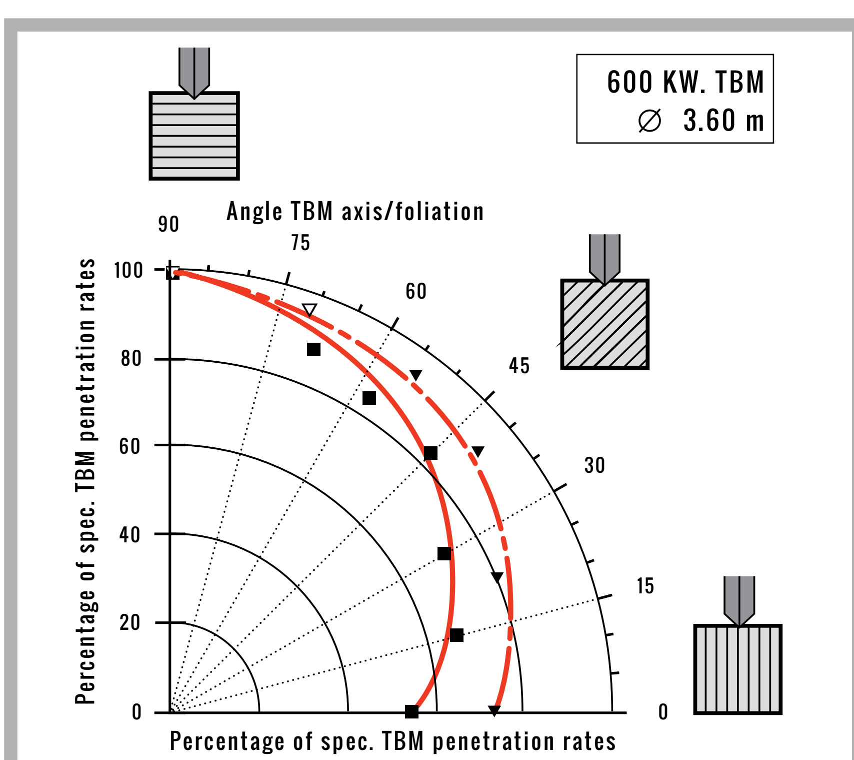
THE METHOD OF SELECTION: THE ANALYTIC HIERARCHY PROCESS (AHP) AND SELECTION CRITERIA

As we stated, the choice of excavation equipment to use in a tunnel involves a complex decision-making process with interaction of a variety of factors that cannot all be analyzed through a simple cost-benefit analysis. The Analytic Hierarchy Process (AHP) is a multi-objective decision-making approach that enables selection, by means of pair comparison, of the best among the possible alternatives for solving the widest range of problems. The basic principle guiding this method is problem deconstruction: first we identify the criteria that differentiate the problem according to the available alternatives (in our case excavation using hydraulic breakers, Tunnel Boring Machine, roadheaders or by blasting); next, we assign each criterion the relative weight compared to the others; and then by means of pair comparison we can construct the "criteria matrix" whose eigenvector with its own components allows identification of which criteria have the biggest weight. Once assigned these weights, we must determine the preferences of each alternative with respect to all the others through a pair comparison. Finally, we calculate the product between the matrix obtained by means of the preferences to the alternatives **(comparison matrix)** and the eigenvector of the criteria matrix **(priority vector)** to obtain the **rating scale** that provides the best alternative of those proposed.

The method makes it possible to obtain a ranking of preferences of the various options to allow analysis and comparison of all of them during the course of project completion. This means that if, after choosing the most advantageous method, technical or economic difficulties arise (as in our case) that were not considered in a first analysis and that would make the solution unusable, we may proceed with the next choice without having to perform the full analysis again.

The usefulness of the AHP method in a tunnel construction project becomes clear when the designer learns that in order to determine the execution time for the project not only does he have to know the quantity of the excavated rock in a unit of time, but also the geometric and geological variability of the rock mass and the tunnel.

The parameters include: the advancement of the excavation in a homogeneous mass (hourly production measured in [m^3/h] calculated by means of ICR or IBR according to the excavation system utilized); the stability of the advancement given the discontinuities of the rock mass (Rock Mass Rating); and the need to have versatile excavation method relative to the size of the tunnel and variability of geological features noted during the excavation advancement of the



Specific TBM penetration rates in a phyllite (straight line) and a phyllite with carbonate schists between layers (broken line) with respect to foliation angle. Schönberg pilot tunnel, Schwarzach, Austria.

Source: K. Thuro, R.J. Plinninger; Hard rock tunnel boring, cutting, drilling and blasting: rock parameters for excavatability; Technology roadmap for rock mechanics, South African Institute of Mining and Metallurgy; 2003

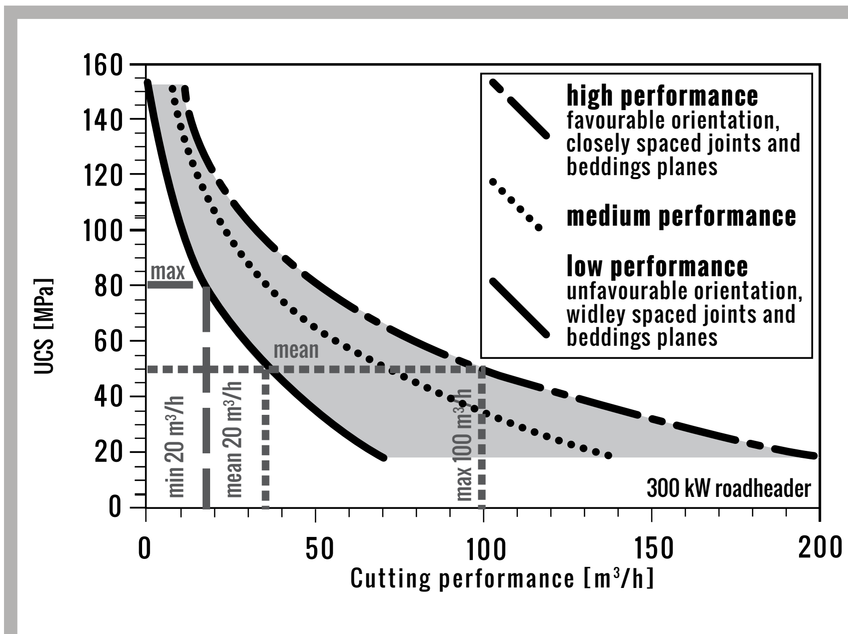
Source: Marinos V., Marinos P., Hoek E.; The geological strength index: applications and limitations; Bell Eng Geol Environ; 2005

tunnel. With this type of choice, we should bear in mind that the excavation will be lined and that it is unlikely that the lining will be the same along the entire length of the tunnel. In the choice of excavation method we must remember that using an "open" excavation machine compared to a "closed" one safeguards the contractor from any sudden changes in the geological situation in terms of a suitable lining to support the excavated section.

Hourly production

The objective of this parameter is to summarize both the resistance opposed by the rock under excavation and the stress-strain response of the excavated section in a rock mass that we consider, in an initial approximation, as if it were a homogeneous and isotropic medium. Many studies have been performed to obtain hourly production both when breakers and the TBM are used.

To evaluate this parameter for hydraulic breakers we must know the compressive strength of the rock (Unconfined Compressive Strength, UCS, determined in a first approximation by the Schmidt hammer test or by laboratory strength tests by means of the maximum principal stress at failure σ_c), the **RQD** (Rock Quality Designation) and the **RMCI**



CUTTING PERFORMANCE OF A 300 KW ROADHEADER RELATIVE TO ROCK UNCONFINED COMPRESSIVE STRENGTH (UCS)

Source: K. Thuro, R.J. Plinninger; Geological limits in roadheader excavation - Fuor case studies; 8th International IAEG Congress; 1998

(Rock Mass Cuttability Index). If a prediction of excavation advancement using a Tunnel Boring Machine is required, it is necessary to know the expected power of the machine and the optimum specific energy, which represents the energy necessary to excavate the unit of volume of the rock.

The hourly production is equivalent to the average m^3/h the equipment can excavate in the rock mass; however, we should add penalizations to the efficiency of the excavator due to the stabilization of the excavated section and mucking (for the

breakers) or to down time due to the TBM, which stops after a certain amount of metres of advancement to bring the body of the machine up to the excavation face.
In our case it is important to predict the metres of advancement per hour, so as to give the correct importance to the alternatives with respect to the first criterion identified.

For hydraulic breakers we can use the following relation:

IBR = $4.24\ P\ (RMCI)^{-0,567}$ [m^3/h]
[N. BILGIN, C. Balci]

If roadheaders are used:

ICR = $0.28\ P\ (0,974)^{RMCI}$ [m^3/h]
[N. BILGIN, C. Balci]

where in both cases:

P = Power of the hydraulic breaker or the roadheader [Hp]
RMCI = Rock mass cutting index = $\sigma_c\ (RQD/100)^{2/3}$ [MPa]

Whereas if a TBM is used, we can use the empirical formula:

ICR = k P / SE [m^3/h]
[N. BILGIN, C. Balci]

where:
k = energy transmission coefficient, equal to approx. 0.75;
P = expected power of the machine (kW);
SE = optimum specific energy (kWh/m^3), is function of the ratio between the distance between two consecutive tools and their depth of incision into the rock and is a value derivable by laboratory tests.

Specifically:

P = $2\pi NT$, where N are the rpm of the rotating head and T is the total torque acting on the rock.

When it comes to blasting, however, obtaining a value of volume of rock demolished per hour is more complex, as several factors are put into play in the dimensioning of the blasts, e.g., the charge of the explosive selected, the percentage of hole filling or the required piece size of the rubble.
At this point, specific tests to calculate the load of rock involved in the single blasts should be carried out.
Hereinafter we will indicate with the acronym ICR (Instantaneous Cutting Rate) the hourly production expressed in [m^3/h] for the different methods of excavation.
The formulas above will be used for hydraulic breakers, the TBM and for blasting. In fact, the values of hourly production calculated by these means provide homogeneous results that can be compared with each other.

RMR (Rock Mass Rating)

Basic to understanding the response of a rock mass to the stresses induced by tunnel construction is to know the characteristics of the rocks composing it and the discontinuities crossing it, both qualitatively (i.e., knowledge of the mechanical parameters of resistance) and quantitatively (number of discontinuities). As a parameter to describe these characteristics of the rock mass, the index chosen is the RMR of Beniawski and the derived classification. It is easy to comprehend that hydraulic breakers are the best equipment in the case of highly fractured rock masses because they are not affected by the anisotropy of the distribution of the discontinuities of the rock mass and their diffusion. At the same time, difficulties may arise in these types of rock masses when blasting is chosen due to evaluating the right positions of the loads for the correct release of energy; similarly TBMs can encounter difficulties because they risk not finding the right support to make contrast and advance. So, if on the one hand we have roadheaders and breakers that are benefited by a rock mass with a low RMR, on the other we have blasting and TBM that do not yield the best productivity.

We need to quantify this by means of a simple relation that indicates the degree to which hydraulic breakers and roadheaders are advantageous compared to blasting and TBM and vice versa. Let us hypothesize that the breaker or roadheaders are more advantageous with respect to blasting or the TBM with RMR<60 (low quality rock according to Beniawski) and more disadvantageous with RMR>60. Therefore, we can define the parameter RMR/60 which takes on this significance: if 60/RMR>1 the breaker is more advantageous; if 60/RMR<1 the breaker is more disadvantageous. For example, if RMR=20, 60/RMR=3, the breaker is three times more advantageous than the TBM.

Geometries and variables

In engineering a tunnel excavation it is essential to perform an analysis of the project size in relation to the method of excavation selected. Generally speaking, and apart from the geomechanical conditions of the rock mass, it can be stated that mobilizing a system of excavation such as the TBM is not realistic for tunnels with short lengths and wide sections. By contrast, if the ideal geomechanical conditions for the TBM exist, the other mechanical systems and blasting offer lower productivity in terms of advancement in tunnels with lengths exceeding two kilometres.

Furthermore, in making this decision we cannot ignore the fact that the transport of very large machines can pose challenges. While machines such as excavators fitted with hydraulic breakers or drilling systems for blasting can be transported and made operative (almost) anywhere, huge machinery such as the TBMs, which can reach and even exceed 100 metres in length, present considerable logistical challenges in their transport and assembly, especially if carried out in remote areas without adequate infrastructure.

It is especially important to consider that one of the main difficulties in tunnel construction is attaining in-depth knowledge of the characteristics of the rock masses to be traversed and the evolution of their characteristics along the entire axis of the route. Although by now modern geognostics limit the margin of error, in certain cases this is still a big challenge. For the preliminary studies there are restraints due to tight budgets, logistical limits of the techniques used (surveys, seismic explorations, georadar etc.) to fully describe the rock mass that will be excavated.

All these considerations have to be taken into account when evaluating the versatility of the excavation system. A certain system can turn out to be more versatile when, irrespective of the designer's choices, the conditions around the perimeter change. For example, if rock strength values increase, a roadheader or hydraulic breaker may run into problems; similarly, it makes no sense to blast if faced with layers of unconsolidated rock. Or else a highly fractured rock mass can slow or stop a TBM, triggering a set of logistical problems difficult to solve.

In summary, the AHP offers a simple formula that makes it possible to articulate how much a system (in our case, an excavation system) is more advantageous than another. Taking two kilometres as a realistic length for all methods, we will try to translate the judgment on the advantage of a system that utilizes less bulky equipment than another:

(2/tunnel length)xA, with A = probability of finding differences (unpredicted) in the composition of the rock mass during the advancement of the excavation, variable between 1 (minimum probability) and 3 (maximum probability). Parameter A will be calibrated each time, according to the excavation systems the designer takes into consideration and the rock mass to be excavated. This means that, for example, when comparing blasting and roadheaders, if the designer suspects that he will find masses characterized by rocks with strength values as resulting from the laboratory tests, he will have to assign to A a higher value than he would for the same site when the choice is between blasting and TBM. Likewise, having to choose between hydraulic breakers and roadheaders, it is evident how parameter A would make the choice lean toward hydraulic breakers (more versatile), whereas the value due to the length (and therefore dimensions) loses importance and is assumed equal to unity.

Criteria matrix

Once defined the criteria on which the method is based, it is now possible to assign the weight of each criterion in comparison with the others and arrange them in the criteria matrix. In our case, we let ICR be 1.3 times more important (for the purposes of the analysis in question) of the value of RMR of the rock mass and 2.25 times more important than the geometry and the variables of the route, and the value of RMR be 1.75 times more important than the geometry and the variables verifiable.

That stated will be expressed in an ordered way in the criteria matrix:

CRITERIA MATRIX	ICR	RMR	Geometry
ICR	1	1.3	2.25
RMR	0.77	1	1.75
Geometry	0.45	0.57	1

Fundamental for using this method is to calculate the eigenvector derivable from the criteria matrix once calculated the main eigenvalue of the matrix. The eigenvector (called **priority vector)** associated to the eigenvalue $\lambda = 3$ has for components **(0.84; 0.47; 0.27)**. These components are indication of the weight of the criteria determined in the analysis; hence it is clear that a greater importance was given to ICR with respect to the RMR and to the geometry of the tunnel. We then construct the preference matrix between the alternatives of excavation method for each criterion; that is, we assign each alternative a value of how many times more advantageous it is than the other and then derive the eigenvector corresponding to the principal eigenvalue (λ_{max}). After deriving the eigenvectors for each criterion, we can construct a matrix that has these eigenvectors for columns to allow a simple matrix product to be carried out between the matrix constructed and the eigenvector of the criteria matrix. The result will be a 3-dimensional vector, whose components indicate the advantage of using the first or second alternative. It is obvious that the larger component points to a greater advantage than the associated alternative.

Cost analysis

The analysis is not terminated, however. We cannot overlook the economic aspect of the choice, without which the applicability of the method would be limited and fail to have actual utility in the design decisions.
Cost analysis is essential: it must evaluate all the activities for the construction of the infrastructure, and thus an evaluation will be necessary of the cost/rental of machinery for excavation, cost/rental of machinery for mucking operations, costs of material and machinery for tunnel reinforcement and lining, and fuel for the machinery. After obtaining the costs for each alternative, these costs must be compared with the components of choice obtained with the AHP. Dividing the components by corresponding costs allows us to obtain a real benefit value in the choice of an excavation method.

Examples

Below we provide some examples that illustrate how the method can be used to show how the suggested choice for the excavation method varies in relation to the geomechanical conditions characterizing the route of the tunnel.

Case A

Suppose we find ourselves having to decide the excavation method to utilize in order to construct a 4 km tunnel, whose route runs through a rock mass with medium-low lithological variability (or, in other words, a rock mass whose lithology along its entire length is sufficiently noted).
We are to evaluate if it is the case to use as an excavation method breakers (Alternative 1), TBM (Alternative 2) or blasting (Alternative 3).

Criterion 1

In a first analysis we must evaluate the ICR indices of the breakers and the TBM selected using the formulas given in the preceding paragraphs.
It is the task of those selecting the excavation method to have a notion of the average compressive strength of the rock (σ_c), the RQD of the mass and the power of the specific breaker.

Let us assume we have the following data to start with:

σ_c = 245 MPa
RQD = 70%
P = 95 HP

Once we know σ_c and RQD, as we have seen, it is easy to obtain the RMCI of the mass; therefore we have all data available for deriving the corresponding ICR.

$$RMCI = \sigma_c\,(RQD/100)^{2/3} = 193\ MPa$$
$$ICR = 4.24\ P\ RMCI^{-0.567} = 20.3\ m^3/h$$

Now, proceeding with the calculation of the ICR of the TBM, let us assume that we have a machine with K energy transmission coefficient of 0.80, whose expected power is equal to 160 kW and specific energy is 2.1 kWh/m^3.

$$ICR = k\ P\ /\ SE = 61\ m^3/h$$

Let us assume an average production by means of blasting of 30 m^3/h. We can therefore construct the preference matrix relative to the first criterion.

CRITERION 1	Breaker	TBM	Blasting
Breaker	1.00	0.33	0.68
TBM	3.00	1.00	2.03
Blasting	1.48	0.49	1.00

The eigenvector associated to this matrix has for components (0.42; 0.86; 0.28).

Criterion 2

We now proceed with the evaluation of the RMR of the rock mass to be excavated:
If the strength of the rock matrix is equal to 200 MPa; if the RQD is at 70%; if the average spacing between the discontinuities in the segment less favourable to safety is 6-20 cm; if the surfaces of the discontinuities are uniformly worn; if the rock mass, relative to the hydraulic conditions, is defined as "wet"; and if the slope of the planes of discontinuity is unfavourable to the stability of the excavated section, then we can state that the mass totals 40 points according to the Beniawski classification (RMR=12+13+8+10+7-10=40).

Strength of intact rock	PLSI (Mpa)	>10	4-10	2-4	1-2	Use UCS
	UCS (MPa)	>250	100 - 250	50 - 100	25 - 50	5 - 25
R1	Rating	15	12	7	4	0
RQD	%	90 - 100	75 - 90	50 - 75	25 - 50	<25
R2	Rating	20	17	13	8	5
Spacing of discontinuities		>2 m	0.6 - 2 m	200 - 600 mm	60 - 200 mm	<60 mm
R3	Rating	20	15	10	8	5
Condition of discontinuities		Very rough	Slightly irregular	Slightly irregular	Internally smooth or hollow <5 mm	Hollow >5 mm
		Discontinuous, without separation	Separation <1 mm	Separation <1 mm		Separation > 5mm
		Unaltered	Slightly altered	Very altered	Continous	
R4	Rating	30	25	20	10	0
Hydraulic conditions		Completely dry	Slightly wet	Wet	Very wet	Dripping
R5	Rating	15	10	7	4	0
Orientation and inclination (strike and dip) of joints	Tunnel	Very favourable	Favourable	Insignificant	Unfavourable	Very unfavourable
	Rating	0	- 2	- 5	-10	-12

Applying the formula suggested in the paragraph regarding the use of the RMR value in the proposed method, the breaker results 1.5 times more advantageous than the TBM according to this criterion. Now, when we compare breakers with blasting relative to the RMR value of the rock mass, we can assert that in a rock mass of medium-poor quality using the breaker is definitely the favoured method considering that the blasts can affect the stability of the excavated section during later excavation operations.

We quantify this by asserting that the use of the breaker for this criteria is 2.5 times more advantageous than blasting. Last, comparing the behaviour of a TBM with blasting, it is likewise true that, to a lesser extent than in the previous case, the TBM is more advantageous than blasting. We quantify this slight advantage at around 1.2 times.

CRITERION 2	Breaker	TBM	Blasting
Breaker	1.000	1.500	2.500
TBM	0.667	1.000	1.200
Blasting	0.400	0.833	1.000

The eigenvector associated to this matrix has for components (0.79; 0.48; 0.35).

Criterion 3

Assuming that the project in question is for the construction of a 4 km-long tunnel and that the probability of discovering unexpected differences in the lithologies present in the rock mass is 1.2 (value between the minimum suggested 1 and the maximum 3), according to this criterion the use of breakers results 0.6 times more advantageous than the use of the TBM (it is therefore less advantageous).

Comparing breakers and blasting, considering such lengths and lithological variability, we can hypothesize a slight advantage in favour of blasting, not so much for differences due to the length of the route, but for the fact that a low uncertainty in the geological variability would protect from risks of unexpected segments in which explosives may be unusable. This would indicate an advantage of blasting 1.25 times greater than using the breaker.

Finally, comparing the TBM and blasting, the use of the full-face tunnel boring machine is certainly more advantageous. We quantify the TBM's advantage as 1.5 times greater compared to blasting relative to this criterion.

CRITERION 3	Breaker	TBM	Blasting
Breaker	1.000	0.600	0.800
TBM	1.667	1.000	1.250
Blasting	0.667	1.250	1.000

The eigenvector associated to this matrix has for components (0.42; 0.73; 0.55)

Grouping in a single matrix the eigenvectors obtained to now from the preference matrices, we have:

0.42	0.79	0.42
0.86	0.48	0.73
0.28	0.35	0.55

Multiplying this matrix by the priority vector (0.84; 0.47; 0.27) we obtain the preference vector, whose components are (0.84; 1.15; 0.55). Considering that the first term corresponds to the advantage of using breakers, while the second refers to the TBM and the third to blasting, we can state that in Case A the use of TBM is more advantageous than the breakers, which in turn are preferable to the blasting method.

Case B

We now take into consideration the project for a tunnel with a length of 1 km, whose route runs inside a rock mass with a moderate lithological variability that the geognostic surveys did not allow to be reconstructed with extreme precision. Once again, we presume that the choice of excavation method must encompass breakers (Alternative 1), TBM (Alternative 2) or blasting (Alternative 3).

Criterion 1

In the first analysis we must evaluate the ICR indices of the breakers and the TBM chosen using the formulas proposed in the preceding paragraphs. It is the responsibility of the decision-maker to have a notion of the average compressive strength of the rock (σ_c), the RQD of the mass and the power of the breaker at hand.
Let us assume we have the following data to start with:

σ_c = 100 MPa
RQD = 40%
P = 120 HP

Once we know σ_c and RQD, as seen, it is easy to obtain the RMCI of the mass, and therefore we have available all data to derive the corresponding ICR value.

$RMCI = \sigma_c (RQD/100)^{2/3} = 54.3$ MPa
$ICR = 4.24\ P\ RMCI^{-0.567} = 52.84\ m^3/h$

Proceeding with the calculation of the ICR of the TBM, we assume we have a machine whose K energy transmission coefficient is 0.80, expected power is 160 kW and specific energy is 2.1 kWh/m^3.

$ICR = k\ P / SE = 61\ m^3/h$

Now let us hypothesize an average production rate by means of blasting of 45 m^3/h.

We can therefore construct the preference matrix relative to the first criterion.

CRITERION 1	Breaker	TBM	Blasting
Breaker	1.00	0.87	1.17
TBM	1.15	1.00	1.36
Blasting	0.85	0.74	1.00

The eigenvector associated to this matrix has for components (0.57; 0.66; 0.49).

Criterion 2

We now proceed with the evaluation of the RMR of the mass which will be excavated.
If the strength of the rock matrix is 100 MPa; if the RQD is at 40%; if the average spacing between discontinuities in the segment less favourable to safety is from 6-20 cm; if the surfaces of discontinuity are uniformly worn; if the mass, relative to the hydraulic conditions, is to be defined as "dripping"; and if the sloping of the planes of discontinuity

is very unfavourable to the stability of the excavated section, then it can be stated that the mass totals 26 points according to Beniawski's classification (RMR=10+8+8+7+5-12=26).

Strength	PLSI (Mpa)	>10	4-10	2-4	1-2	Use UCS
of intact rock	UCS (MPa)	>250	100 - 250	50 - 100	25 - 50	5 - 25
R1	Rating	15	12	7	4	0
RQD	%	90 - 100	75 - 90	50 - 75	25 - 50	<25
R2	Rating	20	17	13	8	5
Spacing of		>2 m	0.6 - 2 m	200 - 600 mm	60 - 200 mm	<60 mm
discontinuities R3	Rating	20	15	10	8	5
Condition of discontinuities		Very rough	Slightly irregular	Slightly irregular	Internally smooth or hollow <5 mm	Hollow >5 mm
		Discontinuous, without separation	Separation <1 mm	Separation <1 mm		Separation > 5mm
		Unaltered	Slightly altered	Very altered	Continous	
R4	Rating	30	25	20	10	0
Hydraulic conditions		Completely dry	Slightly wet	Wet	Very wet	Dripping
R5	Rating	15	10	7	4	0
Orientation and	Tunnel	Very favourable	Favourable	Insignificant	Unfavourable	Very unfavourable
inclination (strike and dip) of joints	Rating	0	- 2	- 5	-10	-12

Applying the formula suggested in the paragraph regarding the use of the RMR value in the method proposed, in comparing TBM and blasting, the use of the breaker results 2.4 times more advantageous than using the TBM according to this criterion.

Proceeding with the comparison between the use of the breaker with blasting relative to the RMR value of the rock mass, we can assert that in a rock mass with poor quality the use of the breaker is definitely more advantageous since the blast can affect the stability of the excavated section during later excavation operations. We quantify this by asserting that the use of the breaker for this criterion is three times more advantageous than the blasting method.

Last, comparing the behaviour of a TBM with blasting it is also true that, to a lesser extent with respect to the previous case, the TBM is favoured over blasting. We quantify this slight advantage as about 1.5 times.

CRITERION 2	Breaker	TBM	Blasting
Breaker	1	2.400	3.000
TBM	0.417	1.000	1.500
Blasting	0.333	0.667	1

The eigenvector associated to this matrix has for components (0.86; 0.39; 0.27).

Criterion 3

Assuming that the project in question is the construction of a 1 km tunnel and that the probability of finding differences in the lithologies present in the rock mass is 1.5 (value between the minimum suggested 1 and the maximum suggested 3), according to this criterion using breakers results 3 times more advantageous than using the TBM.
Comparing breakers and blasting, considering such a length and lithological variability, we can hypothesize a slight advantage in favour of blasting, not so much for differences due to the length of the route, as for the fact that a low uncertainly in the geological variability would protect from risks of unforeseen segments in which blasting may be unusable. This indicates an advantage in using the blasting method 1.3 times greater than using the breaker.
Last, comparing the TBM and blasting method, the use of the full-face tunnel boring machine is certainly less advantageous due to its size. We can quantify the advantage of blasting as 1.2 times greater than the TBM relative to this criterion.

CRITERION 3	Breaker	TBM	Blasting
Breaker	1.000	3.000	0.769
TBM	0.333	1.000	0.833
Blasting	1.300	1.200	1.000

The eigenvector associated to this matrix has for components (0.72; 0.35; 0.62).

Grouping in a single matrix the eigenvectors obtained to now from the preference matrix, we have:

0.57	0.86	0.72
0.66	0.39	0.35
0.49	0.27	0.62

Multiplying this matrix by the eigenvector associated to the criteria matrix (0.84; 0.47; 0.7), we obtain the preference vector that will have for components (1.08; 0.83; 0.71). Considering that the first term corresponds to the advantage of using breakers, whereas the second refers to the TBM, we can state that in Case B using breakers is more advantageous than using the TBM. Here we have shown how by varying only the characteristics of excavation systems the analysis is subject to sizeable variations even when geotechnical and geometric conditions are the same.

CONSIDERATIONS ON THE SIMPLIFIED METHOD

This proposal of a simplified method for selecting the tunnel excavation method originates from a precise assumption: focusing attention on the characteristics of the system that we want to use and the site where it is to operate.

In essence, the AHP method a simple tool (versus the complexity of the problem) that gives the designer an initial credible evaluation criterion for the best choice of excavation method. To this we must add others that inevitably contribute to the execution of intrinsically complex works, such as tunnels.

(Trevi Group)

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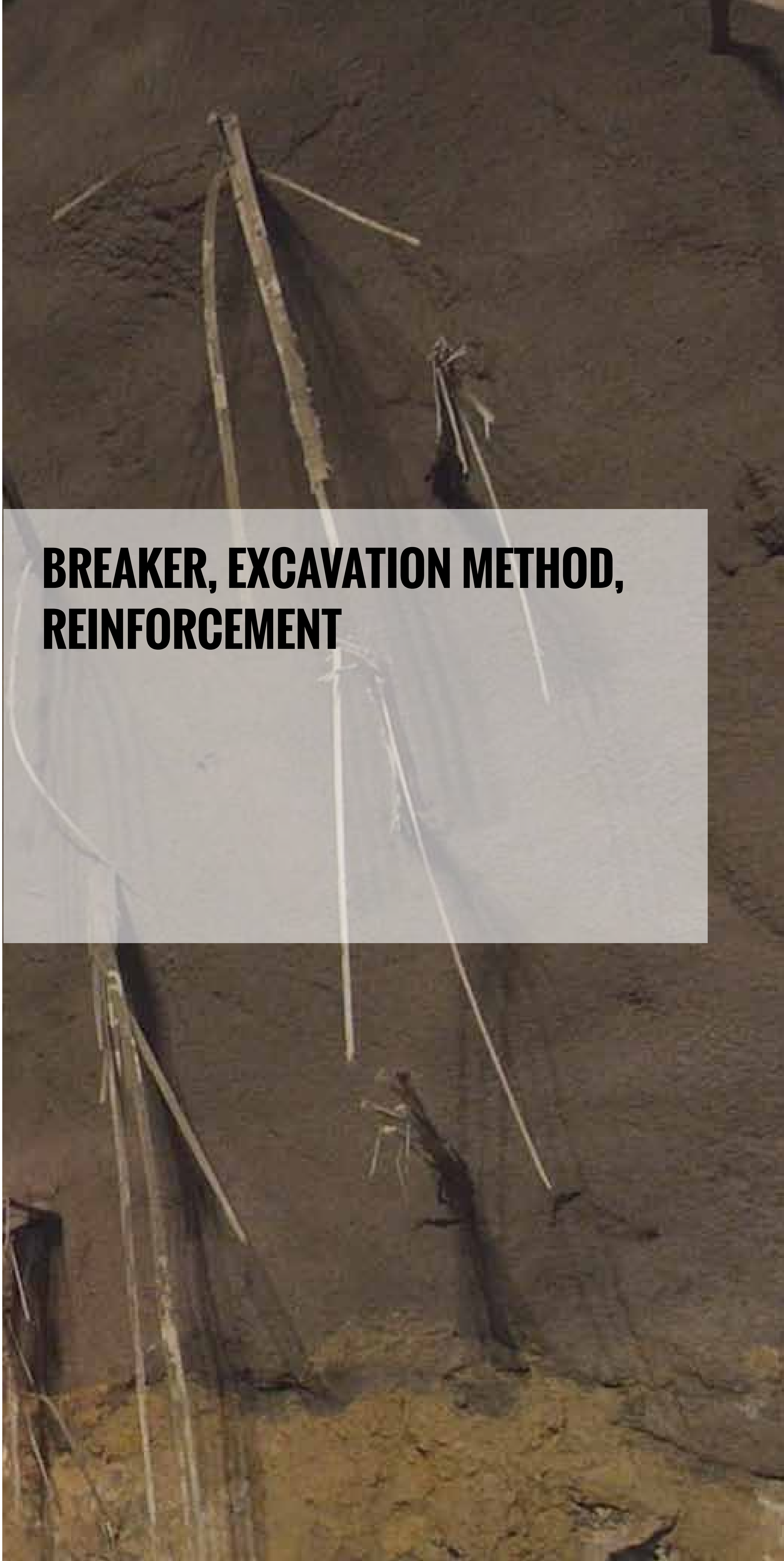
FOCUS ON



BREAKER, EXCAVATION METHOD, REINFORCEMENT

- A primer on breaker technology
- Demolition
- A criterion of productivity
- Main tunnel excavation methods using the hydraulic breaker
- Reinforcement of the excavated section
  - Pre-reinforcement of the core-face
  - The first-phase lining
  - Rock bolting and nailing
  - Excavating and casting the invert
- Selecting the hydraulic breaker for tunnel excavation
- Preparing the breaker for tunnel applications

BREAKER, EXCAVATION METHOD, REINFORCEMENT

A PRIMER ON BREAKER TECHNOLOGY

The breaker is a machine whose function is to transform the energy of a fluid under pressure into mechanical energy (reciprocating motion of a piston mass) in order to break up material with fragile behaviour, generally made up of rock, cement or similar materials. The piston has a weight ranging from a few kilos up to a ton and speeds of impact can easily reach 10 m/sec. The impact between the piston mass and the tool transform the kinetic energy of the moving mass into impact energy which travels through the tool and is transferred to the material to be demolished.
In the technology of breakers, there are two main categories based on operating principle:

a) Hydraulic thrust breakers: these feature a piston which is thrust downward by the hydraulic pressure on the piston head and "accelerated" by the oil-gas charge of the accumulator. The Indeco system adopts this technology. The main advantages of the hydraulic thrust system include:

1) gas charge and energy per blow remain constant
2) low degree of wear and high resale value
3) efficiency little affected by temperature variations
4) hydraulically dampened, do not stress booms and slewing rings on excavators
5) do not overstress delivery and return hoses
6) reduced maintenance and lower costs as a result (reduced number of seals do not require gas/oil gaskets which are not reliable and inevitably lead to seeping)

b) Gas thrust breakers: these have a gas chamber (usually pre-loaded nitrogen) in the upper part of the piston. The pressure of the gas increases when the piston, thrust by the oil, moves upward. This pressure then thrusts the piston in its travel downward until it hits the tool. The main characteristics of gas thrust breakers are that over time they reduce the energy per blow, have a high number of seals, and require gas/oil gaskets which are not reliable and inevitably lead to seeping.

1) high susceptibility to ageing and early wear
2) efficiency greatly affected by temperature variations
3) low second-hand value
4) high stress on excavator pumps
5) stress on booms and slewing rings on excavators
6) stiffer hydraulic system puts stress on delivery and return hoses

DEMOLITION


Indeco Breaker on excavation face

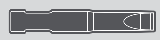
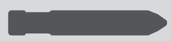
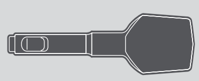
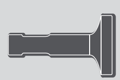
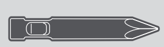
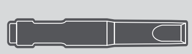
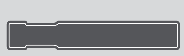
Hydraulic breakers work principally in two different modes: **demolition by penetration and demolition by impact**. Demolition by penetration consists of crushing rocky material through a combination of stress waves (high level of stress that acts in a very short span of time) and of the wedge effect produced by the particular shape of the tool utilized. In an application typical of demolition by penetration the tools used are chisels or moil point tools to crush cement asphalt or other soft materials.
In this type of demolition the sharpness and the shape of the tool utilized are fundamental to achieving a good production rate of the breaker. Thanks to their long experience in the field of heavy demolition in tunnels, Indeco has developed different types of tools with the aim of achieving the best performance in any condition of use. The wedge shape of the chisel or the special double chisel of the Indeco Cobra tool both assure deep penetration into the rock; however, penetration generally decreases as the chisel advances into the rock until almost stopping. The reduction in penetration is very quick, and once the chisel has penetrated the rock, due to the strong friction effect between the body immediately behind the chisel and the rock itself, a considerable amount of energy is dispersed.

The special shape of Indeco tools allows the friction with the rock to be reduced and favours penetration of the body of the tool situated immediately above the chisel. This design emphasizes the effect of crushing of the rock also in the case of high values of penetration. In these cases, the experience of the operator is very important for changing work position and avoiding dispersions of energy. The striking time in the same point should not exceed 45 seconds, after which the operator should reposition the tool to maximize productivity, moving it approximately 20 cm from the previous striking point.

Demolition by impact produces the fracture of the material only by means of stress waves with a minimum contribution of penetration; in fact the most efficient transmission of stress waves occurs with the use of flat tools. Typical applications are the demolition of blocks and large masses, heavily reinforced concrete structures, or slag generated by the production of steel. The choice of the best tool is a determining factor in achieving maximum productivity from the Indeco hydraulic breaker.

Therefore, the geometry of the tool should be suited to the type of material to be demolished, as well as to the type of work to be performed. Indeco tools are designed and built to accommodate the broad requirements of demolition, and in order for them to carry out their role with the highest efficiency some rules should be observed regarding the choice of the most suitable point, the correct use and maintenance. The preferences of operators, the type of machine and the particular working conditions can influence the choice for the most suitable one.

Below is a brief description of the most common types of tools used for demolition:

	1) Chisel tool: suitable for all earthworking or narrow-section excavation.
	2) Moil point tool: suitable for breaking up concrete, or medium-hard non-stratified rock. Secondary demolitions: average, hard or extremely hard blocks.
	3) Asphalt cutter: suitable for cutting asphalt, breaking up flooring, as well as brick or sandstone walls.
	4) Pile driver: suitable for pilework or press-moulded supports for guardrails, etc.
	5) Pyramidal point: suitable for demolishing hard reinforced concrete flooring, as well as sedimentation material.
	6) Cobra chisel tool: suitable for all types of excavation work on medium-hard to hard rock, non stratified rock or rock which tends to pulverise when being broken up, “puddingstones”.
	7) Blunt tool: suitable for breaking up blocks of any hardness, or to reduce the size of rubble. Secondary breaking, breaking oversize material.

A CRITERION OF PRODUCTIVITY

Hydraulic breakers are an effective method for excavating tunnels featuring geological profiles and sizes that make blasting a difficult or uneconomical solution. As we pointed out in the first chapter, while the TBM is the most efficient excavation method today, there do exist a range of situations (size and position of the tunnel, radii of curvature, logistical complexities, etc.) where its use is not feasible or advisable due to the costs or hazards that this method would involve. By contrast, blasting, the traditional method of excavation, ensures good rates of production provided the rock mass has characteristics of compactness that permit blasting to be efficient. Alternatively, the hydraulic breaker assures good productivity when the rock mass has a limited hardness (usually under 50 MPa) and especially limited fracturing so that blasting cannot guarantee satisfactory production levels. From this standpoint, breaker and blasting can also be considered complementary excavation methods and, contrary to the tunnel boring machine (exclusive method due to the costs and time that switching methods would involve), can be alternated whenever the geological profile includes rock masses that oscillate between strong compaction and hardness and higher fracturing with reduced levels of hardness. Obviously switching is not unaffected by costs and in any event involves time, though

minimal, for suspension of works. However, the delay is not comparable to what would be the case if the excavation technique were to be changed after originally establishing that the TBM would be used on the construction site. When utilized in the most appropriate situations, the hydraulic breaker also has an impact on site logistics, since it allows for a reduction in the number of personnel and the number of machines required for excavation (teams assigned to drilling and inserting explosives, or drilling rigs themselves are not required) with positive effects on the contractor's profitability. Also the project timetable benefits from the use of the breaker because, as shown, when the size of the tunnel permits, the use of this method enables excavation and muck hauling to be carried out at the same time.
There are many technical documents and reports on the use of the breaker for quarrying; however, it rarer to find documentation on the production capacities when this equipment is used for excavating tunnels. One of the most well-known references is the study **Performance Prediction of Mechanical Excavators in Tunnels** by Turkish engineers Nuh Bilgin and Cemal Balci in 2005. Included in the study is a calculation criterion that makes it possible to add or at least to establish parameters necessary for determining the productivity of the breaker used for tunnel excavation. The prediction of net breaking rate according to that formulated by Bilgin and Balci using an empirical equation was defined through the collection of data in several tunnels seeing the use of the breaker, and is calculated as follows:

PREDICTION OF NET BREAKING RATE OF HAMMER

The following empirical equation was obtained using a database on the application of impact hammers in different applications.

$$IBR= 4.24P(RMCI)^{-0.567}$$

$$RMC= \sigma_c(RQD/100)^{-2/3}$$

where:

IBR	is the instantaneous or net breaking rate m^3/h
P	is the power of the breaker in HP
RMCI	is the rock mass cuttability index in MPa
σ_c	is the uniaxial compressive strength in MPa
RQD	is the rock quality designation in percentage

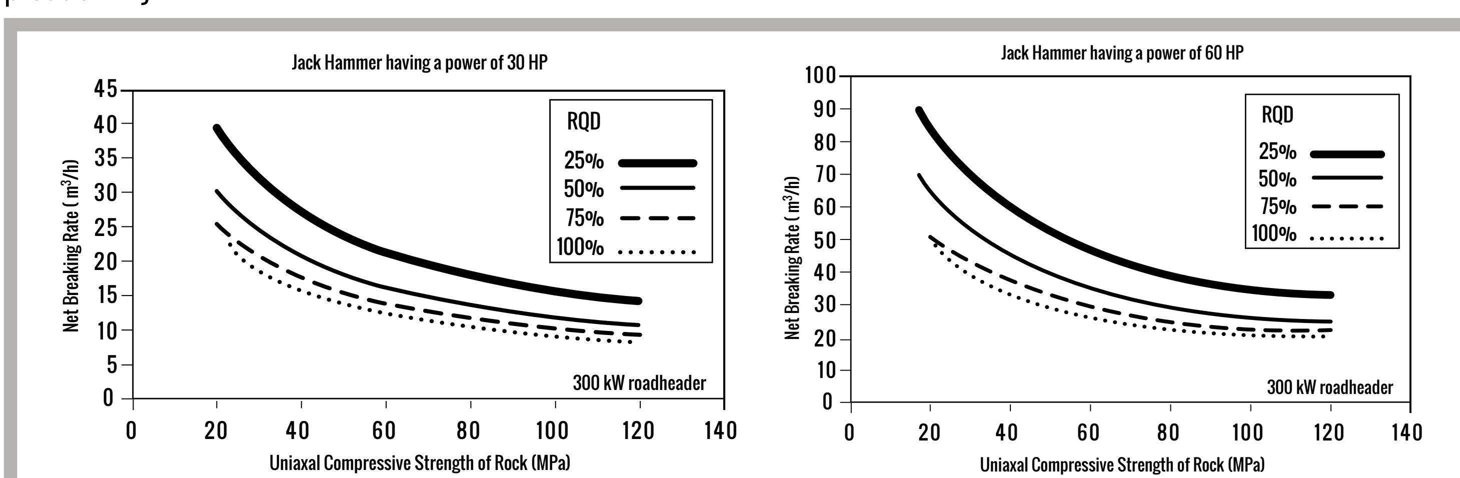
Performance prediction of mechanical excavators in tunnels by Bilgin, N & Balci, C.

The productivity of hydraulic breakers also depends on various factors such as the energy of impact and the frequency, the strength and the tenacity of the rock mass, the ability of the operator, the excavation techniques, the condition of the excavator, the logistics at the excavation site, and finally the extent of the load exerted on the breaker by the excavator. It is precisely the load exerted on the breaker by the excavator to be essential in the process of transmitting energy from the breaker to the rock. If this load is insufficient, part of the energy produced by the breaker is not transferred to the rock mass and instead generates an undesired movement of the point, so-called bouncing, and clumps of dust between the tool and the material. The result is reduced breaking efficiency, rapid wear of the tool, and strong vibrations of the breaker body and excavator boom. The clump of dust absorbs the energy of the tool resulting in a significant reduction in productivity and the tool needs to be quickly repositioned in order to avoid this problem. The Indeco-designed damping system isolates the breaker body from the casing by absorbing most of these undesired vibrations and protecting the excavator from possible damage and the operator from the risk of being submitted to strong vibrations. A load generated by the excavator that is too high could cause the premature wear of the breaker and very high stresses due to impact to the excavator when the rock mass collapses.

The output power for a breaker is the product of the impact energy and frequency. The optimum value of the impact frequency depends on the material that will be demolished. A weak material characterized by high penetration requires a high striking rate. If the material being demolished is very hard, a striking rate that is low and characterized by a higher energy per blow favours the crushing of the rock.

A lower striking rate also lowers the degree to which the point is heated up, avoids the reduction of hardness of the sharp edge due to the heat and significantly reduces its wear. As we may deduce, the ideal breaker should allow **the automatic adjustment of the work parameters**, such as the frequency and striking energy, according to the characteristics of the rock in order to maximize productivity in any work condition. In demolitions using the breaker the crushing of the material generally takes place after a high number blows, approximately 2-200.

During **breaking by penetration**, the value of the penetration of the tool in the rock is considerably reduced progressively as the tool penetrates into the rock. Instead, when demolishing very hard rock no penetration is noted until collapse. It is known that the optimum values of impact energy depend on the hardness and the fissure of the material to be demolished. If the rock is penetrated or the rock masses are fractured with a very low number of blows (2-5), this means that the energy of the blow is too high for the application. In this case a high percentage of energy of the blows may damage the breaker (blank firing) and a potential reduction in the impact energy will not affect productivity.

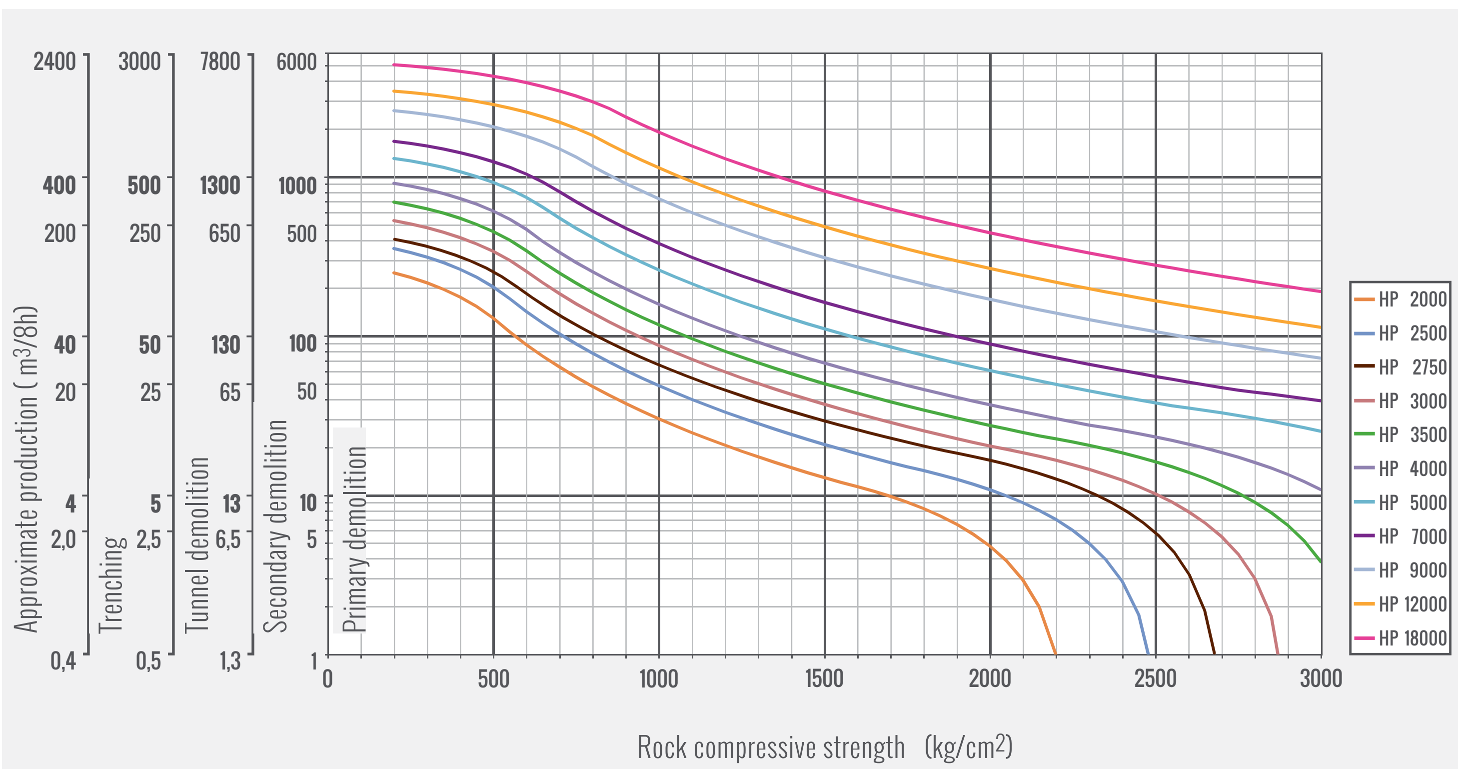


The statistical relationship between rock compressive strength and instantaneous breaking rate of hammers for a given RQD and power of the hammer.

For this, the efficient ABF system (Anti Blank Firing) included on all Indeco mid-range and large breakers eliminates blank firing of the tool by deactivating the breaker's percussion cycle if the tool is not stably resting on the surface to be demolished. The system consequently extends the life of the parts subject to wear and reduces the stresses transmitted to the body of the breaker and the excavator boom. Should the rock mass be very hard the ideal operation of the breaker would be a reduced striking rate and a high energy per blow to allow the maximum transfer of energy by the tool to the rock and permit it to be crushed. Indeco breakers, thanks to their intelligent hydraulic system, are able to automatically vary the energy and frequency of the blow according to the hardness of the material to be demolished. As a result, the hydraulic power delivered by the machine is optimized to the advantage of productivity and a higher overall efficiency. Based on experience and measurements performed directly on the field it has been possible to obtain an empirical graph of the indicative value of productivity (m^3/8h) of the Indeco hydraulic breaker.

As we can see, **the hyperbolic development of the graphs** clearly shows that:

1) the productivity is significantly reduced with the increase of the compressive strength of the rock to be demolished plotted on the x-axis;
2 the size of the breaker (proportionate to its impact energy) implies an upward translation of the productivity curve and therefore contributes proportionally to the increase in the volume of demolished material.



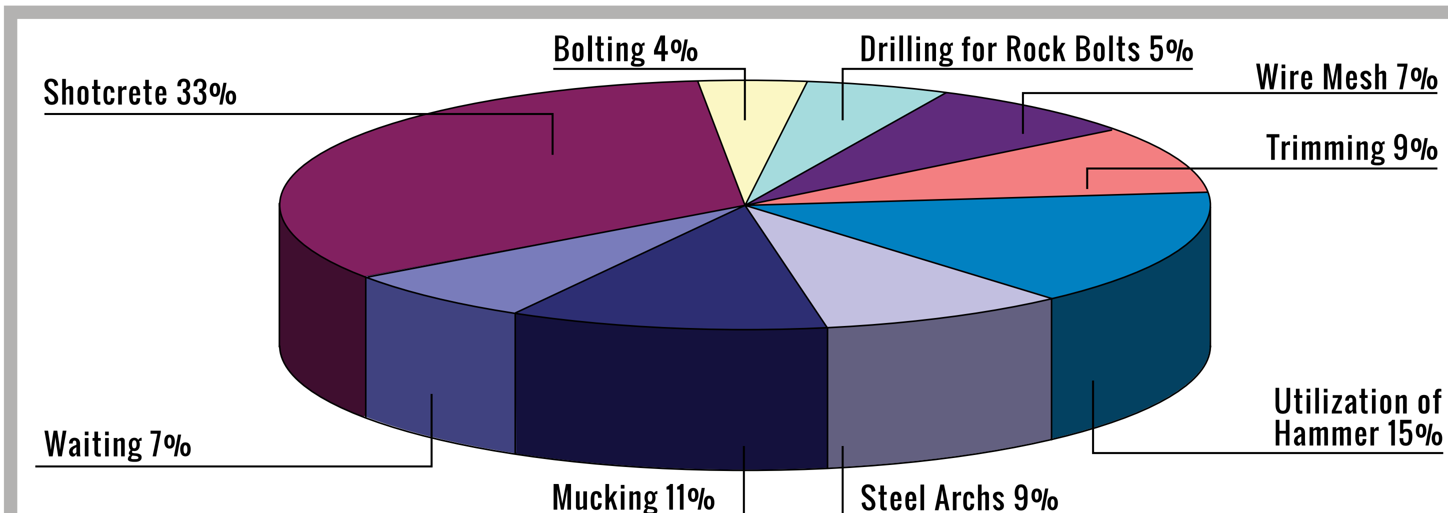
Approximate production (m^3/8h) of Indeco breakers based on rock compressive strength and type of demolition.

Productivity is strongly related to the type of demolition work the breaker is performing; heavy applications such as tunnel excavation and trenching where the excavation face is closed result in lower productivity compared to less difficult applications on open faces, such as the primary demolition or secondary demolition of rock masses.

According to the different **uses of the hydraulic breaker**, we can identify four main applications: primary demolition, tunnel excavation, trench excavation and secondary demolition of rock masses. In **primary demolition**, where blasting is difficult or prohibited, hydraulic breakers, especially large sized, have proven a valid alternative both in terms of productivity and even more so of cost-effectiveness.
Significant values of productivity (m^3/h) are noted in the presence of slightly or highly fractured rock (RQD 25-50%). As is already noted by the GSI classification, the breaker can also be complementary to blasting and covers a very broad range of use, from rock structures that are hard and slightly fractured (like porphyries and dolomite rocks) to softer, fractured and stratified rock (such as limestone, sandstone and mica schist).

The use of hydraulic breakers in primary demolition (in tunnels or quarries) offers these advantages:

1) low cost of investment
2) use of static hydraulic booms on the crusher unnecessary since the rock is broken up into pieces by the breaker
3) good control of the work site since the breaker is a precision demolition tool and allows selective excavation during scaling operations
4) secondary demolition unnecessary
5) possibility of working with two different breakers and two excavators if the size of the tunnel or site permit
6) reduction in advancement time by mucking during excavation operations (not possible with blasting)
7) higher safety of work site compared to the risk of using explosives
8) lower ground vibration values compared to blasting
9) low noise output by using silenced models called Indeco Whisper
10) better distribution of excavated aggregates (with reduction of dust produced by excavation)
11) fewer interruptions in the surrounding work area



Overall excavation performance using breaker, Istanbul metro tunnel

Compared to drill-and-blast demolition, tunnel excavation utilizing Indeco hydraulic breakers has demonstrated efficacy and cost-effectiveness, especially in Europe and Asia where it has been successful when the fractured structure of the rock mass precluded blasting. In cases where it was necessary to use both systems, however, the breaker turned out to be the most suitable tool as a complement to blasting, since it is flexible, economical and in any case always necessary (scaling, profiling of sections, excavation of the invert).

Using the breaker for tunnel excavation requires only a few work phases and a less specialized work force compared to drilling and blasting. In addition, compared to the TBM, the breaker involves a much lower cost of investment and the ability to construct tunnels with a variety of shapes.

Evaluating the cost-effectiveness of tunnel excavation using hydraulic breakers depends on several factors, including:

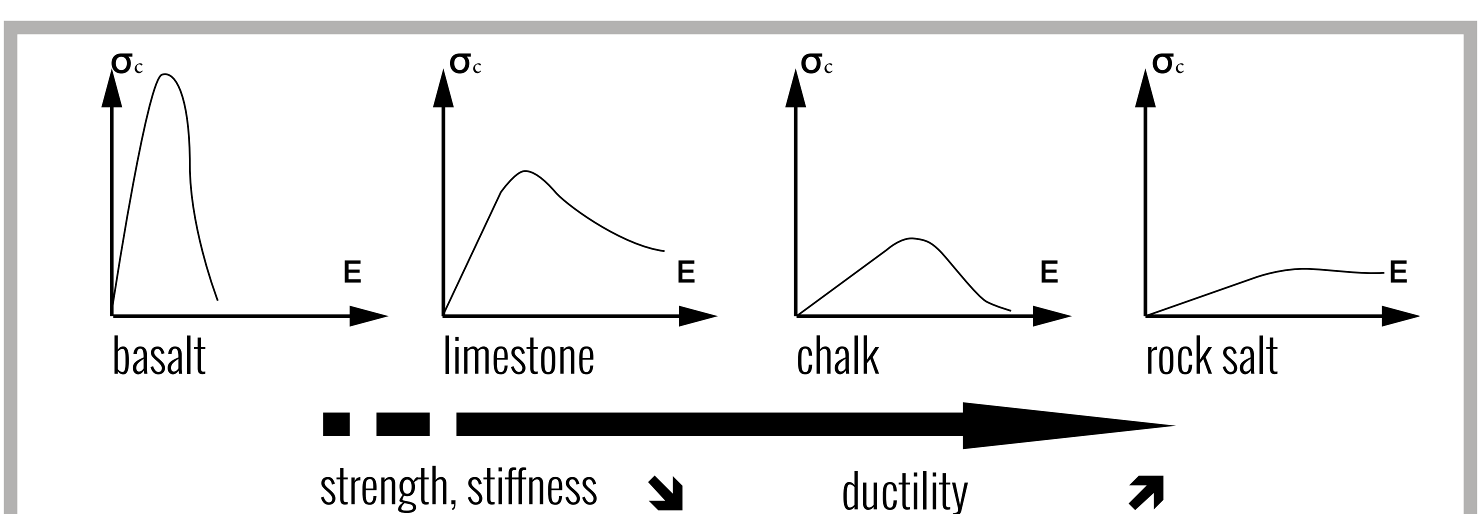
1) rock type
2) tunnel length
3) tunnel section (circular, polycentric, invert)
4) tunnel position (in locations with little access and in proximity to viaducts)
5) completion time
6) equipment availability
7) training of work force

According to **the size of the tunnel**, the excavators utilized range from 20 to 50 metric tons with breakers in tunnel configuration from 1500 kg up to 4000 kg; the tools most commonly used are the chisel and the Cobra chisel tool, and if the material is very abrasive Indeco supplies special Silver tools with a greater hardness. In a typical tunnel excavation application using hydraulic breakers, the chief advantages compared to other methods are:

1) low cost of investment
2) low cost of work force
3) safer work site (without explosives)
4) the highest precision in excavation, with significant reduction in costs due to scaling and profiling as with blasting

For excavation using hydraulic breakers to be economical, a reasonable rate of productivity is required.
The type of rock that best lends itself to demolition using the breaker should have:

1) a fragmentary rock mass with discontinuities and fractures of 30-50 cm
2) RQD < 40-50%
3) a compactness and hardness (500-1500 kg/cm^2) that allow suitable productivity by penetration of the tool
4) strength, degree of abrasion and tenacity affect productivity



Rock compressive strength (σ_c) according to deformability module (E).

Rocks with a low tenacity (they require high energy per blow but lower striking frequency) lend themselves better to breaking by impact; rocks with higher tenacity better absorb the energy of the tool (they require low energy per blow and a higher striking frequency) and collapse due to breaking by penetration, as do stratified and discontinuous rock masses. Finding homogenous and slightly fractured rock during the construction of a very long tunnel is a rather rare occurrence. Blasting as a complement to the breaker should the rock mass be particularly hard and compact is always possible, especially in the lower part of the excavation section. Using a breaker for excavating tunnels also generates an admissible level of ground vibrations under 5-10% with respect to drilling and blasting.

This is a decisive factor in the choice of excavation method when in proximity to structures or populated areas where there are limits on vibration levels.

MAIN TUNNEL EXCAVATION METHODS USING THE HYDRAULIC BREAKER

The tunnelling method using hydraulic breakers is dictated by section area and by the length of the tunnel. For reasons related to logistics and size, excavation with hydraulic breakers is suitable for tunnels with a minimum section of 30 m^2, for smaller dimensions breakers with a weight under 2000 kg and excavators of <20-25 tons. In tunnels with a height of the section under 7-10 m and area of 30-70 m^2 only an excavator with hydraulic breaker can be positioned on the excavation face. Generally speaking, the work phases include:

1) Excavation at face using the hydraulic breaker and eventual scaling
2) Transport of excavated material, mucking
3) Reinforcement of the excavated section
4) Eventual construction of the invert with mucking operations

On average, during a normal 8-hour shift the duration of excavation operations are roughly divided as follows:

- 20-25% (1.5-2 hours) excavation using breaker
- 15-20% (1.2-1.5 hours) for mucking
- 10-15% (0.8-1.2 hours) for eventual scaling and transport of debris
- 40-55% (3.2-4.4 hours) for reinforcement of the excavated section

The most common application in tunnels having an area larger than 70 m^2 is with a single excavator mounted with breaker operating on the excavation face; with this configuration excavation and mucking can be performed contemporaneously and the work phases will be reduced to the following:

- excavation using the breaker and mucking using a wheel loader
- operations to reinforce the excavated section (unsupported span)

A larger work area allows debris to be removed at the same time excavation is taking place; and the excavator mounted with breaker, the wheel loader for mucking, and truck or articulated dump truck for debris hauling can be positioned in proximity to the face. In reality, the phases of excavation and debris hauling are completed in sequence: when the

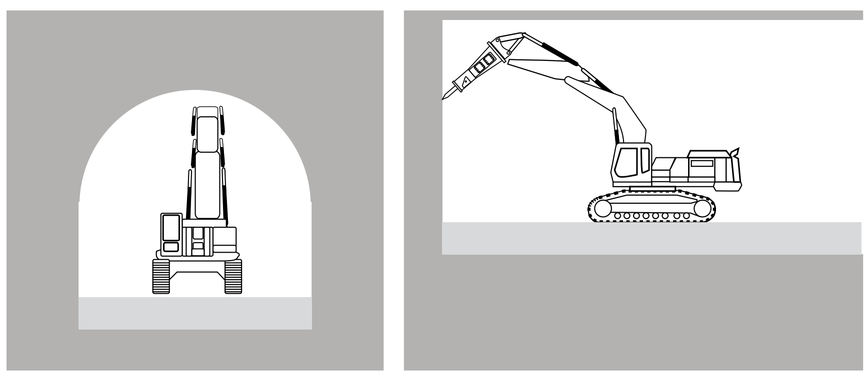
Partial excavation of tunnel enlargement, A3 SARC Normanno, HP 7000 on Hitachi 470

material has been excavated from one side of the face, the breaker can be moved to the opposite side and the material excavated is immediately removed. The immediate removal of the debris also improves the operator's visibility in the successive excavation operations.
If the tunnel section allows, excavation can be split into two phases or into partialized excavation (currently not a common technique):

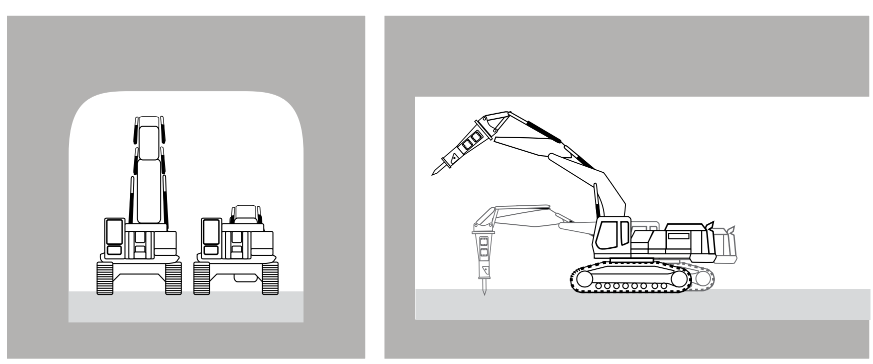
- main excavation of the face using an excavator mounted with hydraulic breaker
- secondary excavation to follow using a second excavator that removes the rock mass underneath

More common than partialized excavation is traditional excavation with two excavators in a staggered position with respect to the face (if the size of the tunnel permits) and the use of two hydraulic breakers operating on the same excavation face. However, it is not unusual to use smaller excavators and breakers to ensure the highest safety of the excavation operations and provide access to the face by other machines for mucking and debris hauling. This type of application leads to a considerable increase in productivity due to two breakers working at the same time and ensures the continuity of the excavation of one side of the face while mucking is carried out on the other. Excavation by hydraulic breaker and excavator does not require highly specialized personnel as is the case when explosives are used; in addition, it is a continuous process without the long interruptions necessary for ensuring the safety of the face and making preparations for the blasts. If the tunnel to be constructed is very long, it is advantageous to perform excavation using hydraulic breakers on both sides, or according to the resources available for excavation and reinforcement, excavation can be alternated with excavation on one side and reinforcement on the other; once the operations for each side have been completed the work phases can be inverted.
The excavation method generally employed consists of initiating the excavation at the centre of the tunnel section at a height of approximately 1-1.5 metres (pos.1) by creating a niche with a depth of about 1.2-2 metres.

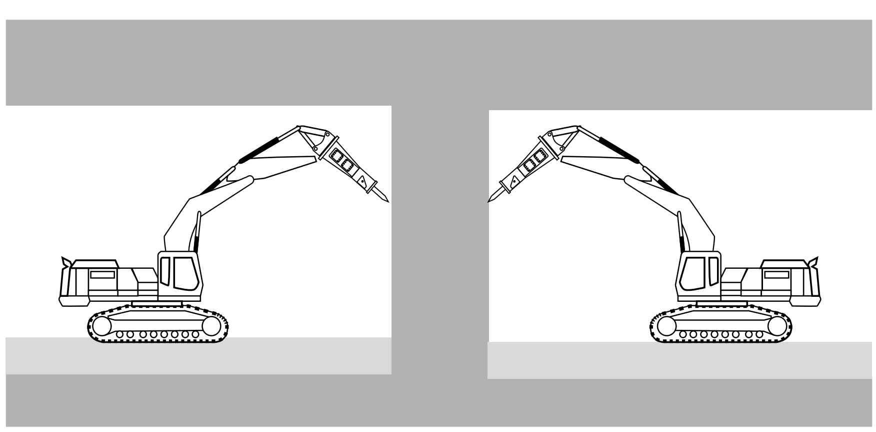
The excavation proceeds laterally with respect to the first niche with a width almost equal to the entire width of the tunnel (pos.2). After this phase is completed, excavation continues according to the same logic (pos.3 and pos.4) from the base of the tunnel up to the maximum height. The excavation niches positioned higher (pos.7-8-9-10) will reach different widths according to the shape of the tunnel. Once all excavation niches have been made, scaling operations, if required, will follow, then mucking and removal of debris. In the case where the rock of the face has planes and joints, the excavation sequences should follow the fault planes always starting from the base of the section until reaching the maximum height. In this way, by exploiting the natural weak points of the rock the productivity of the hydraulic breaker can be maximized.



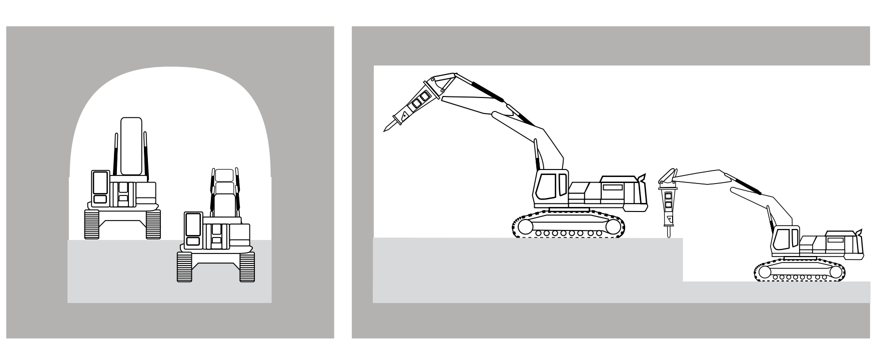
Tunnel excavation with breaker



Excavation using two breakers

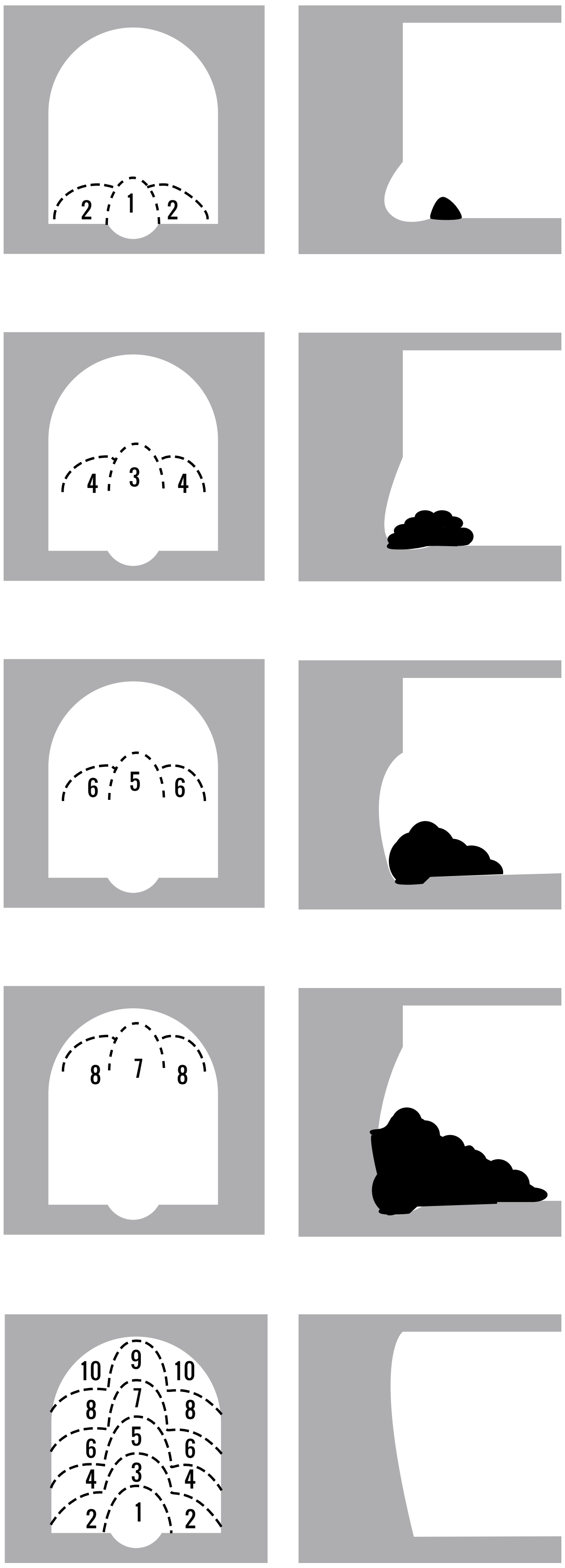


Tunnel excavation with breakers on both sides

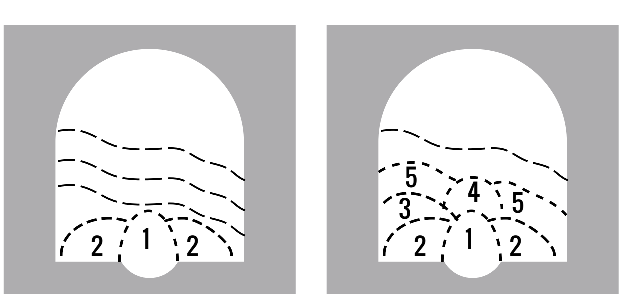


Partialized excavation with breakers staggered

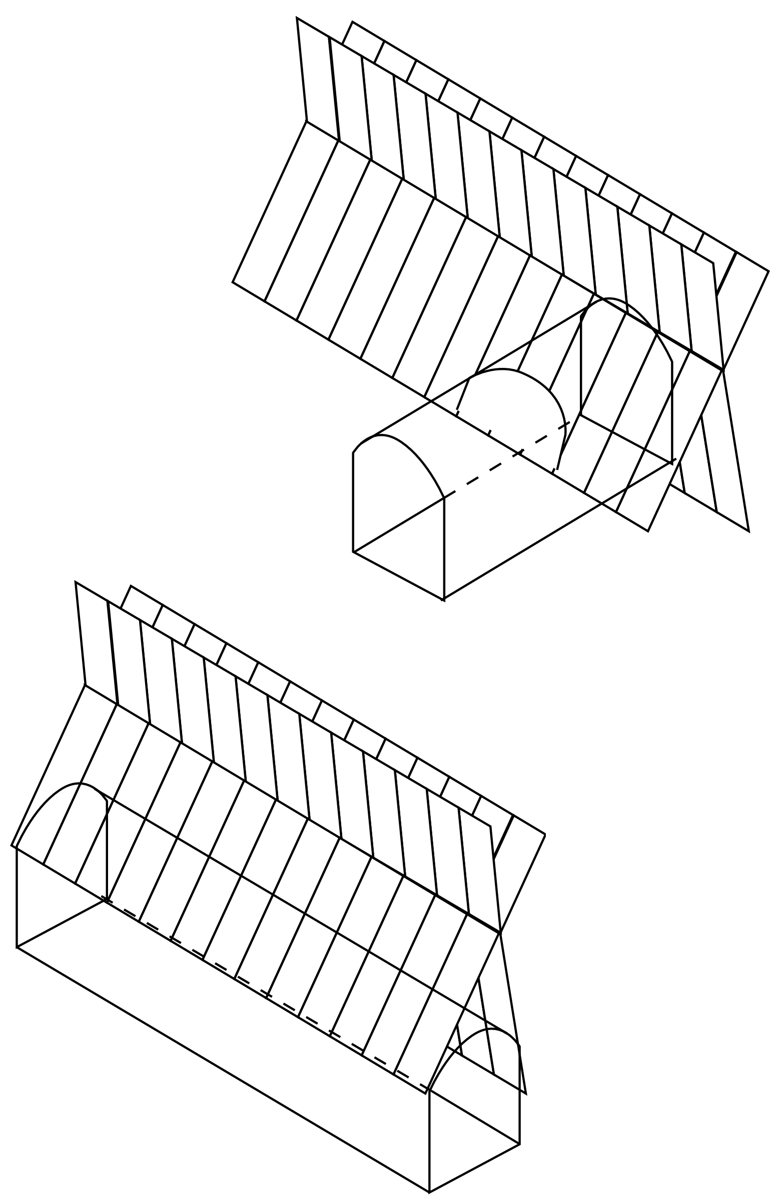
Performing a tunnel excavation is one of the toughest jobs for a hydraulic breaker. Striking times are longer and harder and can take up even 80% of the time the excavator is in operation (whereas in primary demolitions in quarries this is about 30-50%). The force that applies the excavator to the breaker in a subhorizontal position is much higher compared to when working in a vertical position; precisely due to these extreme working conditions frequent preventive and periodic maintenance is essential for the continuity and productivity of the excavation project (scheduled maintenance of the breaker is advisable). When uninterrupted production is critical and execution times for the excavation are tight, a system that utilizes two breakers working and one in stand-by is the optimum solution.



Excavation sequence



Fault planes



Effect of excavation orientation in relation to discontinuity planes

REINFORCEMENT OF THE EXCAVATED SECTION

As mentioned in the last chapter, reinforcement of the excavated section is a key aspect of tunnelling whether excavation is performed by drilling and blasting or using the hydraulic breaker, and involves procedures that impact advancement times. Both methods require that reinforcement of the excavated section be performed before the creation of the final lining. From this standpoint, the basic differences have to do with logistics and economics.

As also emphasized earlier, using the breaker has a dual advantage with respect to blasting. When conditions of size permit, such as with faces having a surface of approximately 140 sq. m typical of highway tunnels, the breaker enables excavation and mucking to be performed at the same time. In addition, use of the breaker avoids scaling operations, as are necessary with the blasting method, because the breaker can profile the section with precision during excavation.

When it comes to reinforcement, however, the differences are practically non-existent for the phases to make the first lining, and minimal as regards timing. For both excavation methods, reinforcement operations have a considerable impact on advancement times (intended as excavation, first-phase lining, waterproofing, excavation and casting of the invert, and casting of the second-phase or final lining). In any event, reinforcement is an essential part of tunnel construction, whether the method is by blasting or hydraulic breaker, because it has the function of contrasting the possible deformations of the excavated section and must be performed immediately after excavation and as close as possible to the face.

Excavation is therefore only one of the aspects of advancement and this often generates confusion when comparing the two excavation methods. The fact that using explosives allows the progression of the excavation in a single blast of even four or five metres does not mean that construction of the tunnel, as a whole, is advancing.

This is why comparing the faster speed of excavation offered by blasting with respect to the breaker is inappropriate; when explosives are used, the time taken for blasting preparations and mucking are definitely longer than for using the breaker, and therefore produce an advancement of the tunnel construction that is equal and sometimes even slower compared to the breaker. In order, the operations required for tunnel advancement are as follows:

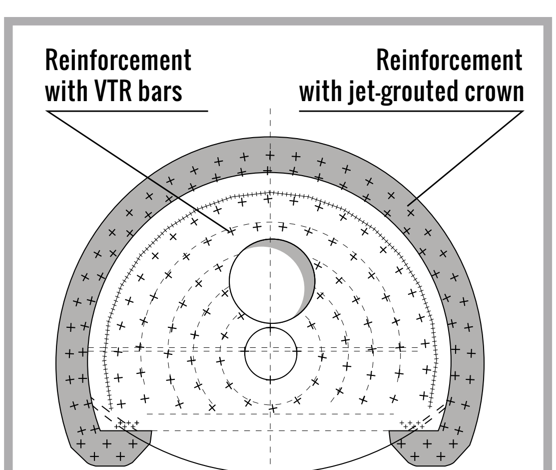
1) Pre-reinforcement of the core (when necessary)
2) Excavation
3) Installation of ribs and/or rock bolting and nailing
4) Application of fibre-reinforced shotcrete
5) Excavation of invert
6) Casting of invert and shoulders
7) Installation of PVC lining
8) Casting of final lining

In certain cases between Phase 2 and 3 the process calls for the installation of a large mesh to reinforce the shotcrete, which is not fibre-reinforced in this case.

Pre-reinforcement of the core-face

Using the breaker for a full-face excavation, by now much more common than for partialized sections, often implies that if the face is characterized by a rock mass where phenomena of instability can arise, typical for example of loose, incoherent clay soils, it is necessary to perform pre-reinforcement of the core. The technique is well defined by the ADECO RS (Analysis of Controlled Deformations in Rocks and Soils, a method developed by Lunardi) which makes it possible to work full face, even in very loose terrain, without resorting to partialized excavation, as provided for in the NATM method, in these cases the only method possible to deal with very difficult conditions.

ADECO RS was developed in Italy to cut through highly unstable formations, such as the “chaotic” formation of the Tuscan-Emilian Apennines, where in the 1990s the new high-speed rail was built, followed by the Variante di Valico, a deviation of the A1 highway, between Bologna and Florence. The extreme variability and unreliability of the geology, especially along the route of the high-speed rail where a total 100+ km of tunnels were constructed including principal (over 73 km), secondary and service tunnels, did not allow for full-face excavation following the NATM method, and only in a few cases fully mechanized excavation technologies (shielded TBM). The method was used in other countries as well, such as France where it proved extremely efficient for the Tartaguille Tunnel along the Marseilles-Lyon line. In effect, this reinforcement technique makes it possible to work on the whole face because it creates a sort of “temporary nailing” of the face-core

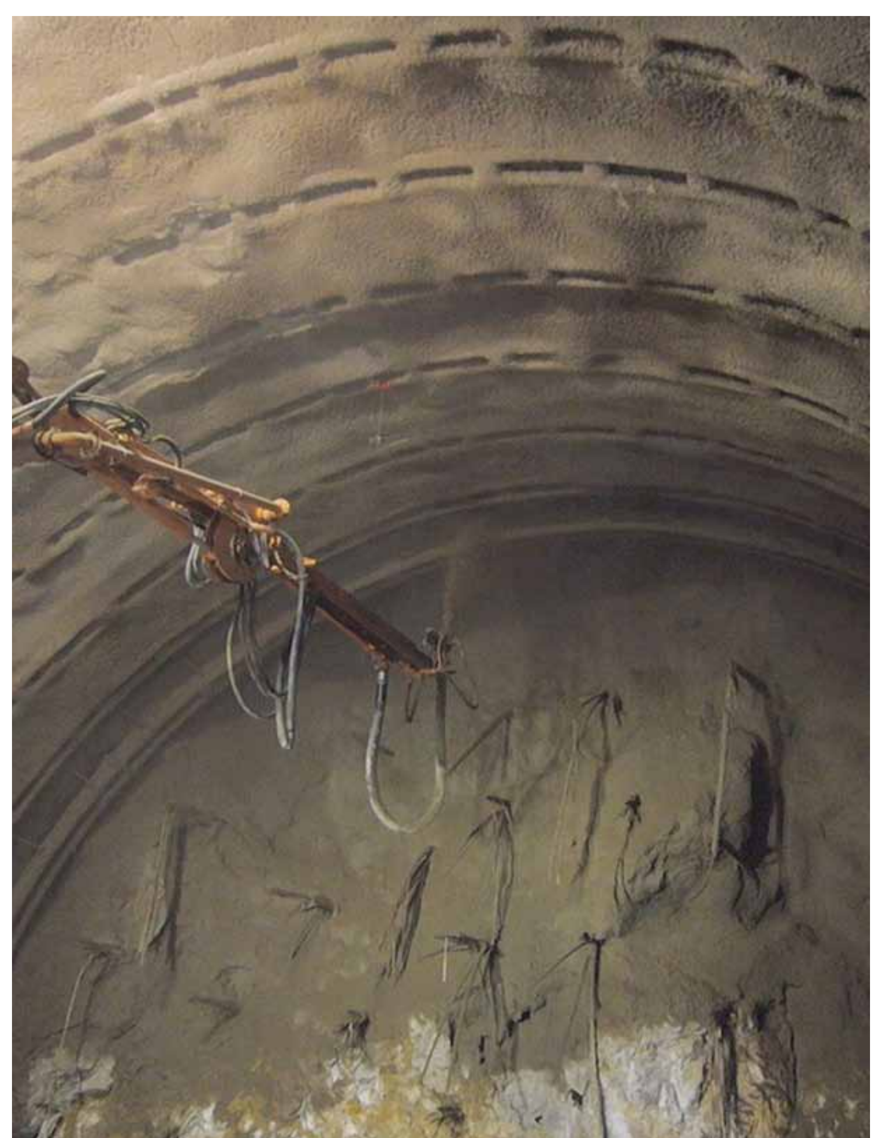


Section with reinforcement

that assures its stability; during excavation operations it counters the loads, thereby preventing dangerous phenomena of extrusion. The length of the fibreglass reinforcement elements and their number vary according to the geology of the rock mass, but these elements can reach 18 metres and on larger excavation faces can exceed 100 units.
The bars, which usually have a diameter of 60 mm, are hollow on the inside and can be injected with special grout. Once the fibreglass reinforcement elements are installed, excavation continues until, after the various cycles of the first-phase lining (0.50 -1.50 metres according to the case), it arrives at approximately 1/3 of their length. The fibreglass bars are easily destroyed by the excavation action and do not cause any problem to the breaker. The excavation is then suspended and new fibreglass bars are inserted so that the face is always reinforced and secure. In the event of high instability a permanent crown around the exterior is constructed via jet grouting to create an arch of pre-support and reinforcement around the perimeter so as to further relieve the core from the loads that could contribute to its extrusion. From a timing perspective, the pre-reinforcement of the face-core is directly related to the number of bars in fiberglass to be positioned, their length and the procedure to inject them. Usually, the operations require an average time of two to three days, but can arrive up to five working days if a jet grouting crown must be created.
Taking, for instance, an advancement of one metre a day (excavation, mucking, rib installation, shotcrete) and formulating an example to determine execution time, we could say that with a bar length of 18 metres, before proceeding any further with the excavation (considering that two-thirds of the length must always be inserted) the pre-reinforcement of the face must be performed every six days.

The first-phase lining

The first-phase lining is essential for a short to medium term reinforcement of the excavation and is achieved by installing ribs and concrete (shotcrete), which can also be reinforced with an electro-welded wire mesh, or reinforced using steel or polymer fibres. After the muck is removed and prior to installation of the ribs, the face is stabilized by spraying of a layer of fibre-reinforced shotcrete. Subsequently, if the reinforced mesh is not required, after procedures to assure safety of the face, the ribs are assembled at ground level, then erected into position, centred and fastened to the preceding rib by means of chains (rigid fittings), which are inserted into slots along the ribs. The space between the ribs, which can usually vary from 1.50 m to 50 cm, is determined by the project according to the characteristics of the rock mass's stability. The average time for assembly and



installation of the ribs, together with the application of a layer (5-10 cm of fibre-reinforced shotcrete) is estimable at around 4-5 hours for a tunnel with a 120-130 sq. m face.

Rock bolting and nailing

According to the type of rock mass, the first-phase lining can also involve nailing or rock bolting. The main difference between the two techniques is that while the dowel stresses the material in order to force its movement such to achieve an effective locking action, the rock bolt, acting like a permanent tie, aims by counter action to prevent the rock bolt from moving. Depending on the case, both systems can be integrated with the installation of wire mesh and shotcrete. What is highly variable is the time needed to perform this phase of reinforcement. If, in fact, the system of rock bolting/nailing is only applied to the roof, the time can be limited to within four hours. However, if the procedure requires a "crown" to be positioned with reduced spacing, a longer time must be taken into consideration, even extending to 24 hours.

Excavating and casting the invert

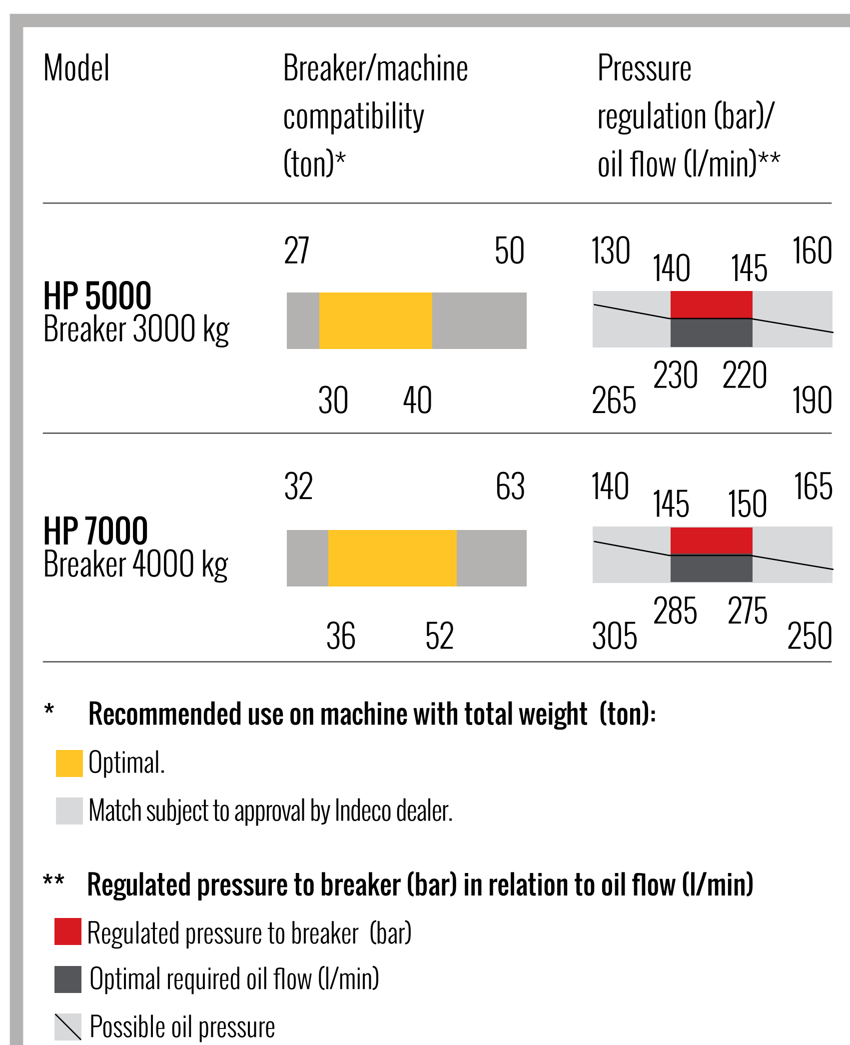
The invert is a structural element essential to limiting and controlling deformations in tunnels. Structurally speaking, the invert is connected to the side walls, both in circular sections and polycentric sections.
Constructing the invert is therefore an integral part of tunnel excavation. Moreover, unless the rock is highly fractured and unconsolidated, the invert is created using the breaker even when the blasting method is used for the excavation of the actual tunnel.
Theoretically, the invert, which does not require a first-phase lining, just the final lining, may be constructed right after each field excavated on the face (equivalent to the diameter of the tunnel), but production restraints and logistical considerations impose, where conditions of the rock mass permit, a ratio of four fields to the excavation face; in the presence of highly unstable rock masses, this ratio is reduced to two. The execution of the invert involves a series of phases (excavation, formwork, reinforcement, curing, formwork removal), which have a significant impact on the site logistics considering that the invert and excavation cannot be executed at the same time. Hypothesizing a field of 10 metres with material characterized by strengths of approximately 45 MPa, 6-7 hours will be dedicated to the excavation, one day (24 hours of work) to the installation of pre-assembled reinforcement and casting, and approximately 8 hours to allow for the curing of the cast and the removal of the formwork.

SELECTING THE HYDRAULIC BREAKER FOR TUNNEL EXCAVATION

As we pointed out, choosing a breaker primarily depends on the section of the tunnel, which determines excavator size. Generally speaking, the choice will be for the largest breaker possible which obtains the best coupling of breaker-excavator. Utilizing an excavator specially prepared for tunnelling (with short boom and larger under carriage) usually allows for mounting a heavier breaker that can deliver greater productivity; by increasing the size of the breaker and reducing the size of the excavator (if coupling criteria, such as machine stability and generated hydraulic power are met) the result is a more efficient coupling of the breaker-excavator thereby reducing the costs of the excavator in relation to the quantity of material excavated. Generally speaking, breakers are classified on the basis of operating weight and tool diameter, both parameters giving an idea of the size and power (parameter related to productivity, but not always does higher power mean high productivity) of the breaker. The breakers most commonly used for tunnel excavation weigh between 3000 kg and 4000 kg (73-84 Kw) with tool diameters from 160 mm to 180 mm, and the most suitable excavators for this type of work respectively have an operating weight ranging from 30 to 50 metric tons (power from 180 Kw to 280 Kw). Based on field experience, the breaker manufacturer supplies information regarding the optimum coupling between the breaker and excavator (see figure). The optimum coupling for a 3000 kg breaker is achieved by installing it on 30-40 ton excavators, whereas coupling is possible with excavators weighing 27-50 tons. Supposing we want to use a 3000 kg breaker for tunnel excavation, the use of a 50-ton excavator (a possible combination) instead of a 35-ton excavator (an ideal combination) assumes:

1) a higher cost of investment for the excavator
2) a higher cost of excavator maintenance
3) a higher cost of use
4) difficulty in handling due to size
5) practically unvaried excavation productivity since productivity is determined by the performance of the breaker installed

With their numerous models, divided into large, mid-range and small ranges, Indeco boasts the widest range of hydraulic breakers there is. This enables users a broad choice in order to obtain the ideal carrier-breaker combination.



Machine/breaker compatibility and regulation parameters

PREPARING THE BREAKER FOR TUNNEL APPLICATIONS

As we said, the excavation of a tunnel is one of the toughest jobs that a hydraulic breaker can perform. Striking times are long and hard and can reach up to 80% of the time the excavator is in operation. Special precautions must be made when preparing the breaker in the tunnel in order to ensure maximum reliability of its operation and safety of the excavation face in terms of dust concentration in the air and visibility.
Below is a list of some technical characteristics that a breaker operating in a tunnel should have:

1) Special coupling plate between breaker and excavator to enable acute angling.

2) Dust abatement kit and high pressure water misting system (150 bar) to reduce the quantity of dust in the operating zone of the breaker and to assure the full safety and visibility of the excavation operations.

3) Dust protection kit for breaker. Significantly reduces the entry and the presence of dust in the bushings and consequently the area of impact between the piston mass and the tool.

4) Internal pressurization kit by means of compressed air to neutralize the entry of dust into the breaker. This avoids the premature wear of sliding components and damage to the breaker's percussion system.

5) Anti-blank firing system. In breakers fitted with this system, the cycle of percussion of the piston onto the tool will not be activated if the tool is not stably resting and pressing onto the surface of the material to be demolished. This system reduces wear and increases the reliability of the breaker.

6) Automatic centralized lubrication kit, assures the perfect lubrication of the bushings and the tool in any working condition, significantly reducing the wear of the bushings and protecting the tool from breakage. Specifically, the centralized greasing system allows sliding parts to maintain their lubrication even when the breaker is operating in a horizontal position.

7) Air/water compressor kit to be installed in the excavator cabin for production of compressed air required needed for pressurization (7-10 bar) and water under pressure 150 bar) needed for the breaker's misting system to reduce dust produced during demolition.

8) Silenced casing of the breaker. Casing is lined on the inside with sound-proofing material, features sound insulation paint and sound-proofed bushings in the tool area to significantly reduce noise emissions.

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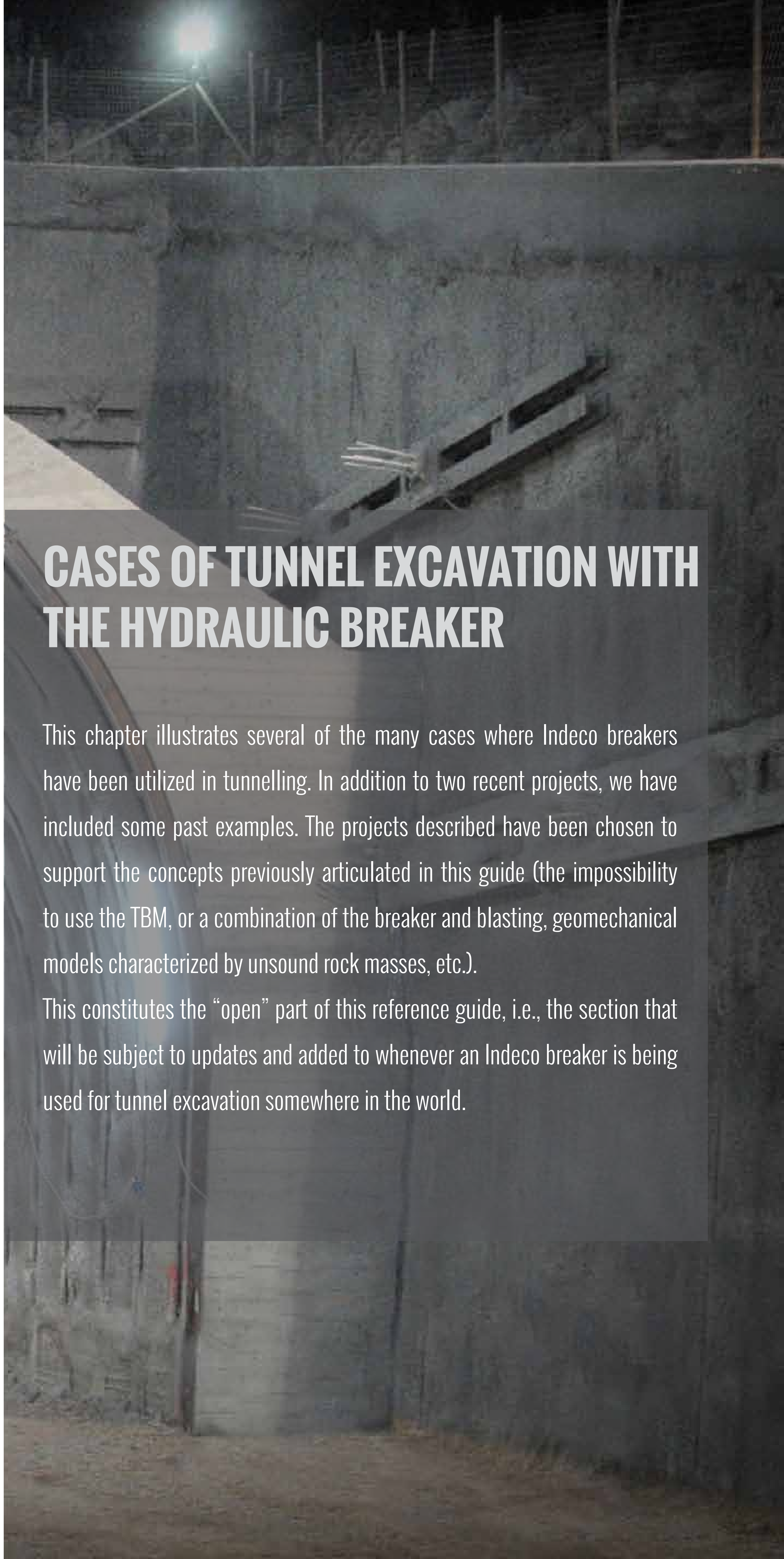
FOCUS ON

- SGC E 78 - Greppoli Tunnel
- A3 HIGHWAY - Serra Rotonda Tunnel

Past cases

- The Bologna-Florence high-speed rail "Alta Velocità"
- The new Lausanne metro
- The "Variante di Valico"



CASES OF TUNNEL EXCAVATION WITH THE HYDRAULIC BREAKER

This chapter illustrates several of the many cases where Indeco breakers have been utilized in tunnelling. In addition to two recent projects, we have included some past examples. The projects described have been chosen to support the concepts previously articulated in this guide (the impossibility to use the TBM, or a combination of the breaker and blasting, geomechanical models characterized by unsound rock masses, etc.).

This constitutes the "open" part of this reference guide, i.e., the section that will be subject to updates and added to whenever an Indeco breaker is being used for tunnel excavation somewhere in the world.

SGC E 78
GREPPOLI TUNNEL

Route of the SGCE 78 and position of the Greppoli Tunnel

The HP 7000 hydraulic breaker and an HP 5000 were used for the excavation of a small tunnel where blasting could not have performed since the tunnel was being constructed alongside a trafficked road.

In March 2014, works were completed to excavate the “Greppoli” Tunnel situated between Grosseto and Siena in the section of road near Civitella Paganico on the SGC E 78, also referred to as the “Highway of the Two Seas” because it connects the Tyrrhenian coast with the Adriatic. This major road is a category A highway, which when complete, in part by upgrading an existing route and in part by creating a new one, will connect Grosseto to Fano on a southwest/northeast axis. The 100-metre long Greppoli Tunnel is one of the many projects included in the macro-lot of Civitella Paganico (Grosseto) - Monticiano (Siena).
Considering the geomechanical model, the short length of the tunnel, and the fact that in that particular segment the existing road to be upgraded ran nearly parallel to the new tunnel, the blasting method was discarded in favour of the hydraulic breaker. Selected to perform the works were Indeco HP 7000 breakers (in several short sections also using an HP 5000) utilized by Strabag, participating contractor in the Nuova F.A.R.M.A.Scarl Consortium assigned to perform the works of the new macro-lot. Also included is another larger tunnel (Casal di Pari), it too excavated with Indeco breakers and in course of completion at the time of publication of this guide.

The geomechanical model

Data obtained from various geognostic surveys indicated that the rock mass through which the tunnel cuts was primarily characterized by cavernous limestone with medium-poor mechanical characteristics attributable to the RMR III-IV classes with short-term face stability but stable excavated section. However, during the stages of excavation there was determined to be a heterogeneous development of the rock from the south entrance where the tunnel face was opened. This featured limestone and compact microcrystalline dolomitic limestone, homogeneous, and resistant to

being excavated. The compressive strength, evaluated via sclerometer tests (Schmidt L type breaker) in that section was variable between JCS=39÷44 Mpa. Advancing from the south entrance and working north, the rock mass immediately underwent a progressive deterioration in quality and widely demonstrated the presence of more altered portions of the formation composed of breached limestone including dolomitic clasts with variable granulometry generally coarse-grained with calcareous cementation, from altered to very altered, slightly fractured, and relatively resistant to excavation. The compressive strength of this section, evaluated via sclerometer tests (Schmidt L type breaker) was instead variable between JCS=28÷33 Mpa. The discontinuity and marked fracturing of the rock mass prompted engineers to perform short-term reinforcement of the stable face using injected fibreglass tubes and sub-horizontal reinforcement elements (Adeco RS system). The works to reinforce the face had an impact on project completion time, but was necessary in order to guarantee medium-term stability, which was put at risk due to the characteristics of the rock mass.

The excavation

As pointed out earlier, the tunnel measured 100 metres and according to the section, had an excavation face with a surface that varied from 136 to 143 sq. m (two carriageways plus emergency lane). Initially, due to the hardness and compactness of the rock characterized by limestone and compact microcrystalline dolomitic limestone, excavation output was low and chisel wear was higher than average. However, by using “Cobra” chisels and then, once reaching the more fractured material, output stabilized at an average excavation rate of approximately 14 cubic metres per hour corresponding to an average advance rate of two linear metres per day, considering the time required for the pre-shotcrete and first-phase lining (shotcrete, rib assembly and installation). Again, the invert was constructed using the breaker. Works commenced in early November 2013 and were completed in early March 2014.

A3 HIGHWAY
THE SERRA ROTONDA TUNNEL

Route of the A3 highway and position of the Serra Rotonda Tunnel

Blasting alternated with the hydraulic breaker is a collaborative method for excavating particularly hard rock masses. Two HP 7000 have contributed significantly to the excavation of the Serra Rotonda Tunnel along the Salerno-Reggio Calabria highway.

The A3 Highway

The A3 Salerno-Reggio-Calabria highway, a non-toll road managed by ANAS (the state-owned company that constructs and maintains highways) runs a total of 442.9 km, The road infrastructure was originally built between 1966 and 1974 in an area where road construction is a unique challenge due to the orography, geology and in certain sections levels of seismicity. Since 2001 the A3 has been the subject of major works as part of a project encompassing both the incorporation and upgrading of the old highway and the definition of a new and parallel route. To date, 339 km have been completed with success, whereas the remaining 68.5 km are currently undergoing construction.

The Serra Rotonda Tunnel

The twin-tube tunnel of Serra Rotonda is part of the macro-lot 3 part 1 of the new route of the A3 contracted to GLF Spa. The site of the tunnel is located in the Basilicata region in proximity to the town of Lauria. The north tube measures 3,725.50 metres, plus a 135.86 metre manmade section at the north portal and a 7.10 metre manmade section at the south portal. The south tube has a total length of 3,740.00 metres plus a 128,65 manmade section at the north portal and a 7.10 metre manmade section at the south portal.

The geomechanical model

In the first 600 metres after the north portal, the tunnel cuts through deposits of “Lagonegro”, alternations of siliceous marl, argillite and calcilutite with poor geotechnical characteristics that give rise to settlement or subsidence on the surface. Here it was necessary to organize the work in sections in order to counter the loads. The remaining segment runs entirely within the formations of the carbonate unit of Monte Pollino, consisting of limestone and graded calcarenite and in dolomitic limestone, with maximum overburdens of about 430 metres. In the central zone, instead, the excavation cut through dolomitic limestone and dolomites that were intensely fractured indicating the presence of karts formations. The south side, where the works commenced, features limestone and calcarenite, as well as several faults, and

was adjacent to the slope. From preliminary surveys performed along the route, it was verified that the water table would always be under the tunnel route. Because the geological model varied, seven different type sections studied according to the stress state of the rock mass would be used.

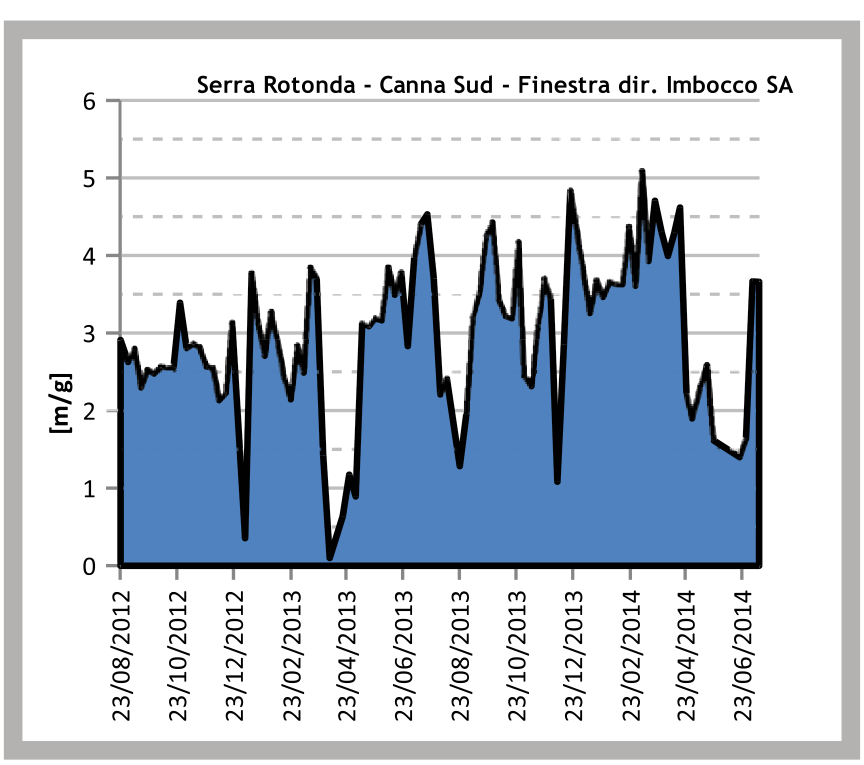
The excavation

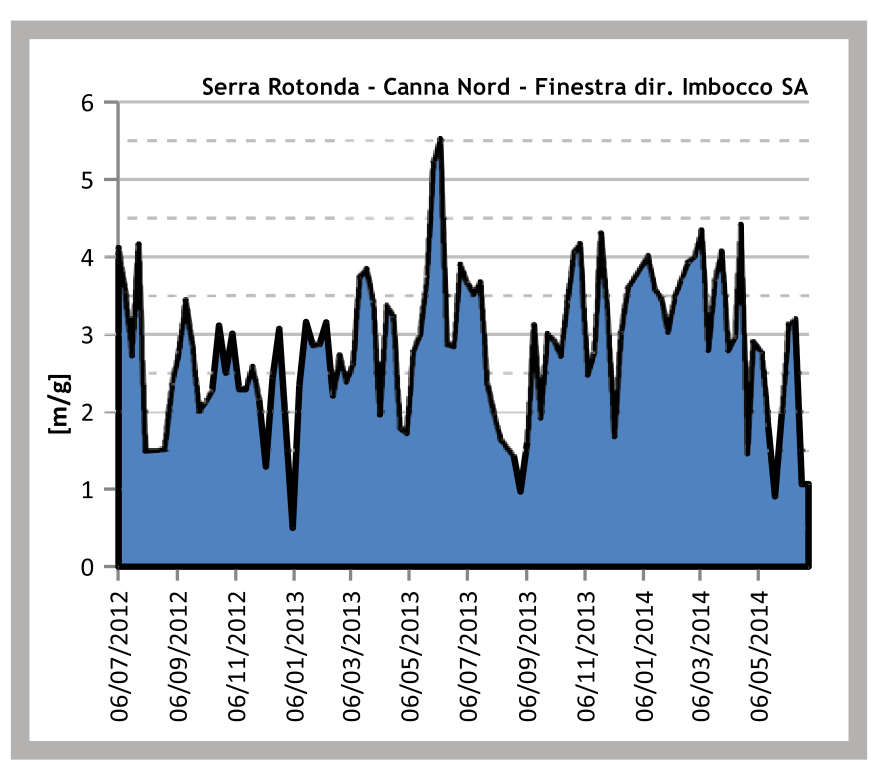
Blasting and breaker were chosen for the excavation 1) due to the characteristics and lack of homogeneity of the geological model, and 2) because in the south direction both the tubes would lead out directly onto a viaduct under construction, a condition that by itself would make the TBM an unviable solution.

The excavation commenced from the south entrance (Reggio Calabria side) and was carried out with the breaker in the north tube for a length of 2,424 metres, while in the south tube for a length of 2,357 metres. The rock mass did not always demonstrate levels of fracturing and hardness to permit excavation with the breaker. Specifically, the production rate (averaging 4/m/day with peaks of 6-7 m/day) progressively decreased until reaching levels below 1 metre per day, when the advancement reached the area with limestone and graded calcarenite, slightly fractured and with pronounced karst phenomena with values approximating 70 MPa. At that point it was decided to suspend use of the breaker and opt for blasting. For a short segment the production in the tube continued according to a technique that could be defined as "hybrid", where for reasons due to the fracturing of the rock mass the blasting method failed to be completely efficient. For less than 50 metres the breaker was utilized to complete the actual excavation and profiling operations and not just scaling, while it continued to be used for the excavation of vehicle-accessible bypasses that would allow transit from the north tube to the south tube and vice versa. At metre 2,795.00 an opening was created from which Castellano SpA (subcontractor assigned to the excavation) advanced in both directions, toward Salerno and Reggio Calabria, in both tubes so as to accelerate advancement of the excavation. Castellano used the Indeco HP 7000 hydraulic breakers from the opening in the north tube for 1,156 metres, whereas blasting was selected for the rest of the segment of roughly 806 metres; from the opening in the south tube, the breaker was used for 1,064 metres, while the remaining length of 753 metres was excavated using explosives until the rock mass (featuring alternations of siliceous marl, argillite and calcilulite with poor geotechnical characteristics) required the reinforcement

of the face with fibreglass subhorizontal reinforcement elements using the ADECO RS system. In this area, a presence of methane gas was detected (already noted during the geognostic survey), which could have been in enough quantities to fall within the stoichiometric ratio hazardous for excavation operations (between 5 and 16%). The Operations Management then requested the use of special excavators equipped with explosion-proof protections, which were provided by Technoscavi. In this case too, the subcontractor utilized Indeco HP 7000 breakers for a segment of 344 metres in the north tube and 401 metres in the south tube. Even working on material that was minimally cohesive and highly fractured, with values in some cases under 8 MPa, the breaker proved an excellent excavation method regardless of the presence of gas, which obviously made it necessary. Blasting, when the material to be excavated is dishomogenous, highly fractured and somewhat cohesive would have delivered production rates that were too low, with preparation times, blasts and mucking that would have been nearly identical to those typical of more solid and compact rock masses.

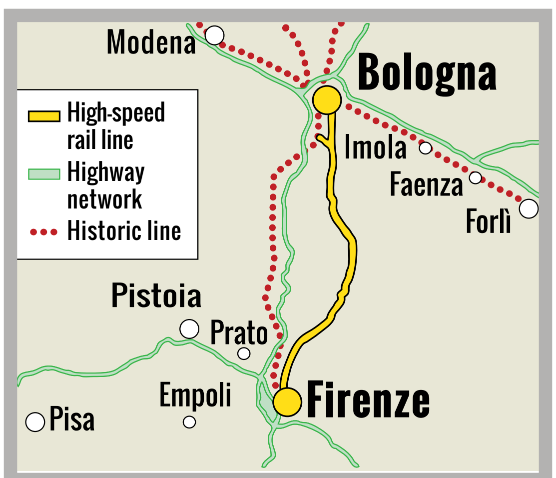
As we can see from the graphs referred to monthly production, very good production results were achieved where the use of the breaker was most intense. This was made possible by the ideal conditions created by a very fractured rock mass with RMR equal to 36 correct (CLASS IV of Beniawski), characterized by GSI values between 33 and 38 and a uniaxial compressive strength of 15-40 MPa.





PAST CASES

BOLOGNA-FLORENCE HIGH-SPEED RAIL "ALTA VELOCITÀ"



Bologna - Florence high-speed rail route

The Bologna-Florence high-speed rail line, part of the Milan-Naples high-speed route, is 78.50 km long and travels underground for 73.31 km (in nine different tunnels), with a diameter of 11.50 metres. Train speed is 300 km/h with a minimum radius of 5,500 metres and a maximum slope of 15 per thousand. The first construction sites were opened in 1996 and the line, which entered into operation in 2009, is today one of the most highly trafficked of the Italian and European rail network. This rail infrastructure was the result of intense work: in eight years, between 1996 and 2004, over 100 km of tunnels were excavated. In addition to the nine tunnels of the line with excavation diameter of 13-14 metres and 140 sq. metres of section, there are various access tunnels and service tunnels used for emergency and escape as well as maintenance of the line. Added to these is a long service tunnel of 10 km (mostly parallel to the final segment of the Vaglia tunnel). The construction of the main tunnels and the secondary tunnels required the removal of over 12 million cubic metres of material.

Like the new route of the A1 highway (known as the Variante di Valico) that winds along a route crossing through the Tuscan-Emilian Apennines and the A3 highway of Salerno-Reggio Calabria, this infrastructure project was constructed in one of the most difficult and complex geological contexts in the world and demanded an enormous logistic and organizational effort. For its construction, 31 site areas were set up, ten base camps built to accommodate personnel, 21 industrial sites to service production put into operation, and on a daily basis (7 days a week, 24 hours a day) over 3,500 people were set to work. As we pointed out, the rail line cuts through a territory characterized by complex geology featuring high variability and incoherence of the formations. The Bologna-Florence segment was constructed as a joint collaboration among the major Italian construction companies under the management of a single general contractor, the Consorzio Cavet. The distance along the route that runs through tunnels (over 73 km) and the difficult geological conditions necessitated several methods to be used for the excavation with a prevalence of blasting and the hydraulic breaker, although in some cases the methods also included a roadheader and a special TBM designed specially for a service tunnel with a reduced section (6.5 metres) 9.259 metres long partly parallel to the Vaglia tunnel. In many lots, the breaker found favour with engineers and contractors because generally speaking it assured better flexibility, guaranteed better production rates and logistical conditions compared to blasting, and in particular because it allowed mucking to be done at the same time as excavation. Indeco contributed to the construction of this major infrastructure project with breakers that worked in several segments of the route.

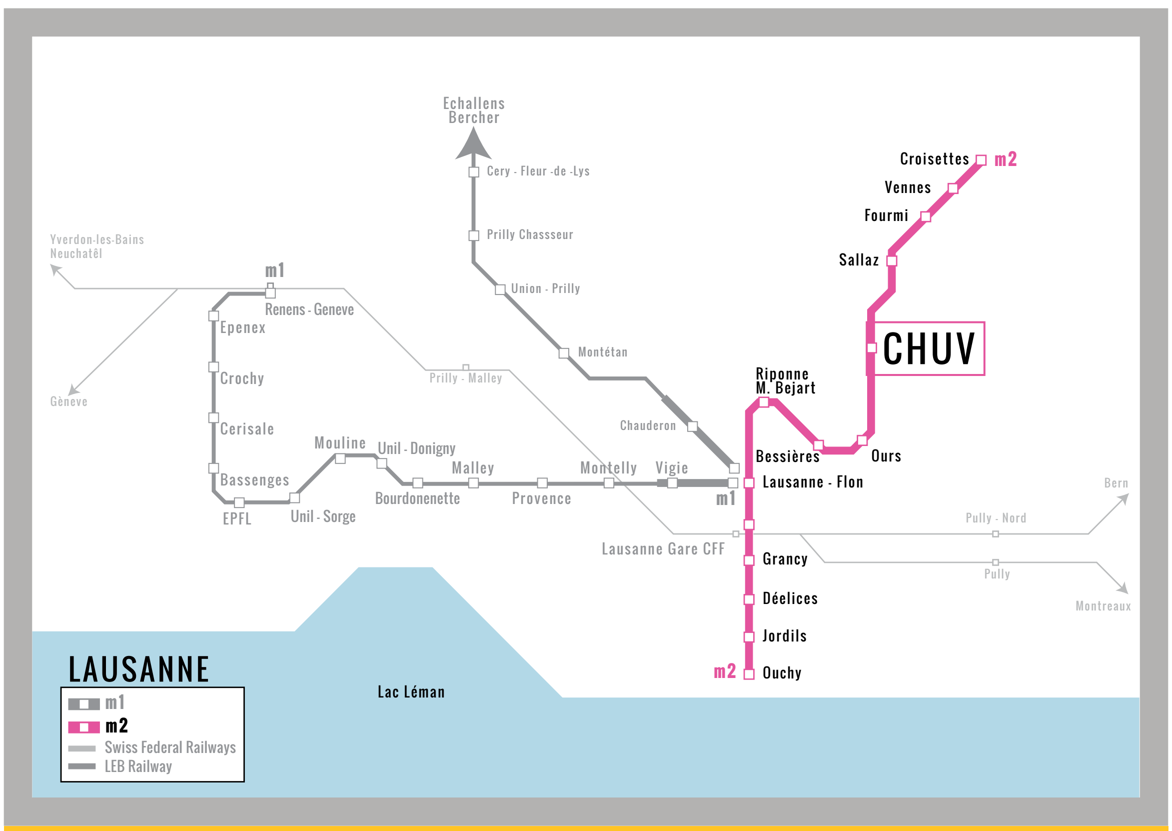
The Monte Bibele and Raticosa Tunnels

The tunnels of Monte Bibele Sud (9,243 metres) and Raticosa Nord (10,450 metres), which saw several excavation faces opened are among the longest of the Bologna-Florence segment. The consortium of Trevi-Adanti (the latter now a part of the Austrian company Strabag), was assigned a lot that required the excavation of the Monte Bibele Tunnel from the south entrance for a length of 2,772 metres and of the Raticosa Tunnel from the north entrance for 1,552 metres. Despite the limited distance between them, the two tunnels crossed through different geological formations, imposing the use of different excavation techniques and reinforcement works. From the south entrance of the Monte Bibele Tunnel, the hydraulic breaker was utilized for the excavation of the face, whereas in the north entrance of the Raticosa Tunnel the breaker used for works to excavate the invert; in fact, the excavation was performed with the ripper since the route crossed intensely fractured and tectonized scaly clay of poor geomechanical quality. The tunnel of Monte Bibele Sud extends through the flysch of Monghidoro in a dense alternation of argillites, argillaceous marl, limestone and calcarenite, highly tectonized, with evident folds at the excavated scale of the face and intensely fractured. Initially blasting had been planned for the excavation, but the appearance of a stratification with very weak and fractured interposed material indicated that this technique be abandoned. The presence of rock masses that were coherent (with values that varied between 8 and 40 MPa), alternated with clays, found an efficient solution in the use of the hydraulic breaker, which guaranteed a high production rate (from 2.5 metres/day in the unweathered zones to 1 metre/day in the argillaceous areas) and allowed precise execution of the perimeter of the excavated section. In the Monte Bibele Tunnel, work was performed by an Indeco HP 7000 breaker mounted on a Fiat-Hitachi FH 450 excavator, a solution that turned out to be perfect for the production requirements of the site, also giving excellent results for the construction of the support for the base of the rib. The breaker was subjected to a particularly heavy duty use, where it gave proof of its reliability and robust construction. In both tunnels the full-face excavation was possible thanks to the ADECO RS method, which demonstrated an effective design decision.

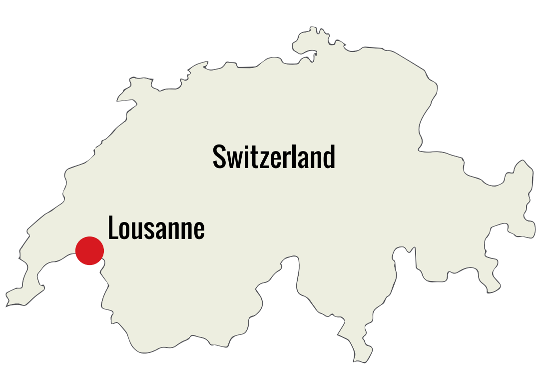
PAST CASES

THE NEW LAUSANNE METRO

The breaker proves effective in an urban area where blasting would not have been permitted.



New Lausanne metro line: M2



Put into service in 2008, the M2 line of the Lausanne metro is part of a much larger plan to upgrade the metro system of the city intended to transform and improve local public transport.

The 6 km route runs underground for 4.5 km, from the Ouchy station on the lake (almost at the Olympic Museum) to the Croisettes station located in the hills. In that point the line interconnects with the regional and inter-regional transports. This important infrastructure was responsible for eliminating approximately 6,000 vehicles that crowd the city streets on a daily basis, leading not only to a reduction in traffic, but pollution levels as well.

The particular characteristic of the line is that it connects the high and low parts of the city, a difference in altitude of 375 metres, ascending with a grade that stabilizes on an average of 5.7% with maximum grades that reach 12%. In order for the trains to be able to ascend this slope at a speed that accommodates the transport of passengers, only two cars of special rubber-tyred trains were used. The trains have a high frequency and are fully automated, i.e., with no driver.

A challenging project

Building the M2 line presented challenges from a construction standpoint; the biggest problems especially had to do with a route that crossed the city centre, winding through major thoroughfares and running alongside public and private buildings. In some stations partial-section excavation had to be done, a slow procedure performed in four phases. It was this characteristic that made the excavation so highly complex and that led to multiple logistical and construction problems, culminating in February 2005 with the caving-in of the roof under Place Saint Laurent, and the resulting collapse of the excavation with more than 500 metres of material that opened a 15-metre wide pit, and damage to a building. Engineers then had to make careful consideration of all aspects regarding reinforcement and to the underpinnings near buildings adjacent to the route. The geology of the area coinciding with the M2 line is characterized by formations of grey molasse, marl and sandstone.

Accident at Place Saint-Laurent (www.dwill.ch)

The Chuv Tunnel

Situated approximately halfway into the route, the Chuv station was part of an especially problematic lot. The stop runs alongside the most important hospital complex of Lausanne and is located along a curvilinear segment with a considerable slope.

The station was built on an open trench of 94 metres situated between the entrances of two tunnels. The south tunnel, in the direction of the lake, measures 500 metres and was excavated entirely using the breaker (an Indeco HP 4000), entailing the removal of a volume of 35,000 cubic metres. The project was assigned to a consortium of contractors (JPF Construction, Induni, Evequoz and Getra), with JPF designated to perform the excavation and the reinforcement works. The subsoil material of the tunnels of the Chuv stops is composed primarily of sandstone, which have a low or medium hardness (about 10-35 MPa) according to the position. Excluding blasting due to the high density of the urban area and with the roadheader used in other lots due to the characteristics of the rock mass, the choice fell on the breaker. With its weight of two and half tons, an energy class of 5650 joules and blows/min. between 370 and 820, the Indeco breaker lent itself perfectly to being mounted on the Liebherr 934 with swivelling boom, guaranteeing good rates of production.

PAST CASES
THE “VARIANTE DI VALICO”

Variante di Valico route

Once again, the breaker proved an efficient solution for cutting through the insidious rock masses of the Tuscan-Emilian Apennines.

The Variante di Valico, now completed and soon to be opened to traffic, runs between the toll booths of Sasso Marconi and Barberino di Mugello and is part of a more ambitious project aimed at upgrading and improving the Apennine section of the A1 between Bologna and Florence, one of the most highly trafficked and dangerous stretches of the entire Italian highway network. The project, which in its first segment in a south direction cuts through and flanks the present highway that has been in service for more than 50 years, features a route that stands out for the limited slopes and high number of viaducts and tunnels. With a length of 59 km, the Variante di Valico is made up of 23 viaducts and 22 tunnels. Other aim of the project was to create an infrastructure with fewer slopes than the historic highway so as to absorb heavy traffic. In construction terms, however, the project design had to deal with the fact that this was geologically speaking one of the most difficult territories in the country to traverse, with characteristics analogous to the route of the Bologna-Florence high-speed rail. This factor demanded different techniques of excavation and reinforcement of the underground works. The Tuscan side, in particular, presented the greatest difficulties as it involved reliefs made up of incoherent formations that were, among other things, characterized by an extensive presence of natural gas and water. As with the construction of the Bologna-Florence high-speed rail, the tunnels were built using a variety of methods, prevalently blasting and hydraulic breaker. The Sparvo Tunnel (twin tubes measuring 2.5 km each) was excavated using the TBM EPB with the largest diameter (15.62 metres and excavation area of 192 square metres) ever used in Europe and a cost exceeding 52 million euros. Despite an uncertain start-up phase and some problems during the excavation phases that had led to mediocre production rates, the TBM delivered very good production rates, but that did not reflect the time required for assembly, maintenance, down time and preparation of site logistics.

The Monte Mario Tunnel

The tunnel was opened to traffic in 2006 and was the first of the Variante di Valico to be excavated underground in a southward direction. The infrastructure straddles the valleys of the Setta River and the Reno River that flow in proximity to the old highway toll booth, now out of commission. The relief of sedimentary origin is characterized by formations of marl and over-consolidated clays, which differ in consistency and distribution in the north direction towards Bologna and in the south direction towards Florence. The tunnel is made up of two tubes (respectively 2,266 and 2,209 metres) separated by a partition with a thickness that varies between a minimum of 35 and maximum of 64 metres. The two tubes have divergent axes and are designed to have upward gradients of 0.7% to 1% on the north side, and vice versa a downward gradient of 0.7% to 1% on the south side. Each tube had a section of 145 square metres and crossed through unsound formations that date back to the Early Pliocene (marl/grey-blue overconsolidated clays) and Late Pliocene (grey-yellowish sands with arenaceous banks) that are instead have relatively greater cohesiveness. The different characteristics of the formations and their location with respect to the route imposed the use of two different reinforcement techniques for each tube.

Two Indeco breakers for the north entrance

The nature of the geological formations had induced designers to select the hydraulic breaker as the most suitable excavation method due to the high degree of fracturing. With the exception of an initial segment of about 700 metres, very critical due to the presence of lithoids having hardnesses exceeding 50 MPa which required the use of explosives, the excavation of the north entrance was performed with two Indeco UP 7000 W silenced breakers fitted with dust abatement systems. Most of the advancement, i.e., over 1,800 metres, was carried out using the breakers, again which proved to be a complementary and alternative method to blasting and that did not involve long down times or excessive costs when switching excavation technique. The reliability and working capacity of the breakers guaranteed a production rate of 1.5-2 metres per day.

FOCUS ON

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