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Selected technologies for destruction of rocks cohesion by using their tensile strength properties

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Słowa kluczowe: niszczenie spójności skał, wyrywanie fragmentów skał, akcje ratownicze w kopalniach, niekonwencjonalne techniki urabiania, badania wytrzymałościowe skał

Abstract:

Basic mechanical properties of rock material, crucial for its destruction, and the basic condition for its destruction - the Mohr-Coulomb criterion, are presented at the beginning. The basic strength feature of rocks is their low tensile and shear strength. In practice, this first property is used for mining and processing of rock materials. The article presents selected technologies of rock destruction based on this feature, such as: rock splitting by the expanding method (mechanical wedging, expanding materials, EDH electrohydraulic method). An innovative technology of rock loosening using a fixed bolt is presented as an alternative solution. This technology has been tested and developed at KOMAG for several years, under the projects. The selected results of research work and literature analysis of the problem are given.

Streszczenie:

Na początku artykułu przedstawiono podstawowe własności wytrzymałościowe materiału skalnego, kluczowe dla jego zniszczenia oraz podstawowy warunek ich zniszczenia – warunek Coulomba-Mohra Podstawową cechą wytrzymałościową skał jest ich niska wytrzymałość na naprężenia rozciągające i ścinające. W praktyce, ta pierwsza własność wykorzystywana jest do realizacji procesów urabiania i przeróbki materiałów skalnych. W artykule przedstawione zostały wybrane technologie niszczenia spójności skał wykorzystujące tę właściwość, takie jak: rozłupywanie calizny skalnej przy wykorzystaniu *rozpierania* (klinowanie mechaniczne, materiały ekspansywne, metodą elektrohydrauliczną EDH). Jako rozwiązanie alternatywne przedstawiono innowacyjną technologię odspajania za pomocą utwierdzonej kotwy. Technologia ta jest badana i rozwijana w ITG KOMAG od kilkunastu lat, m. in. w ramach realizacji projektów badawczych. W artykule przytoczone zostały wybrane wyniki prac badawczych i podana szersza analiza literaturowa przedstawionego zagadnienia.

1. Introduction

Significantly lower rock tensile strength than its compressive strength (and shear strength) is the main feature of the rock material. This feature is used in rock mining technologies. This article reviews these technologies, together with an assessment of their scope of application.

One of the least studied and described in the literature methods of using low tensile strength of rocks is the technology of mechanical rock loosening with the use of a bolted string; this method is constantly being extended to include other force input variants.

The concept of a method for mechanical rock loosening and the tests aimed at assessing its applicability were developed for the first time within the INREQ project, for designing the portable device for driving the rescue tunnels [1].

The project presented the main advantages of this method, that is its safe use in the conditions of rock outburst hazard, methane hazard and unstable rock mass. This technology enables the mining of solid rock pieces without destroying the rock mass, even in the case of hard rocks. Simple mechanization of the technology ensures its reliability, however, the slow progress of the roadway development can currently provide satisfactory results only in the case of driving small-size rescue tunnels. The method intended for solid rock driving is based on the use of lightweight and easy to transport manual tools. Due to the degree of mechanization, this method of roadway development has no restrictions concerning the methane concentration. Moreover, it cause destruction of the rock mass only in a strictly defined area and allows for mining the hard rocks [2, 3]. This method has potential for wider application, e.g. rock mining, as an alternative to blasting technology. Its development depends, however, on the basic tests determining empirical models of destruction of various rocks types, which will allow to determine geometry of the pulled off solid and the critical force P causing the material destruction.

Such work was carried out as part of the next RODEST project, the results of which allowed to undertake the development of technology and equipment intended to use in drilling by this method and to evaluate the efficiency of the process comparing to the conventional methods.

Work carried out so far and planned in the future within the framework of the projects financed, among others, by NCBiR, allow to replenish the knowledge on the strength properties of rocks in the complex conditions of stresses, when using this innovative technology. In practice, the developed models of the destruction of rock materials will be used for the development and popularization of the innovative mining technology of mechanical rock loosening by a fixed bolt method [4].

2. Main constants of rock materials determining their strength properties

A rock is a natural concentration of several minerals resulting from various geological processes, such as flooding and solidifying of volcanic lava, deposition of salt or the formation of gravel and sand in river beds. Rocks can be composed of one mineral (simple) or composed of several different minerals (complex). Due to the genesis of the formation, the rocks can be divided into the following three groups [5]:

- igneous (they are a product of magma freezing)
- sedimentary (they are formed on the surface of the lithosphere from the remains of older rocks or from the remains of plant and animal organisms, a characteristic feature is their layered structure (usually parallel to each other)
- metamorphic (these are rocks of igneous or sedimentary origin, which get into deeper parts of the earth as a result of high pressure and temperature, where they change in their original structure and mineral composition).

The mechanical and physical properties of rocks largely depend on the following factors [6, 7]:

- type of rock and their origin,
- rock tectonics (faults, crevices, scratches, cracks, cleavage),
- rock porosity and water content,
- grain size, shape and strength,
- binder properties,
- the direction of force in relation to the foliation.

The most important mechanical properties of rocks include: cohesion c, angle of internal friction φ, uniaxial compressive strength σ_C (or R_c), tensile strength σ_T (or R_r) and shear strength τ [6].

A commonly used material constant for rocks is the uniaxial compressive strength σ_C (or R_c). Uniaxial compression tests are the most popular as they are easy to perform and there is a large database on compressive strength of rocks.

Rocks are granular materials. Mineral grains are bound together to form aggregates. The failure of rocks, despite the compressive forces applied from the outside (and compressive stresses), occurs as a result of exceeding the shear and/or tensile strength. Also, the samples subjected to uniaxial compression tests are generally sheared in one or two planes (Fig. 1).

The bonds between mineral grains and grain aggregates are broken as a result of exceeding the tensile strength.

The uniaxial tensile strength σ_T (or R_r) is the material constant that describes the strength properties of rocks in a best way. Unfortunately, uniaxial (direct) tensile tests are difficult to perform so they are very rarely used. In accordance with the recommendations of the International Society of Rock Mechanics, these tests should be carried out on cylindrical specimens with a slenderness of h:d = 4, glued to the holders of the testing machine, performed with appropriate accuracy and test regimes [8].

The relatively few results of the tests carried out in this way show the specific behaviour of rocks under tension (Fig. 2) for example:

– nonlinearity of the stress σ - deformation ε characteristics in the entire range of tensile stresses (as opposed to compression tests),
– variability of deformation properties, i.e. modulus of longitudinal elasticity E and Poisson's ratio ν together with an increase in tensile stress σ,
– plastic deformations (permanent, irreversible), which are also experienced by rocks under tension.

The analysis of the results of uniaxial tensile, mono- and multicyclic tests and a discussion of the tests conducted so far by Polish and foreign researchers are presented in a few studies. In Poland, Tomiczek dealt with this problem more widely [9, 10, 11, 12].

a) b)

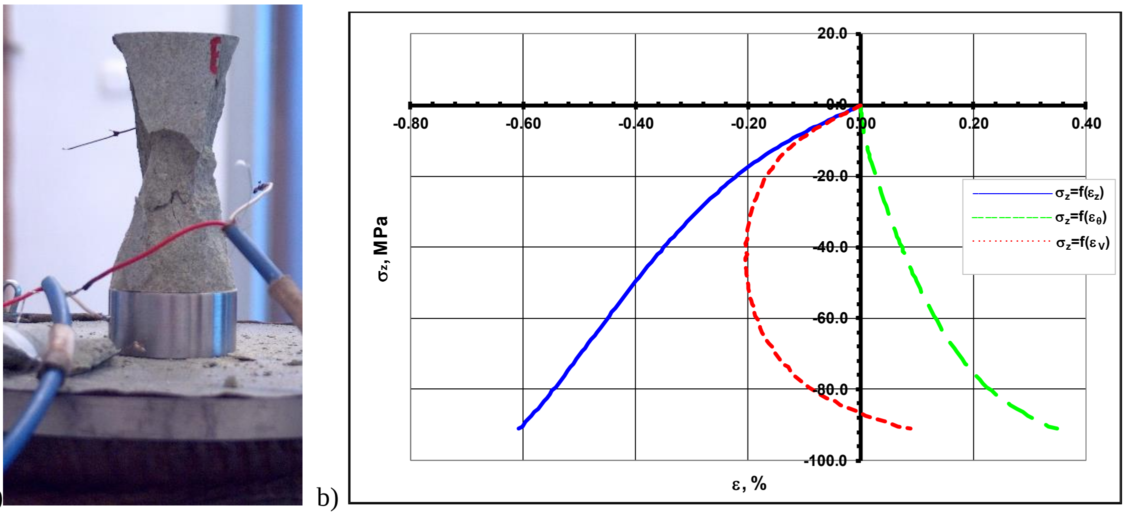


Fig. 1. Typical view of the failured sample (a) and stress σ - strain ε characteristics for rocks (b) in uniaxial compressing test; *Brenna* sandstone [9]

a) b)

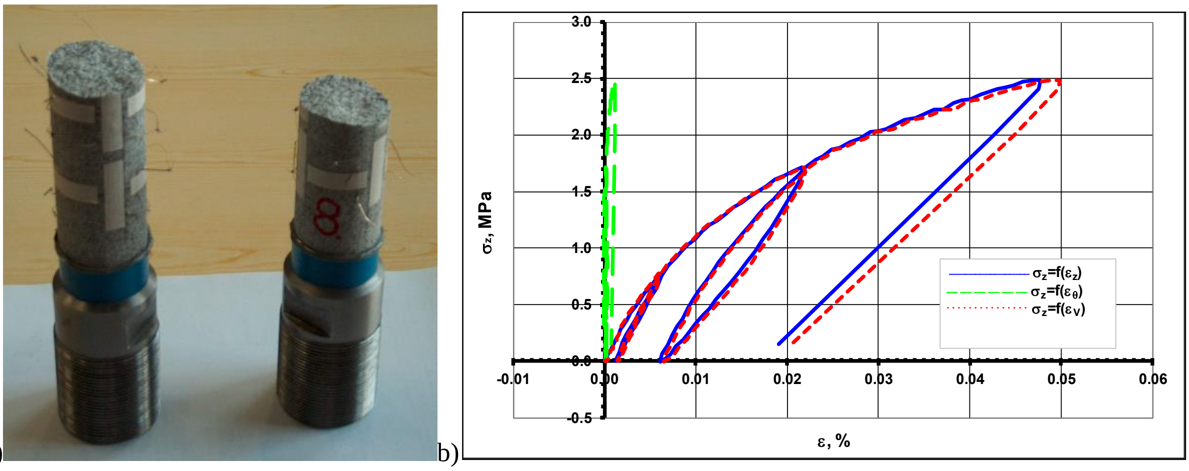


Fig. 2. Typical view of the failured sample (a) and stress σ - strain ε characteristics for rocks (b) in uniaxial tensile test; *Brenna* sandstone [9]

As already mentioned, uniaxial tensile tests are technologically difficult, therefore usually the strength (and deformation) properties of rocks under tensile conditions are determined by indirect methods, e.g. the Brazilian method [13] or the three bending point test [14]. It should be emphasized, however, that the constants determined by indirect methods are different from those determined by the uniaxial tensile method, and the latter are the exemplary values of the constants for rocks in the field of tensile stress (e.g. Tomiczek [9, 10, 11, 12]).

Coulomb-Mohr criterion is one of the basic strength criteria used to describe rock behaviour and failure. It combines all the basic constants characterizing the strength properties of rocks such as: cohesion c, uniaxial tensile strength σ_T (and compression strength σ_C), angle of internal friction φ and shear strength τ.

Coulomb in 1776 suggested the relationship (1) in which he assumed that rocks (also soils and some granular materials) are failured after exceeding the shear strength.

$$\tau = c + \tan\varphi\sigma \tag{1}$$

where:

τ	shear strength,
c	cohesion,
φ	angle of internal friction
σ	normal stress.

This equation was completed by Mohr in 1900 (Fig. 3), Paul in 1968 as well as described, among others, by Labuz and Zang in 2012 [15].

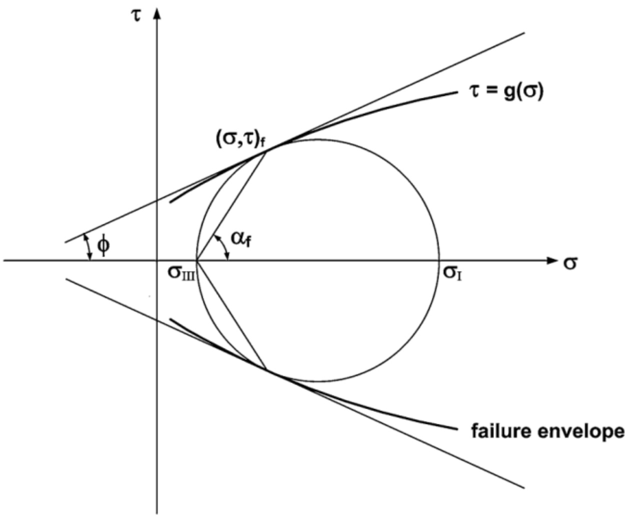


Fig. 3. Mohr circle and envelope; τ – static stress, φ (or ϕ) angle of internal friction, σ_I and σ_{III} – the highest and the lowest main stress [14]

Equation (1) can be written as [14]:

$$(\sigma_I - \sigma_{III}) = (\sigma_I + \sigma_{III}) \sin\phi + 2c\cos\phi \tag{2}$$

Coulomb-Mohr criterium in the convention of principal stresses can be written as [14]:

$$\pm\frac{\sigma_1-\sigma_2}{2} = a\frac{\sigma_1+\sigma_2}{2} + b, \pm\frac{\sigma_2-\sigma_3}{2} = a\frac{\sigma_2+\sigma_3}{2} + b, \pm\frac{\sigma_3-\sigma_1}{2} = a\frac{\sigma_3+\sigma_1}{2} + b \tag{3}$$

while:

$$a = \frac{m-1}{m+1}, \qquad 0 \le a < 1$$
$$m = \frac{C_0}{T_0} = \frac{1+sin\emptyset}{1-sin\emptyset},$$
$$b = \frac{1}{m+1},$$

$$C_0 = \frac{m}{m+1},$$
$$T_0 = \frac{C_0}{2}(1 - sin\emptyset),$$

where:

c	Cohesion
C_0	Uniaxial compressive strength (σ_C, R_c),
T	Uniaxial tensile strength (σ_T, R_r),
T_0	Theoretical *MC* uniaxial tensile strength,
ϕ	Angle of internal friction (φ),
$\mu=tan\phi$	Coefficient of internal friction,
σ	Normal stress on plane,
τ	Shear stress on plane,
σ_1, σ_2, σ_3	main stresses (refer to σ_I, σ_{II}, σ_{III})

Coulomb-Mohr envelope in the convention of normal stresses σ and tangential stresses τ is presented in Fig.4.

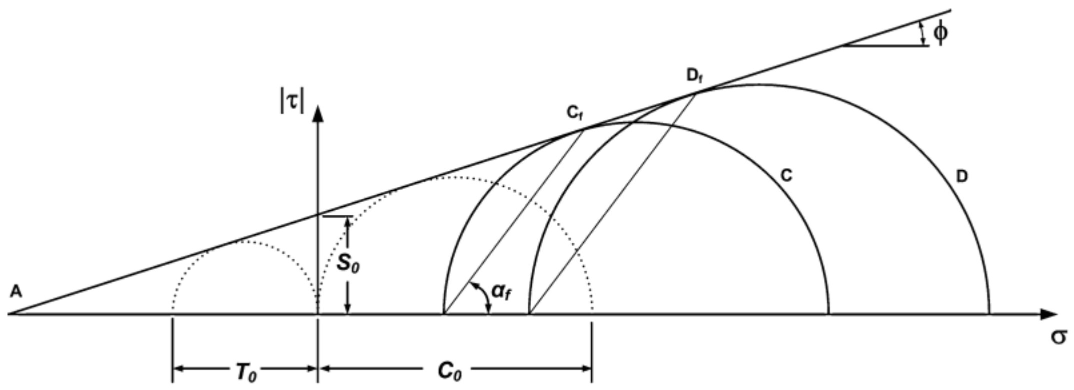


Fig. 4. Coulomb-Mohr envelope in the convention of normal stresses σ and tangential stresses τ [14]

Graphical interpretation of the rock sample failure surface after the test of three-axial compression for $\sigma_1 \neq \sigma_3$ and $\sigma_1 > \sigma_3$ and $\sigma_2 = \sigma_3$ for Coulomb – Mohr criterion is presented in Fig.5.

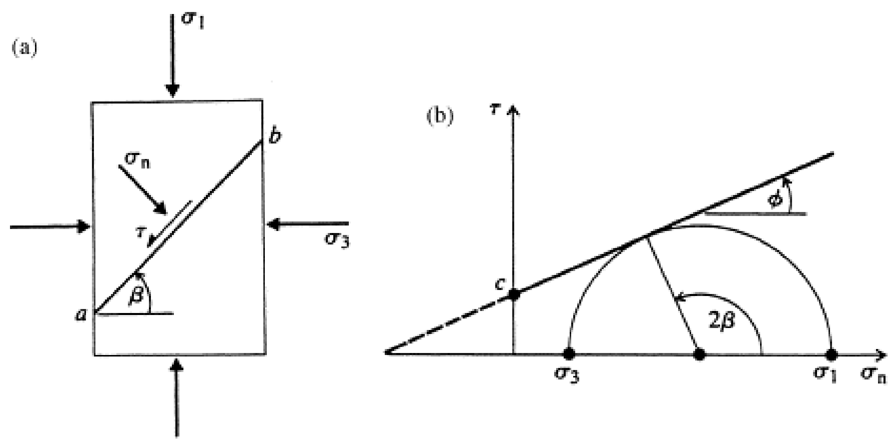


Fig. 5. Graphical interpretation of the rock sample failure surface after the test of three-axial compression for $\sigma_1 \neq \sigma_3$ and $\sigma_1 > \sigma_3$ and $\sigma_2 = \sigma_3$ for Coulomb – Mohr criterion [16]

Knowing about the imperfections of the Coulomb-Mohr criterion in the part concerning the tensile stresses, it seems appropriate to use it to describe the phenomenon of rock failure (or destruction) by the rocks pulling out method, after taking into account and supplementing it with Paul or Labuz's solutions, and own solution.

3. Selected technologies of destruction of rock cohesion with the use of tensile strength

Compressive strength of rocks is much higher than their tensile or shear strength [16, 17]. This property of rocks is often used to develop, design and realize the mining processes with the lowest possible energy consumption. Selected technologies using low tensile strength of rock materials in the process of splitting the rock solids by the expanding method, e.g. mechanical wedging, expanding materials or the electrohydraulic method (*EDH)* are presented and described. The method of mechanical loosening with the use of a string embedded in the solid rock is presented as an alternative to these technologies.

Splitting rock mass by the expanding method

– **Expanding using the *drilling saw* method**

Expanding method is the most widely used method for loosening stone blocks from the deposit and when separating the already mined blocks by drilling holes in the planned partition plane and then applying the *R* forces perpendicular to this plane. The nature and magnitude of these forces depend on the type of rock and the conditions under which the rock is separated. The diagram of the conditions of rock separation by drilling and splitting as well as the adopted terms are presented in Fig. 6.

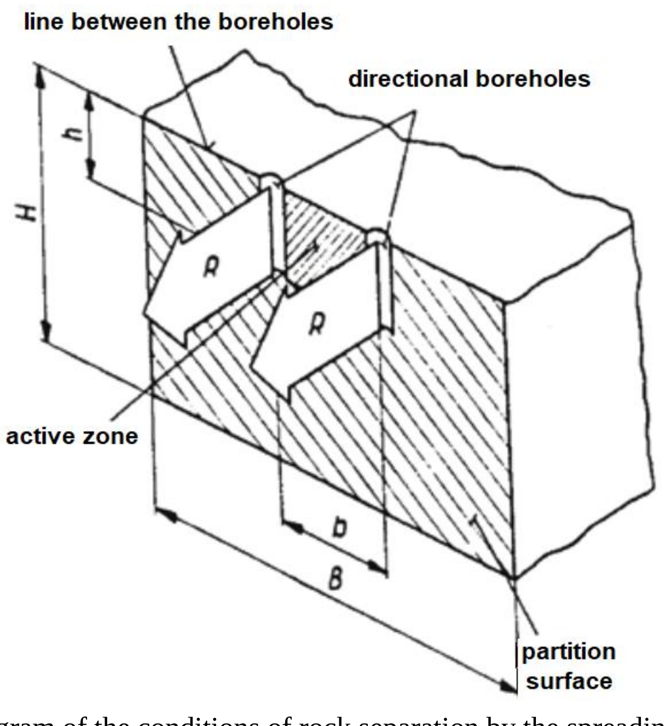


Fig. 6. Diagram of the conditions of rock separation by the spreading method;
b – hole spacing, *h* – hole depth, *R* – expanding force, (based on [18])

After drilling the directional boreholes in the partition plane, mechanical, chemical or hydraulic "wedges" are inserted into the holes, generating the *R* force perpendicular to this surface. If the magnitude of these forces exceeds the tensile strength of the material, a macrocrack appears, beginning in the active zone (between the boreholes). A set of parallel boreholes marking the separation area is called a *drill saw*.

Tests showed that the *splitting* process is the least energy-consuming method of stone partition, and is many times less energy-consuming than cutting with diamond discs and ropes. This technology is irreplaceable in mining the blocks from deposits with a divisible structure with a clear divisibility and/or stratification, and in splitting the already detached blocks into smaller pieces [18].

– **Mechanical wedging**

Rock mass can be split by mechanical wedging, i.e. joint, dynamic expanding of several elements inserted into previously drilled holes in the solid rock. Wedging can be done by manual hammering, or mechanically - with the use of portable pneumatic hammers powered by compressed air, or smaller electrically powered impact hammers. Wedges are placed in the directional holes and hammered successively deeper and deeper, leading to the separation of rock along the plane marked by these boreholes. The separated rock block is further processed to obtain stone parts with specific shapes and textures. An example of a rock block fragment separated by manual hammering the wedges into the previously drilled holes is shown in Fig. 7.

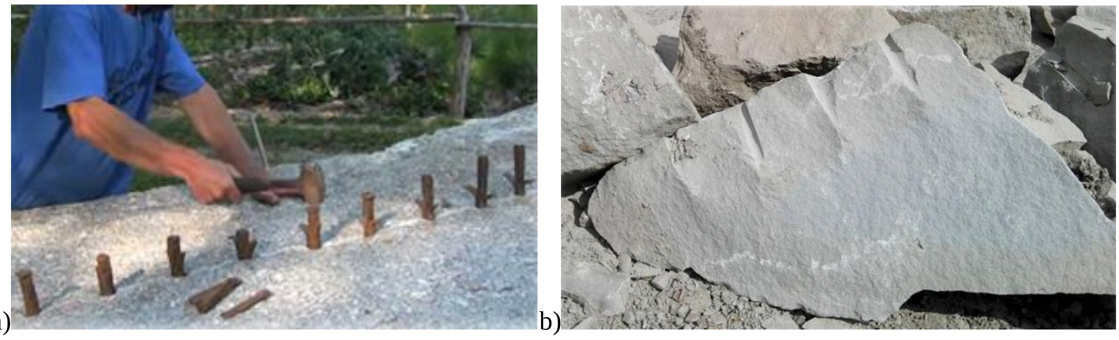

a) b)

Fig. 7. An example of manual mechanical wedging: a) process in progress [19], b) the fracture plane of the rock block after using this method [20]

For many years, mechanical wedging has been the basic technology of rock solids mining and stone block mining. With the development of this technology, newer and newer solutions were created to improve the process of wedging and splitting the rock blocks. The splitter shown in Fig. 8 is an example of one of the state-of the-art solutions.

Fig. 8. Hydraulic splitter employed for the non-explosive fracturing of rock in engineering application [21]

– **Rock expanding by use of the expanding materials**

Another way of introducing failure stress into the rock block is to use intumescent materials that are inserted into previously drilled holes. Intumescent materials such as dynacem or cevamite are a dry powder mixture which, when mixed with water, increases its volume and exerts a pressure of 30-40 MPa on the walls of the hole. Materials of this type are successfully used in demolition of buildings and wherever it is impossible to use explosives [22].

After filling the boreholes, in a short time, the material swells and exerts an expansion pressure. After overcoming the tear (tensile) strength of the material, under optimal conditions of use, cracks appear after just 30 minutes, progressing until the chemical reaction ceases; the material continues to work. The successive phases of the technological process of splitting rock solids with the use of expanding materials is shown in Fig. 9 [22].

Fig. 9. Phases of the technological process of splitting rock solids with the use of expanding materials [22]

The increase in the volume of the expanding material inside the boreholes causes expansion (tensile) forces acting on the borehole side surfaces in the direction perpendicular to the hole axis. When splitting boulders, one central hole causes 3 or 4 cracks. The more holes, the more cracks and loosened materials. For cracks development, the element must have at least one free surface that can move without external resistance due to the material expansion. The number of holes depends on the expected size of the loosened material. The distance from the hole to the hole- or from the hole to the edge of the boulder should not exceed 12 times the diameter of the hole and the required size of the material fragments. Local options for loading, transport or use of the loosened material on-site are essential.

The holes parallel to the free surfaces provide the highest effectiveness. In this case, the entire expansion force moves the detached material towards the free surface. Properly drilled and filled holes, enable to lead the *cutting line* also *along arc*, or to split simultaneously the whole solid rock into many smaller rock blocks, as shown in Fig. 10.

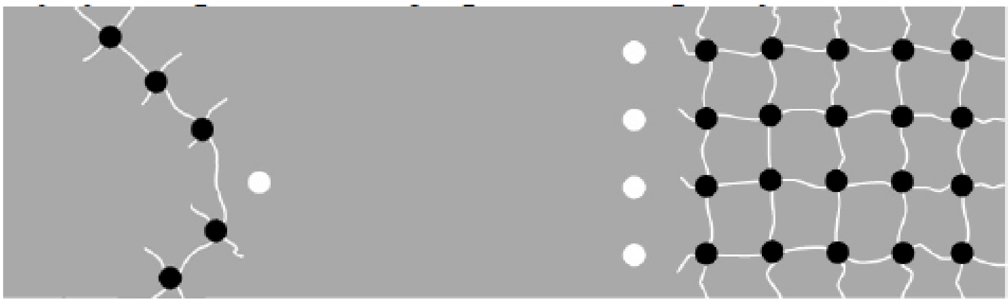


Fig. 10. Directions of cracks propagation in the rock block depending on the place of using the expanding materials [22]

This technology is increasingly used in the construction and demolition industry, as well as for the needs of individual customers. The technology is used for dividing the beams and foundations into parts suitable for transportation, for crushing the structures and boulders, making holes in slabs, drilling tunnels and channels, cutting stone and rock lumps, breaking off concrete from reinforcement, cutting piles, loosening the not cracked rock blocks [22].

– **Loosening the rock blocks using the EHD electrohydraulic method**

Large blocks are obtained during the mining of solid rock masses and demolition using explosives, the blocks size do not allow them to be crushed. The oversized blocks can be broken with the use of hydraulic hammers installed on the excavator's boom. However, more and more often oversized blocks are broken using the electrohydraulic effect (EHD method). A hole is drilled in the block, and after filling it with water, an electrode is placed in it. The electric arc generates pressure shock wave by transferring water into vapour, which gives the effect as in a classical blasting [23, 24]. The idea of loosening the rock material using the EHD method is presented in Fig. 11.

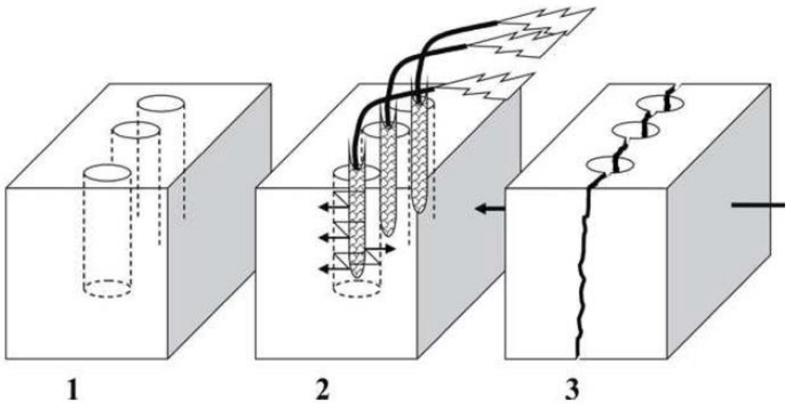


Fig. 11. The idea of loosening the rock material using the EHD method [23]

The first work on designing the device for generation of the electrohydraulic effect was undertaken at the AGH Institute of Mining, Processing and Automation in Krakow in the 1970s under the supervision of Professor Zygmunt Kawecki. As a result of this work, the first devices for crushing rock blocks using the electrohydraulic method were designed. The idea of generating the EHD effect has remained unchanged until today. Schematically, the design of a device generating the electrohydraulic effect is shown in Fig. 12.

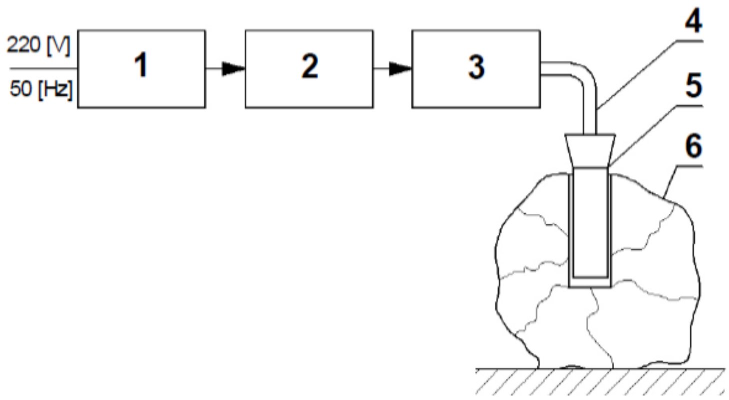


Fig. 12. Schematic diagram of the device for EHD tests [23]

Device for crushing the rock blocks by the electrohydraulic method [23] consists of the following components:

1. Control system
2. System for charging the impulse capacitors
3. Set of capacitors (high voltage power system)
4. Concentric cable
5. Electrohydraulic transducer
6. Object to be loosened

Dimensions of the device depend on the power required to generate an electro-hydraulic wave inside the borehole. Along with the advance in the technology of manufacturing the batteries and electrotechnical equipment, the mobility of using the system is becoming more and more common. The system is mobile and it can be transported in a passenger car. The loosening test together with the test stand components is shown in Fig. 13 [24].

Fig. 13. Loosening the rock blocks by the EHD method [24]

4. Method for mechanical loosening the solid rock using bolts

Under special conditions, the KOMAG's patented technology of destroying the cohesion of rocks using bolts anchored in the solid rock is an alternative method to traditional mining methods, e.g. mechanical or blasting, (Fig. 14). This technology does not damage rocks outside the strictly defined zone and does not affect the close surroundings in any way; there is no emission of gases or generated vibrations [25, 26]. The method can be used for both compact and easy-to-be-break rocks. The drilling direction can be vertical, horizontal or oblique. It does not guarantee rapid progress, but it enables workings development in all mining and geological conditions and is safe.

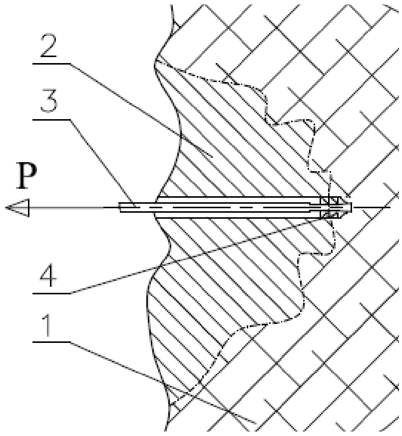


Fig. 14. Idea of mining the solid rock by destroying its cohesion:
1-rock mass, 2- loosened rock, 3-tearing out string, 4-expanding component [2, 3]

Work on the technology of drilling the rescue tunnels with the method of destroying the cohesion of rocks has been carried out at KOMAG for several years. The first concept of the mechanical rock loosening method was developed and the method was assessed within the INREQ project [25, 26, 1]. KOMAG experience gained so far clearly shows that application of under-cutting bolts for this method, due to the nature of the load application, is the most reasonable (Fig. 15). To calculate load-bearing capacity of the bolt, the simplified models of rock loosening, i.e. rock loosening in the form of a cone or a pyramid, were adopted [27, 28, 29, 30]. In the context of the range of loosening, practice shows that this is an oversimplification. The angles at the cone base, in practice, are often more than 2 times smaller than 35º or 45º. As a result, the estimated ranges of loosening, i.e. volume of the loosened solid is much smaller.

Fig. 15. Under-cutting bolt: method of the bolt fixation and range of loosening fracture propagation [20]

Additional limitations in the precise definition of the shape of rock loosening result from the heterogeneous structure of rocks. The impact of lamination planes can determine the angle of the torn out cone, as well as the maximum force required to pull it out. The theoretical impact of the rock structure on the shape of the loosened material is shown in Fig. 16 [31].

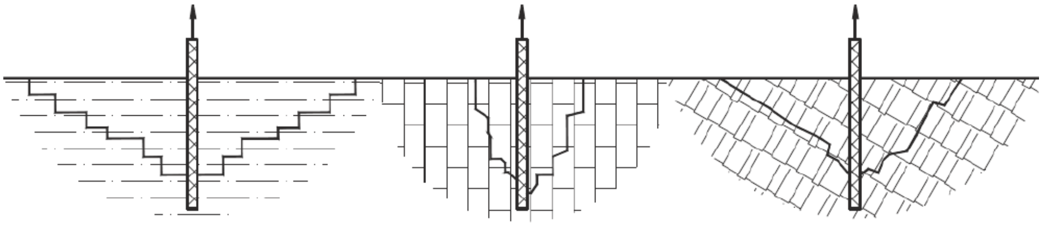


Fig. 16. Impact of the rock structure on a shape of thorn out cones [31]

To analyse the applicability of the rock loosening method using the undercutting bolts, it is necessary to determine of the loosening force, depending on the so-called *effective loosening depth* (undercutting depth in the borehole) and strength properties of rocks.

To understand the loosening mechanism and the state of stress in the tearing out rock material, work under the RODEST project entitled: "Testing and modelling the mechanism of destruction of rock materials in the spatial state of shear and tensile stresses", was undertaken. This project was realized by the scientific consortium: KOMAG Institute of Mining Technology together with the Lublin University of Technology and was financed by the National Science Centre within the OPUS 10 competition [32]. Due to the necessity of testing the rocks of different strength properties, the rock loosening tests were carried out in four different mines, for four different types of rocks. The testing device (Fig. 17a), consisted of a support of a diameter 1 m, a hydraulic cylinder for tearing out the bolts and a manual pump with the possibility of recording the pressure changes in the hydraulic cylinder, and indirectly the tearing out force from the pressure changes time curve (after conversion into force) - Fig. 17b.

a) 

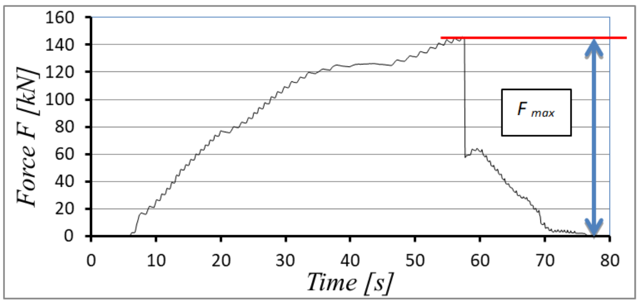
b) 

Fig. 17. Own tests on mechanical loosening of rocks within the RODEST project: a) test stand equipment, b) determination of maximum force (F_{max}), recorded during the loosening test [33]

Geometry of the loosening surface, the maximum and minimum range of the destruction surface was mapped using a handheld 3D scanner. On the basis of the points cloud from the scanner, in the specialized Leyos 2 software, the selected cross-sections of the loosened rock fragments, having a shape similar to a cone, were generated. On the basis of the generated cross-sections, it was possible to determine the basic parameters of the loosening process, such as the effective anchoring depth, range and the loosening angle. Fig. 18 shows how they were determined.

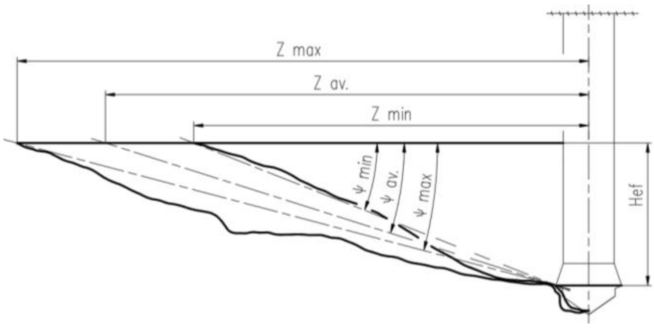


Fig. 18. Cross-section through the loosened solid and the method for determination of the effective anchoring depth H_{ef}, maximum, minimum and average range $Z_{max,\ min,\ av}$ as well as loosening angle $\psi_{max,\ min,\ av}$ [34]

Graph of impact of the effective anchoring depth H_{ef} on the loosening force F_{max}. and the average loosening range Z_{av} for different rock types is shown in Fig. 19 [33]. The analysis of the test results allows for an approximate determination of the conditions of the loosening tests with the use of a fixed bolt at known rock strength and at given effective anchoring depth.

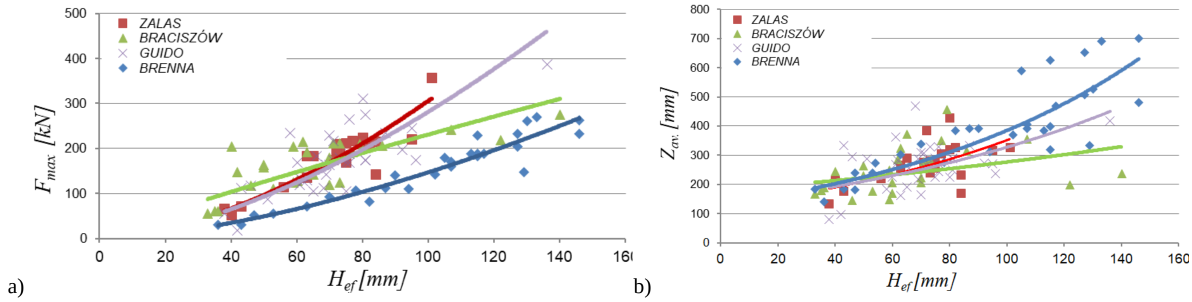


Fig. 19. Functions of the effective anchoring depth: a) loosening force F_{max} and b) average destruction ranges $Z_{av.}$, depending on effective anchoring depth H_{ef} for different rock types [33]

A detailed discussion on the test results is presented in publications [4, 33, 34, 35, 36, 37, 38, 39, 40]. The results provided completely new knowledge about the destruction of rock structures under the load resulting from action of the undercutting bolt. The new knowledge obtained was translated into development of a completely new method of rock loosening, described in the patent applications. The knowledge gained so far in the field of unconventional loosening technology is on the first level of TRL (Technology Readiness Level). The results are important for the potential arrangement of boreholes in the rock loosening technology. Knowing the necessary force needed for loosening the rock, F_{max} and the expected loosening range, rocks loosening is possible obtaining, for example, specified dimensions of the tunnel. It is also possible to precisely tear out only the selected rock fragments, e.g. during rescue operations.

5. Conclusions

Rocks show different strength (and deformation) properties depending on the type of introduced stress acting on them. The mechanism of destroying their cohesion is also different. It is important that the mining process (destroying the cohesion of rocks) is adapted to the mining and geological conditions and the technical possibilities. It is also important that the selected technology corresponds to the conditions in which it is used and is properly optimized in terms of energy consumption and costs of the process.

The methods of splitting rock solids (or blocks) are the methods developed since ancient times, however, the methods of introducing the splitting (tearing, stretching) force are constantly being improved.

The innovative method of loosening the rock fragments with the use of an undercutting bolt or similar methods for introduction of tearing off forces is a new method of loosening technology. The spatial distribution of stresses generated by the undercutting bolt fixed in the rock mass translates into the tear out (loosening) force, as well as to the range and shape of the destruction surface. It was found that the existing models describing the stress distribution in the top area of the crack propagating in concrete, due to the large differences in the internal structure of rocks and concrete, have limited application in describing the cracking phenomena and the development of cracks in rock. For this reason, on the basis of industrial and laboratory tests carried out within the RODEST project, empirical models describing the distribution of stresses in the front zone of the destruction surface were developed and verified, what allowed to predict the tensile force and the loosening range.

The test results provided completely new knowledge about the phenomenon of destruction of rock structures under the action of load resulting from the impact of the undercutting bolt on the solid rock. Studies on development of this technology results from the need to develop tunnels in the vicinity of buildings, which, due to the generated gases and shocks, makes it difficult or even impossible to use conventional methods, e.g. blasting or mechanical drilling.

Clearing the collapsed workings, e.g. during rescue operations, or the liquidation of pillars in board-an-pillar working is another area of application of the suggested technology in the underground mining industry. In such situations, it is not expected that the cutting (loosening) processes will be carried out with efficiency comparable to other methods, but it is expected that the loosening operations are safe or in the case of difficult condition even possible.

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