Analysis of the process of loosening the rocks with different strength properties using the undercutting bolts

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Abstract: The process and the test results of the solid rock loosening by use of the fixed undercutting bolt are described. The tests were carried out within the RODEST project, OPUS 10 competition No. 2015/19/B/ST10/02817, financed by the National Science Centre, where a series of numerical modelling as well as laboratory and in-situ tests were planned. The test stand equipment as well as methodology for conducting the in-situ tests are presented. The tests were conducted in four mines. In each mine tens of solid rock loosening tests were conducted, during which the process parameters were recorded. Additionally, the loosened area outline in each successful test was recreated using 3D scanner. Data collected during in-situ tests as well as strength properties of the tested rocks enabled analysing the loosening process (forces, ranges) in relation to the rock type.

1. Introduction
According to the latest EU recommendations, it is advisable to search for alternatives to the known rock mining methods (mechanical and blasting), which is caused by the need to reduce the emission of gases harmful to human health and the environment, and the restrictions in using the mechanical mining technology in the area of critical buildings and industrial installations (due to e.g. generated vibrations), etc. Also extremely difficult mining and geological conditions as well as space and time limitations during rescue operations, practically eliminate the possibility of using conventional methods for development of mine workings [1, 2]. In such situations, the mining (loosening) processes are not expected to be carried out with the comparable operational and output parameters, but it is expected to ensure safety or even the possibility of carrying out the rocks loosening process.

The technology of rock fragmentation using bolts anchored in a solid rock, patented by KOMAG in several versions, is an alternative method to the traditional ones [3]. This method is safe because it does not create a risk of throwing out the mined rocks and can be used regardless of the level of methane hazard. The technology does not cause the rock mass fragmentation outside the strictly defined zone and in no way affects the immediate environment (no gas emissions or generated vibrations).

This solution has been developed and patented in several versions, mainly differing in the way of exerting tensile stress in the bolt. The main idea of the solution is shown in Figure 1. Lower energy consumption, while maintaining proper fixation of the element securing the bolt, is obtained by
introducing tensile and shear stresses, whose limit values in the case of rocks are several times lower than the limit compressive stresses [1, 3, 4]. The method can be used for both solid and easy-to-be-mined rocks. The drilling direction can be any at will (vertical, horizontal, oblique). The method in its simplest form (made manually) does not guarantee much progress, however, it enables drilling of the roadway in any mining and geological conditions and is safe.

![Figure 1. The concept of cutting the solid rock through destruction of its integrity: 1-solid rock, 2-loosened rock, 3-pulling rod, 4-expansion sleeve [1, 3, 4].](image)

Research work on the technology of drilling the rescue tunnels by the method of destroying the rock integrity have been carried out at KOMAG for several years [4]. The first concept of the method of mechanical loosening of rocks and tests aimed at assessing the possibility of its application were conducted as a part of the INREQ project [5]. The state of the art in the field of bolts applications mainly applies to the fixation systems used in the assembly of industrial infrastructure in reinforced concrete engineering facilities. There is a wealth of knowledge in both experimental, empirical and FEM numerical studies on various aspects related to the formation of the bolt pull-out force, as well as the bolt assemblies and range - propagation of the crack path (loosening gap). European, Japanese and American standards, which allow to simplify the estimation of the pulling force in the context of the useful load capacity of the bolt are the result of this research work. Generally, for the purpose of calculating the bolting capacity, the simplified rock loosening models are adopted, i.e. detachment of the solid in the form of a cone or pyramid [6, 7, 9, 10] (Figure 2).

![Figure 2. Simplified rock loosening models recommended for the practical use: a) conical, b) four-sided pyramid [11].](image)
In the context of rocks loosening range, the practice shows that these are very large simplifications. The angles at the base of the cone, in practice are often more than 2 times smaller than the standard 35° or 45°, what means that the estimated ranges of loosening, and thus, e.g. the volume of the detached solids are significantly underestimated. The actual ranges of loosening (gap propagation) both in the light of literature analysis and own research work are shown in Figure 3.

![Image](image_url)

**Figure 3.** Real propagation of the loosening path: a) concrete in the light of literature data [12], b) sandstone, in the light of own tests [13].

The knowledge resources existing in this area and the models used are not adequate to map phenomena corresponding to mining by loosening the rock fragments with a fixed bolt. Also the computer simulation tests carried out so far using the finite element method do not give an unequivocal answer regarding the scope of propagation of the loosening gap. It is necessary to compare different methods of crack propagation with in-situ tests to check their accuracy [14]. It is indispensable to carry out tests on shaping the loosening force depending on so called effective loosening depth (depth of undercut in the hole) as well as strength properties of the rock to determine possibilities of loosening the rocks with use of undercutting bolts. In order to fully understand the mechanism of loosening and strain in the pulled out rock, the RODEST project entitled: "Research and modelling of the mechanism for destruction of rock materials in the spatial state of shear and tensile stress" has been started. The project is realized by the scientific consortium: KOMAG Institute of Mining Technology together with the Lublin University of Technology and is financed by the National Science Centre as part of the OPUS 10 competition (project No. 2015/19/B/ST10/02817).

2. Testing the process of loosening the rocks using the undercutting bolts

2.1. Undercutting bolt
The stress in rock material during mining tests using a bolt can be referred to the problem of the load-bearing capacity of mechanical bolts. In the fixation technique, many types of fixing bolts are used, differing in the way they are fixed or loaded. The most commonly used types of mechanical bolts are shown in Figure 4.
Figure 4. Types of bolts in the fixing systems: a) expanding bolts, b) undercutting bolts, c) screwed bolts, d) glued bolts [15].

The KOMAG experience [1, 4, 5] in the field of rock cutting tests with the use of mechanical bolts clearly shows that for this method, due to the nature of the loads application, the most reasonable is to use the undercutting bolts. The legitimacy of using undercutting bolts is due to the way the stress is exerted by the bolt, where all the stress caused by the applied force is concentrated at the place of the shape undercut at the bottom of the hole. Figure 5 shows an example of the undercutting bolt manufactured by HILTI.

Figure 5. An example of the undercutting bolt [15]

Setting this type of bolt involves placing it in a hole previously prepared to the appropriate depth. Then, using a hammer drill and a special fixation device, torque and axial force from the impact acts on the expansion sleeve. Such load to the anchor sleeve causes it to expand on the conical end of the anchor while undercutting the bottom hole. After loading the bolt with an axial force directed to the hole bottom, the force begins to act on the walls of the undercut, which, after exceeding the critical value, creates a crack and causes its propagation. In Figure 6, the example of the loosening crack propagation with an illustration of the undercut residues at the beginning of its propagation.
2.2. Test stand
The test stand for the rocks loosening in-situ tests consists of the device which has a simple and reliable structure, enabling manual transportation, assembly and operation. Construction of the testing device was adapted to each test conditions. The arrangement of the testing device for the loosening test is shown in Figure 7.

As a standard, the testing device is equipped with the following components (Figure 7):
1. cylinder support,
2. cylinder with a cylindrical through hole,
3. undercutting bolts with fastening equipment,
4. supply unit (manual pump + hoses, connectors pressure gauge),
5. supply pressure recorder.

The cylinder support 1 enables installation of the cylinder 2 pulling out the fixed bolt. The support allows the use of two types of pull-out cylinders (30 and 60 T) by using a special connection plate. Each cylinder is supplied from the manual pump 4. The support provides resting against solid rock at 3 points located on a diameter of 1000 mm. At each supporting point, there is the possibility of adjusting (adjustment in the range of 0÷180 mm) the supporting point to the unevenness of the operating front.

Figure 6. Line of crack propagation obtained by undercutting bolt [13].

Figure 7. The RODEST test stand equipment.
by tightening the pressure clamps. Pressure clamps also enable coaxial positioning of the cylinder \(2\) with a previously embedded bolt in the rock \(3\). By using the pressure recorder \(5\) and known active surface of the cylinder \(2\), it is possible to obtain the time process of changes in the pulling force during the rock loosening test. The test stand equipment is complemented by auxiliary equipment enabling efficient testing and recording the parameters, their changes and the results of loosening tests. Additional equipment components include: a hammer drill with accessories, a manual hoist and clamping ropes or a set of tools. The tests were recorded using a video camera, while the loosening measurements were taken using the hand-hold measuring instruments and a hand-held 3D scanner.

2.3. Place of tests

Tests of the loosening the rocks from a solid rock, due to the necessity of diversification of rock strength properties, were carried out in the following four mines, i.e. for four different types of rocks:

- The ZALAS open-cast porphyry mine. The tests were conducted on large rock blocks separated in the result of blasting the not damaged rock.
- The BRACISZÓW open-cast sand mine. The tests were carried out on large rock blocks separated as in the result of blasting.
- The GUIDO hard coal mine. The tests were carried out at the level of 320 m, at the longwall, on the mining front made in sandstone.
- The BRENNA open-cast sand mine. The tests was carried out on the mining front of the oblique stratified rock.

Each time, the rock material was collected from the testing site for the laboratory tests. In the laboratories of the Department of Geomechanics and Underground Construction of the Faculty of Mining, Safety Engineering and Industrial Automation of the Silesian University of Technology, strength tests of the material delivered by the KOMAG Institute of Mining Technology in Gliwice were carried out [16].

The mean values calculated from the test results are presented in Table 1:

| Material / Mine               | Mean values of laboratory tests results | Uniaxial compression test, \(R_c\) [MPa] | Uniaxial tensile strength, \(R_{tb}\) [MPa] | Cohesion, \(c\) [MPa] | Angle of internal friction, \(\phi\) [°] |
|-------------------------------|----------------------------------------|----------------------------------------|---------------------------------|-----------------|-----------------|
| Porphyry / ZALAS              | 106.5                                  | 5.9                                    | 8.6                             | 54.0            |
| Sandstone / BRACISZÓW         | 97.4                                   | 6.2                                    | 11.9                            | 49.6            |
| Sandstone / GUIDO             | 155.3                                  | 8.0                                    | 14.5                            | 49.5            |
| Sandstone / BRENNA            | 58.8                                   | 3.9                                    | 6.0                             | 53.0            |

3. Results of in-situ tests

In-situ tests of the rock loosening process using an undercutting bolt was carried out in four different mines. As a result of the work carried out as part of the RODEST project, 175 tests were carried out to detach the rock material with a bolt fixed in the rock mass. The tests were carried out at various anchoring depths, thanks to which detachments of various volumes were obtained (Figure 8).
Based on the data collected in the notes and video materials, the detailed procedure of each test was developed. From recording of the pressure in the cylinder, a graph of its changes and changes in force during the test cycle was developed. Geometric recreation of the loosening surface was made using a Shining3d hand-held 3D scanner. The process of manual scanning of the loosening surface is shown in Figure 9. The 3D cloud of points mapped in this way was used to develop virtual solid models of loosened rock cones. Data from the models made it possible to obtain information on the range and volume of loosened material. All collected data were placed in an individual test report chart and Excel spreadsheet.

The surface of loosened material obtained using the scanned cloud of points allowed to generate for each test sample, cross-sections corresponding to the maximum ($Z_{\text{max}}$) and minimum ($Z_{\text{min}}$) range of the loosening propagation. An example of such a cross-section is shown in Figure 10. The generated cross-section also allowed for precise determination of the effective anchoring depth. The effective anchoring depth is determined by the depth at which the propagation of the loosening crack begins, what is shown as ($H_{\text{ef}}$) in Figure 10.
Figure 10. Cross-section of the loosened fragment, which determines the effective anchoring depth ($H_{ef}$), maximal ($Z_{max}$) and minimal ($Z_{min}$) loosening range.

The maximum force during each loosening test was determined by its highest value on the graph of force changes during the loosening test. A schematic determination of this value is shown in Figure 11. Such a graph was obtained by correlating the changes in cylinder pressure (measured with a connected recorder) to the effective cylinder surface area.

Figure 11. Determination of maximal loosening force ($F_{max}$) during the loosening test.

3.1. Analysis of impact of anchoring depth ($H_{ef}$) on the maximum loosening force ($F_{max}$)

Assessment of the impact of effective anchoring depth on maximum force during loosening consisted in compilation of data collected during the tests, dividing them into the types of tested rocks. Based on the known depth of effective bolting and maximum force ($F_{max}$), all tests were put together. Presented results of each test were initially approximated by the exponential function divided into each mine (Figure 12). The figure also presents the approximation curve and the $R^2$ index.
Figure 12. Maximum loosening force ($F_{\text{max}}$) in relation to the effective anchoring depth ($h_{\text{ef}}$) for different rock types

Analysing the approximating function for each rock type, it can be stated that for each rock, the loosening force increases with the anchoring depth. Exponential function with the exponent close to ~1.6 is the best type of function mapping. The exception is the function describing the test results in the BRACISZÓW mine, with exponent equal to ~0.9.

3.2. Determination of the average loosening range ($Z_{\text{av.}}$)

As it can be seen in Figure 10, for each scanned surface, the maximum ($Z_{\text{max}}$) and minimum ($Z_{\text{min}}$) range was determined, from which the average arithmetic value ($Z_{\text{av.}}$) was determined by the following equation:

$$Z_{\text{av.}} = \frac{Z_{\text{max}} + Z_{\text{min}}}{2} \quad (1)$$

Average loosening range ($Z_{\text{av.}}$) for each measurement depending on the effective anchoring depth ($h_{\text{ef}}$) is shown in Figure 13.

Figure 13. Average loosening range ($Z_{\text{av.}}$) for each measurement depending on the effective anchoring depth ($h_{\text{ef}}$) for different types of rocks.
The average loosening range for each type of rock was approximated by an exponential function. For each type of rock, an increase in the average loosening range can be seen, which is proportional to the increase in the effective anchoring depth \((H_{ef})\). For each test, the coefficient \((R)\) determining the quotient of the average loosening range \((Z_{av})\) and the effective anchoring depth \((H_{ef})\), determined by the following formula:

\[
R = \frac{Z_{av}}{H_{ef}} \tag{2}
\]

In Figure 14 changes in coefficient \((R)\) in relation to the effective anchoring depth for different types of rock are presented.

![Figure 14. Changes in the coefficient \((R)\) in relation to the effective anchoring depth \((H_{ef})\) for different types of rock.](image)

The average values of \((R)\) coefficient for each type of rock within the anchoring depth range 30–150mm do not differ much and are equal to 3.9 ÷ 4.2. These values are presented in Table 2.

**Table 2.** Average values of \(R\) coefficient.

|                  | ZALAS | BRACISZÓW | GUIDO | BRENNA |
|------------------|-------|-----------|-------|--------|
| \(R=\frac{Z_{av}}{H_{ef}}\) | 3.9   | 4.1       | 3.9   | 4.2    |

3.3. **Loosening angle \((\psi)\)**

As it can be seen in Figure 10, the line connecting the beginning of the loosening crack propagation with its end was determined for each maximum \((Z_{max})\) and minimum \((Z_{min})\) range. For both lines, the loosening angle, referred to the base of the loosened cone i.e. maximum \((\psi_{max})\) and minimum \((\psi_{min})\) angles were determined. Then for both loosening angles, the average arithmetic value \((\psi_{av})\) was calculated according to the following equation:

\[
\psi_{av} = \frac{\psi_{max} + \psi_{min}}{2} \tag{3}
\]

Average values of loosening angles \((\psi_{av})\) for each test in relation to the effective anchoring depth \((H_{ef})\) for different types of rock is shown in Figure 15.
Analysing the results of the average loosening angles, it can be stated that the average loosening angle increases with the effective anchoring depth for all tested rock types. The average values of the loosening angle for each rock type in the range of anchoring effective depth 30–150 mm are presented in Table 3.

Table 3. Average values of the loosening angle $\psi_{av}$.

| Rock Type   | $\psi_{av}$ [°] |
|-------------|-----------------|
| ZALAS       | 15.1            |
| BRACISZÓW   | 15.3            |
| GUIDO       | 15.8            |
| BRENNA      | 13.7            |

4. Conclusions
The tests, carried out so far within the RODEST project, indicate that the process of rock loosening using an undercutting bolt is a viable method for unconventional rock cutting. The current analysis of the results of the loosening process with the undercutting bolt allows the following general conclusions to be drawn:

- The maximum loosening force ($F_{max}$) needed to loosen a fragment of solid rock in a shape similar to a cone increases with the depth of effective anchoring ($H_{ef}$).
- The maximum force ($F_{max}$) depends on the strength properties of a given type of rock and increases with the increase of strength under uniaxial compression ($R_c$) and tensile strength ($R_{tb}$).
- Non-homogeneity or internal damages within the fixed bolt impacts the crack propagation and thus the loosening range in this direction. Therefore, the average values determined for the maximum and minimum loosening range from the axis of fixed bolt (Figure 10),
- The ratio of the average range value ($Z_{av}$) and the effective anchoring depth ($H_{ef}$) determined by the ($R$) coefficient is approximately 4. This is more than twice the value used for the calculation of the anchoring capacity (Figure 2). At the same time, one can notice a tendency to reduce the ($R$) coefficient together with increase of the effective anchoring depth for all types of tested rocks.
- Average values of loosening angle ($\psi_{av}$) for each rock type, within the range of tested anchoring depths varies from 13–17°. For each type of rock, there is a tendency to increase the loosening angle ($\psi_{av}$) with the increase of effective anchoring depth ($H_{ef}$).
The conducted tests as well as analysis of the results collected during the tests allow to undertake a research work aimed at building a simplified loosening model that allows estimation of loosening forces and range, depending on the anchoring depth and rock strength in order to enable correct realization of the rock loosening process in mine conditions. The in-situ tests allow the adaptation of the numerical simulation method best suited to the real tests.

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