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On the evaluation of rock integrity around mine workings with anchorage by the shock-spectral method☆

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ABSTRACT

The goal of this study is to investigate the integrity of gypsum-containing rocks during underground mining using non-destructive testing (NDT) anchors by the shock-spectral method. Studies were conducted in-situ at a gypsum deposit in the roof of the transport drift and cleaning chamber of a mine. Steel-polymer anchors were studied. The anchors were fastened in the hole with polymer resin and were fastened outside the hole with washers and nuts. The anchors were free in the middle. The vibrational response after striking the protruding end of an anchor was recorded, a spectrum was calculated, and the frequency (F) of the spectral maximum and the acoustic quality factor (Q) were determined. Q was calculated as the ratio of F to the frequency band at the $1/\sqrt{2}$ level of the spectrum maximum. With a tensioned anchor, it was determined that at the free length of the anchor, half of the wavelength was placed (F is high) and the outer layer of roof rocks determined the measured data. With a weakened anchor, a quarter wavelength was placed on its length (F is low) and the inner layer of roof rocks determined the measured data. All anchors were divided into two groups. When $F \leq 1050$ Hz the inner layers determined the Q-factor, and at $F > 1050$ Hz the external layers determined the Q-factor. The average value of Q-factors of tensioned anchors (outer layers) were below the average value of Q-factors of weakened anchors (inner layers). Large Q values were assumed to correspond to higher rock integrity and strength. The ratio of the average value of the Q-factors of the external layer to the average value of the Q-factors of the inner layer was used to assess roof rock integrity. Smaller values of this ratio were characterized by lower rock integrity and a tendency to collapse and fall.

1. Introduction

1.1. State of the art

One of the problems in mining is ground fall of roof rocks in underground mine workings, which can lead to injuries and potential fatalities, as well as damage and failure of equipment. For example, according to the U.S. Mine Safety and Health Administration (MSHA) [1], from 1999 through 2008, ground fall events resulted in 75 fatalities, 5941 injuries, and 13,774 non-injuries in U.S. underground coal mines. As the strength of rocks decreases, the probability of roof rock fall increases. This occurs because of rocks weakening with time, rock weathering, rock pressure, and moisture in the mine [2–5]. It has also been established that repeated loading even with low energy creates fatigue microcracks in a solid mass [6]. Rocks around underground workings are fatigued in this way by the impact of drilling and blasting during mining and development of tunnels, in addition to when heavy vehicles drive through the tunnels.

Rock supports have been designed to prevent failure. Roof anchoring is most commonly used because of its relatively low cost and high technical efficiency [7,8]. In recent years, methods and devices for testing and monitoring roof bolting and roof rocks have been developed. Methods and devices for roof and roof anchoring monitoring are used to measure the convergence and roof rock layer splitting using telltales, sonic probes, maximum anchor load testing by hydraulic dynamometers, and other methods [9]. The method of maximum anchor load measuring can destroy roof rocks and is not safe for personnel. Non-destructive testing methods of anchoring have been developed since the 1970s.

The method of monitoring anchor bolt integrity [10] in rocks in a borehole involves striking the head of the anchor bolt to create acoustic vibrations and excitation of at least one of mode of vibration. Perception of anchor bolt vibrations, generation of an electric signal by the vibrations, measurement of signal amplitudes in multiple predefined

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frequency bands, and calculation of the resonant frequency of the selected vibration are indicators of the integrity of an anchor bolts. The integrity of roof rock and an anchor is evaluated with a roof bolting electronic tester [11] at the natural frequencies of the anchor and the rock mass in the roof. In the late 1970s, a device called a "Boltometer" was designed [12], which transferred compression and flexural elastic waves to a bolt via a piezo-electric transducer.

In [13,14], the authors describe anchor testing using pulse and sweep sine acoustic signals excited in the anchor by shot and magnetostrictive transducers. In another paper [15], authors describe a system called GRANIT that has been available since 1997. This system uses a small impulse at the protruding end of the bar. Testing anchor bolts using guided ultrasonic waves with frequencies of up to 500 kHz is discussed in [16]. Ref. [17] describes the ultrasonic method of anchoring testing, studied in Germany.

The method of non-destructive rock bolt testing, developed in Poland, uses modal analysis and anchor impact excitation [18]. It consists of two main phases: experimental, which entails measurement of modal characteristics of the investigated object, and theoretical, which involves referencing finite element model databases.

Ref. [19] describes measurement of the length of an installed rock bolt using stress wave reflection by using a giant magnetostrictive (GMS) actuator and a piezoelectric sensor.

Ref. [20] reviews various destructive and non-destructive methods developed for evaluation of bolt performance. The study suggests that none of these testing methods can be used by itself to get all the necessary information about the performance of a rock bolt. Instead, a combination of methods must be used.

The purpose of investigations in [21] was to evaluate the grouted ratio of a pipe roof system using a non-destructive method in the laboratory and the field. In laboratory tests, four specimens embedded in soils and five non-embedded specimens were prepared with different grouted ratios, including 0%, 25%, 50%, 75%, and 100%.

The self-contained non-destructive test system RokTel [22] uses an anchor reaction to the strike and allows assessment of the anchor conditions with solid steel and hollow bolts, and fiberglass rods. This system allows estimation of the anchor length, anchor quality, and state of the anchoring.

The "Anchor-Test" device was been developed for non-destructive testing (NDT) of anchorage and roof rocks of underground workings [23,24]. It uses the shock-spectral method for testing.

This short review shows the relevance of the problem of NDT of anchoring roofs, walls, and slopes of various geotechnical structures. Assessment of anchor lengths, their relationships with the rock massif, and the degree of anchors' concrete filling were the main objectives in the investigations described above. At the same time, assessment of the safety of the rock integrity and strength itself is important, as it allows monitoring and evaluation of the remaining underground structure resources, but is beyond the scope of these publications.

Development of non-destructive methods to assess the integrity and strength of rocks is necessary. Existing geophysical methods are based on regressions of damage, stress or strength of rocks and their physical properties, such as longitudinal and transverse elastic waves [25–27], electrical resistivity [28] of rocks, and other parameters. The disadvantage of these methods is that they are only sensitive in the later stages of rock destruction. The non-destructive testing method of rocks integrity in the early stages of destruction and their long-term stability can be estimated from their relationship to the acoustic (mechanic) quality factor Q (i.e., Q-factor). Physically, Q is the ratio of the total oscillation energy stored divided by the energy lost in a single cycle [29]. As an informative parameter, the Q-factor characterizes properties of the rock. It can be used as an indicator of the integrity of rocks. Large Q-factors correspond to high rock integrity and strength. Conversely, small Q-factors corresponds to low rock integrity and strength.

The Q-factor can also be used to characterize the state of the rock massif together with the anchor installed in it. The Q-factor of a steel anchor in the free state is large, possibly exceeding several tens of thousands. Since the Q-factor of the anchor installed in the rock massif is primarily determined by the Q of the massif itself, the value of which is much less than of steel, measurement of the Q-factor will allow us to evaluate the quality factor of the rock mass. As shown below, testing tensioned and weakened anchors will allow us to determine the status of the internal and external rock layers of the roof.

1.2. Objectives

The main purpose of this study was to test the method of assessing the state of rocks and their integrity in outside and inside layers of massifs around underground mine workings by analysing the vibrational response on anchor strike. Investigations were carried out at a steel-polymer fastening consisting of an anchor, resin in the hole between the anchor and the massif, and a washer and nut at the outer part of the anchor bolt. The middle of the anchor was free.

One of the first in-situ tests of this method was in a gypsum mine in two underground mine workings, a cleaning chamber and a transport drift, with lifetimes of 0.5 and 8 years, respectively. Use of this method for periodic NDT-measurements and extrapolation of their results for prediction of resources and the moment of rock destruction is a further goal of this study.

This work is a continuation of research outlined in [30–36], which were conducted on various rock samples. These studies found a connection between strength and acoustic quality factor, with the increase / decrease of one value being accompanied by a corresponding increase / decrease of the other value. The studies described in this article were carried out in-situ based on the qualitative laws obtained previously.

2. Method and location of measurements

2.1. Device and method of measurement

The Mining Institute of the National University of Science and Technology MISiS (Moscow) developed the "Anchor-Test" device for non-destructive testing of anchoring of underground mine working roofs. A schematic diagram and the principle of operation of the device are shown in Fig. 1.

The device uses spectral analysis of the signal from a bolt being shocked. A hammer with a MEMS transducer strikes the protruding end

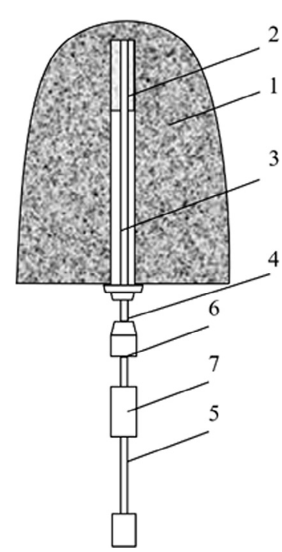

Fig. 1. Schematic diagram of roof anchoring and its testing device: 1 – massif of roof rocks; 2 – poly-resin; 3 – anchor with washer and nut; 4 – protruding end of anchor; 5 – "Anchor-Test" control device; 6 – impact mechanism with converter (striker); 7 – electronic signal processing unit.