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# Trends in non-destructive testing of rock bolts

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Subject review

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## Trends in non-destructive testing of rock bolts

Rock bolts represent a critical element for many rock mass stabilization, tunnel construction, and underground work projects. Therefore, the evaluation of their condition is vital for proving their functionality over the entire life-cycle of structures. A number of techniques for quantifying condition of rock bolts are presently applied or are being developed. These include acoustic-based and vibration-based methods, which take advantage of various types of sensors and signal-processing tools. This paper provides an overview of available non-destructive test methods for rock bolts, considering both current practice and state of the art approaches.

### Key words:

rock bolts, non-destructive test, sensors, force monitoring, grouting quality

Pregledni rad

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## Trendovi u nerazornom ispitivanju stijenskih sidara

Stijenska sidra predstavljaju ključni element u brojnim projektima stabilizacije stijenske mase, izgradnje tunela i podzemnih građevina. Stoga je ocjena njihovog stanja od vitalnog značenja za dokazivanje njihove funkcionalnosti tijekom životnog ciklusa građevine. Brojne su metode koje se primjenjuju, ili su u razvoju, za kvantificiranje stanja stijenskih sidara. One uključuju akustične metode i metode zasnovane na analizi vibracija, te kao takve koriste brojne prednosti različitih vrsta senzora i alata za obradu signala. Ovaj rad daje pregled dostupnih metoda nerazornog ispitivanja sidara, uzimajući u obzir trenutačnu praksu i najsuvremenije pristupe.

### Ključne riječi:

stijensko sidro, nerazorno ispitivanje, senzori, mjerenje sile, kvaliteta injektiranja

Übersichtsarbeit

**Mario Bačić, Kenneth Gavin, Meho Saša Kovačević**

## Trends in der zerstörungsfreien Prüfung von Felsankern

Felsanker sind ein Schlüsselement in zahlreichen Projekten zur Stabilisierung von Felsmassen, im Tunnelbau und in unterirdischen Bauwerken. Daher ist eine Beurteilung ihres Zustands von entscheidender Bedeutung, um ihre Funktionalität über den Lebenszyklus eines Bauwerks nachzuweisen. Es gibt zahlreiche Methoden, die angewendet oder entwickelt werden, um den Zustand von Felsankern zu quantifizieren. Sie umfassen akustische und Methoden basierend auf der Vibrationsanalyse und nutzen als solche die zahlreichen Vorteile verschiedener Arten von Sensoren und Signalverarbeitungswerkzeugen. Diese Arbeit bietet einen Überblick über die verfügbaren zerstörungsfreien Ankerprüfmethoden unter Berücksichtigung der aktuellen Praxis und der modernsten Ansätze.

### Schlüsselwörter:

Felsanker, zerstörungsfreie Prüfung, Sensoren, Kraftmessung, Einspritzqualität

## 1. Introduction

Many rock mass stabilization measures have been developed during the history of construction activities. However, the most significant progress in this area has been achieved after introduction of rock bolts, which are nowadays commonly used in tunnels and foundation pits, Figure 1, as well as in rock cuttings, mines, etc. With hundreds of millions of rock bolts installed worldwide each year, the trend of rock bolt applications will surely continue to grow, as their market is very stable, with a new rock bolt installation technique introduced to the market every 5 to 10 years [1].

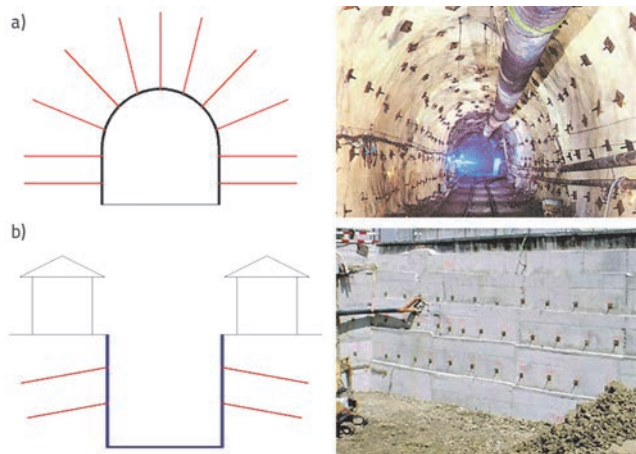


Figure 1. Some examples of rock bolt applications: a) tunnels; b) foundation pits [2]

Stabilization of rock cuttings, tunnels and underground structures presents a challenge since any instability caused by an inadequate support can have negative consequences from the aspect of time, costs and, most importantly, safety. Determination of rock bolt capacity, and monitoring of its condition, including load level and grouting quality, have an important role in ensuring safety on such projects. Rock bolt testing is usually performed in the scope of design verifications and installation quality control. However, it can also be performed prior to design to obtain necessary information on the rock bolt behaviour at a specific location, particularly in cases when little local knowledge is available. The relevant design code EN 1997-1 [3] and rock bolt execution standard EN 1537:2008 [4] focus on destructive testing procedures for rock bolt capacity determination. The so-called 'suitability test' and 'acceptance test' are performed using the destructive pull-out method. The only non-destructive testing methods given in these standards are those linked to electrical testing to assess condition of a rock bolts corrosion protection. There are no recommendations regarding the need for rock bolt load monitoring or grouting quality determination. Considering that the load on a rock bolt can vary over time due to relaxation, creep in the surrounding rock mass, deterioration, etc. there is a strong need to determine condition of rock bolts over time. In recent years, numerous researchers have explored non-

destructive testing methods as these methods are proving to be a highly effective tool in tracking the changing condition of rock bolts with time. However, despite the strong theoretical background, concerns arise when implementing these methods in practice, probably because of lack of knowledge on the handling and interpretation of data. Andersson [5] suspects that this could be due to poor experience in the past linked with the application of older testing instruments. Nevertheless, it is clear that a considerable need exists to continuously develop and verify non-destructive test methods for rock bolts, as this will eventually boost confidence of practical engineers.

Song et al. [6] note that the rock bolt testing increasingly involves the use of instrumentation with sensors, where the selection of sensor type and position of its installation mostly depend on phenomena that are being monitored. Since all non-destructive testing methods depend, at some level, on variations of the rock mass, grout, steel bar, anchoring head characteristics, as well on the overall environment in which the test is performed, non-destructive methods need to be analysed with caution, based on clear understanding of advantages and limitations of each method.

## 2. Determination of rock bolt capacity

Whilst most non-destructive methods focus on determination of the rock bolt load level or grout quality, some efforts have been made towards non-destructive determination of ultimate capacity. Even though one would intuitively consider that determination of capacity implies application of a destructive test technique, some promising work has been made on implementation of the acoustic emission method in the field that is summarised here.

### 2.1. State-of-the-art: pull-out test

A destructive method known as the pull-out test [7] has been widely used in practice for determining capacity of installed rock bolts and geotechnical anchors. Two types of pull-out tests can be conducted. The first type is used to check the actual rock bolt capacity during which rock bolts will fail and be completely pulled out of rock mass, while the second one, the so-called proof load test, is used to verify if rock bolts can withstand load as foreseen in the design [8]. The pull-out method involves application of a gradually increasing tensile force on the exposed end of the installed rock bolt using a hydraulic jack, and determination of the force - displacement relationship, Figure 2. During the testing phase, the imposed force is measured by means of a load cell, while displacement values are measured by displacement gauges.

Detailed instructions for the instrumentation and testing are provided in ISRM standard [7] where it is suggested that at least 5% of all installed rock bolts should be tested. The purpose of the pull-out tests is to determine the pull-out load - displacement response. In the event that the test bolt does not comply with

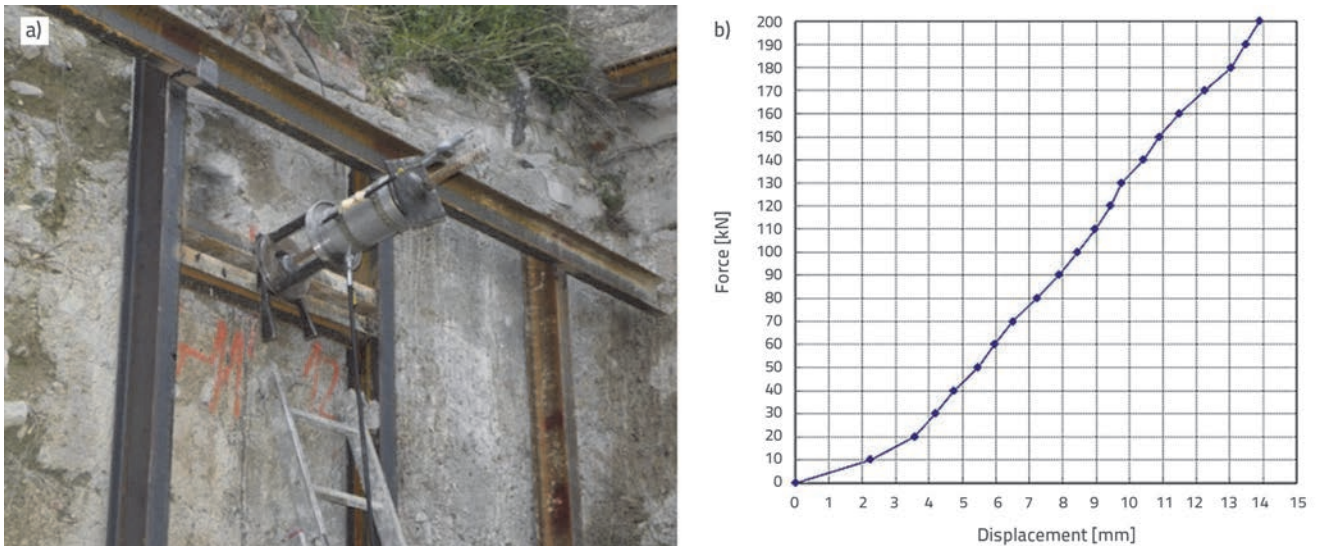


Figure 2. a) pull-out test in progress, b) resulting force-displacement graph of so-called proof load test; test location: foundation pit in Split, Croatia [8]

the specification, the test would be unable to determine the reason, e.g. poor grout quality, uncertain rock properties, flawed design, etc.

## 2.2. Future trend: acoustic emission

Research conducted by Arbanas et al. [9], focussed on finding a test that would be an alternative to the destructive pull-out test method. This investigation was conducted in controlled laboratory conditions and still needs to be verified in real field conditions because of natural variability and quality control effects of field tests. The investigation procedure adopted is similar to the pull-out test, where a hydraulic press is used to increase the test load, which is continuously measured by a digital instrument. As the load increases, micro-cracks are induced in the grout and at the bar – grout interface. The number of cracks increases with an increase in load level. The generation of cracks induces energy emission, and the wave energy is transformed into electrical signals by means of a piezoelectric sensor positioned on the rock bolt head. A rapid increase in the number of peaks of received waves suggests that the load within the rock bolt is approaching the capacity value and that

the investigation can be terminated, without actually pulling out the bar as would be the case with the standard pull-out test.

Forty-eight rock bolt laboratory models of varying composition were formed in order to validate the proposed method. Test results for one of the laboratory models is shown in Figure 3 with Figure 3a showing a typical relationship between the imposed load and displacement, as well as the relationship between the force level and the displacement increment / force increment ratio. The last registered force value is considered to be the rock bolt capacity, since already the next increment causes failure. The diagram in Figure 3b shows the relationship between the imposed force and the number of impulses, as well as the relationship between the force level and the impulse increment / force increment ratio, where a bilinear form of the impulse number increment is visible. In addition, a rapid increase in the number of impulses can occur immediately before the capacity value is reached. A similar phenomenon can be seen in Figure 3c. The authors propose an analytical procedure for determining the force at which the pull-out test should be stopped and, based on an average of all investigated models, this force is around 95 % of the capacity value.

Therefore, unlike the destructive pull-out method, the pull-out test can be stopped before the capacity is reached, by measuring

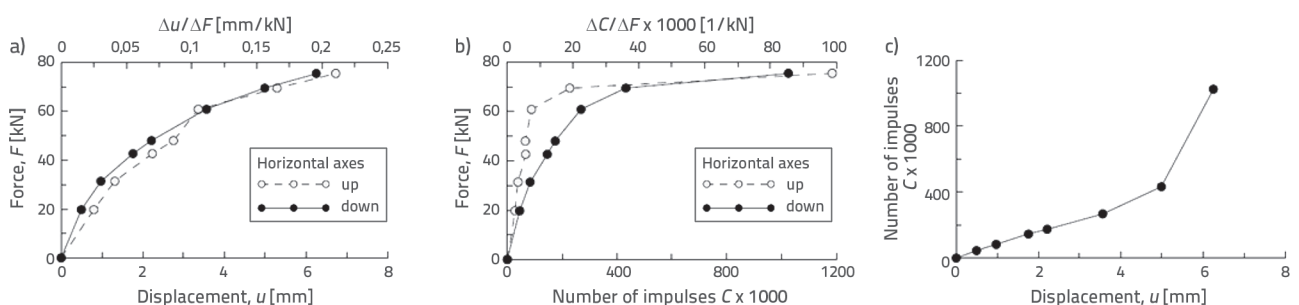


Figure 3. Results of rock bolt model testing by acoustic emission method [9]

the number of acoustic emission impulses. In this case, the investigated rock bolt can remain as a part of the rock mass support system and substantial financial resources can thus be saved. However, as already mentioned, this method needs to be verified in in-situ conditions where the number of factors, mostly environmental, can affect the investigation results.

### 3. Load monitoring

Benmokrane et al. [10] noted that load-monitoring is an important part of checking long-term integrity since the force within a rock bolt changes with time. Significant variations of load can be an indicator of overloading or loosening, both of which can have severe consequences on the overall structure.

#### 3.1. State-of-the-art: load cell and measuring rock bolt

A load cell is commonly used for measuring load within an installed rock bolt. It consists of a steel cylinder fitted with deformation gauges [11]. Deformations are transformed into electrical signals that are then calibrated and the load value in the rock bolt is obtained as the output. However, due to material and installation costs, not all installed rock bolts are equipped with load cells.

An alternative method is the deployment of measuring rock bolts, a combination of rock bolt and extensometers, which are used in a range of geotechnical engineering applications [12]. Their installation does not differ from installation of conventional rock bolts, see Figure 4, with strain gauges installed along the bolt at a pre-defined spacing. The strain distribution as well as the axial force within the bolt is monitored using a portable readout unit. Commonly used electrical-resistance strain gauges do not perform well in the long-term since they are prone to damage during installation, and also during service life under the influence of harsh environments. To overcome this shortcoming, Benmokrane et al. [10] deployed vibrating-wire strain gauges, which rely on the phenomenon of changing the natural vibration frequency of a wire with the tension level, and are more robust for more long-term monitoring applications.

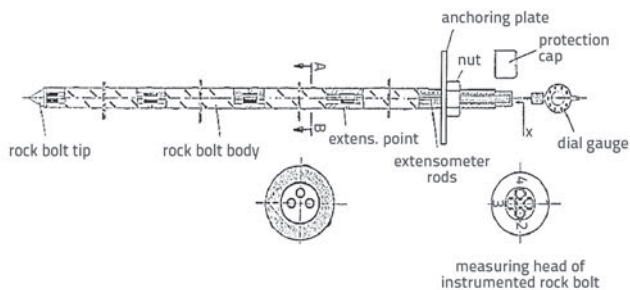


Figure 4. Elements of a measuring rock bolt, modified from [12]

Currently there are some ongoing efforts in enhancing the measuring rock bolts, such as the Smart Rockbolt [13]. The prototype uses the Internet of Things (IoT) technology and

is equipped with a strain sensor, accelerometer, processing module and wireless communication module. It should enable continuous monitoring of strain and load.

#### 3.2. Future trend: fibre optic sensors

Several authors have considered the application of fibre optic sensors as an alternative to electrical-resistance and vibrating-wire strain gauges. These are particularly useful in areas with electromagnetic interference and/or high temperatures. Song et al. [6] give an overview of research focused on the application of optic sensors positioned within rock bolts in order to measure the strain and load levels. Some of the first attempts of using fibre optic sensors were reported by Frank et al. [14], who investigated the possibility of installing the so-called Fibre Bragg Gratings, FBG, sensors in a glass fibre reinforced polymer rock bolt, used for long-term load monitoring of rock bolts in Swiss tunnels [15]. The installed sensor was able to withstand a strain of 1.5 %, significantly lower than the steel rock bolts strain, which can go up to 20 %. Schroeck et al. [16] therefore designed a special positioning of the FBG sensors along the steel rock bolts, which enables measurement of large relative strain values. Ho et al. [17] proposed that a load measuring anchor plate for rock bolt with a FBG optic sensor can be used instead of measuring the strain on the rock bolt itself.

The optical fibre distributed sensing technique, used by Iten et al. [18] overcomes the quasi-distributed nature of FBG sensors and, as such, it is more reliable in determining stress distribution along the rock bolt. The load distribution measured by the Brillouin optical time domain analysis (BOTDA) is shown in Figure 5 for various load steps.

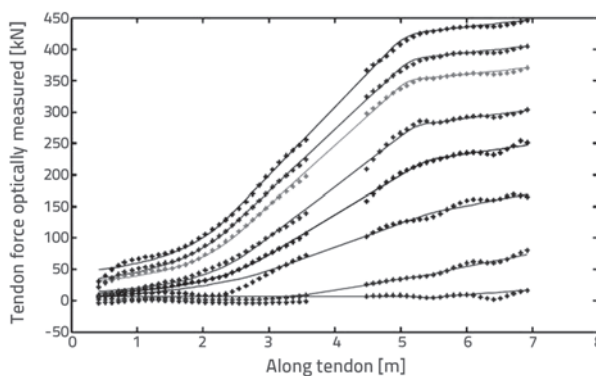


Figure 5. Load distribution along tendon as measured by Brillouin optical time domain analysis [18]

Recently, Vlachopoulos et al. [19] implemented a distributed optical strain sensing (DOS) technology that provides a high spatial resolution to capture the strain along the rock bolt. The DOS method utilizes Rayleigh optical frequency domain reflectometry (ROFDR), providing insight into various mechanisms associated with axially loaded rebar specimens

of different embedment lengths, grouting materials, borehole annulus conditions, and borehole diameter.

Even though the fibre optic based methods provide promising perspective, the instrumentation of the installed rock bolts with different type of sensors (whether strain gauges or optic fibre sensors) is still a relatively costly option. However, this could be changed in the near future, with the cost of electronics becoming cheaper, and with the wider range of different type of sensors. Increased development of communication systems with wireless technologies will most certainly foster a more effective use of various sensors.

### 3.3 Future trend: GRANIT System

An alternative method for load monitoring, without quasi-distributed or distributed positioning of the sensors along the rock bolt, is offered by the GRANIT system (The Ground Anchorage Integrity Testing), developed at the University of Aberdeen [20]. The method includes a non-destructive procedure for the determination of force within an installed rock bolt during its service life, based on the measurement of vibrations by an accelerometer positioned on the rock bolt's head. The system, patented and licensed for use, is based on the analysis of natural frequencies of the installed rock bolt, which can give information on the rock bolt load level. To obtain the response frequency spectra, a device consisting of the device body, the piston, and the clamp [21], is used to generate a controlled impulse on the rock bolt head.

The GRANIT system is divided into six subsystems, Figure 6, which include: the extended part of free length to which the impact device is fixed (Subsystem I), the anchoring part with bearing plate (Subsystem II), the free length part of the anchor not in contact with rock mass (Subsystem III), the interface between steel bar and grout along the fixed length of the anchor (Subsystem IV), the interface between grout and rock mass along the fixed length of the anchor (Subsystem V) and the boundary between affected (by reinforcement) and non-affected rock mass (Subsystem VI).

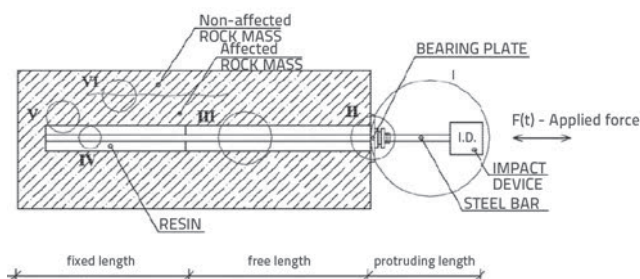


Figure 6. Division of GRANIT system in six subsystems [20]

As a first step in validation of the system, the authors developed a one-dimensional dynamic numerical model, which consists of mass, damping and stiffness of each subsystem. The results obtained with the dynamical model were compared with the laboratory and field investigations. When numerical model characteristics were adapted to those of the laboratory models or

those of field models, the analysis demonstrated that frequencies increased in the laboratory [20] and field [22], see Figure 7.

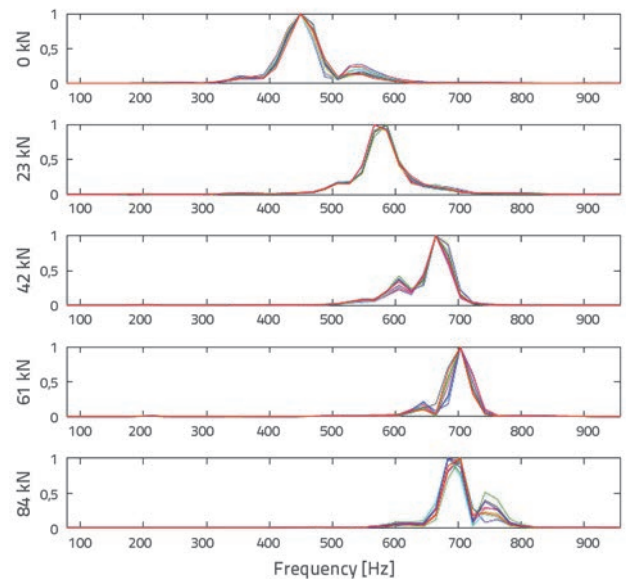


Figure 7. Increase of natural frequencies with an increase in load level in rock bolt [21]

The acceleration signals were interpreted using neural networks, trained on data from the field anchors [22] or data from the dynamic numerical model [23]. With acceleration responses at different levels of imposed load, the neural network can learn complicated non-linear relationships between the anchor load level and the frequency response. However, careful selection of the signal-processing tools, as well as neural network input data, are critical. In order to improve the diagnostic capabilities of the GRANIT system, Cheung et al. [24] state that neural network needs to be trained on a sufficient number of reflected signals for different types of rock bolts, while Song et al. [6] note that the necessity for training neural networks to recognize existing conditions means that the system cannot be easily applied for the new rock bolt conditions that have never been characterized before. This is considered to be the main disadvantage of the GRANIT system.

Ivanović et al. [25] additionally investigated the influence of the system geometry and the characteristics of materials on the rock bolt's frequency values. It was noted that the grout stiffness has a major role in controlling the dynamic response since the rock mass stiffness is usually assumed to be infinite.

## 4. Grouting quality

To ensure proper load bearing capacity of installed rock bolts, their integrity in terms of grouting quality should be examined, since the load transfer largely depends on the steel bar – grout interface, and on the grout – rock mass interface. Poor grouting yields lower pull-out capacity of installed rock bolts. Non-destructive alternatives to destructive determination of grouting quality, such as the over-coring test, are presented in this section.

### 4.1. State-of-the-art: Boltometer

The non-destructive testing of rock bolt grouting quality using the Boltometer started in 1983 with development of the first version of the apparatus [26]. The Boltometer uses a sensor with piezoelectric crystals, which both generates and receives waves at the rock bolt head. The generated waves travel through the installed element and, after reflection, they are recorded. The testing procedure is quite simple - if the rock bolt is well grouted, the energy return will come only from the rock bolt end. However, if there are any anomalies in the grouted section of the rock bolt, a certain amount of energy will be reflected from the anomaly and it will be registered as such on the rock bolt head.

The Boltometer uses both compression waves (primary, P) and shear waves (secondary, S), while the piezoelectric sensor is set to differentiate wave types. Figure 8 shows a typical test result obtained using a Boltometer. While P waves are used to determine the effective length of the rock bolt, the analysis of shear waves has been somewhat revolutionary within acoustic methods. These waves are directly used to determine grouting quality, due to their high sensitivity to the presence of anomalies. Another advantage of shear waves, compared to longitudinal waves, is the fact that they are less attenuated, and so better results can be obtained. Based on the level of returned energy, a Boltometer classifies anchors into four classes, from A to D (A being continuously grouted rock bolt with good quality grout, D being a rock bolt with significantly reduced grouting quality). To classify the investigated rock bolts into one of the classes, the Boltometer uses reference classification lines, through which the returned signal is evaluated.

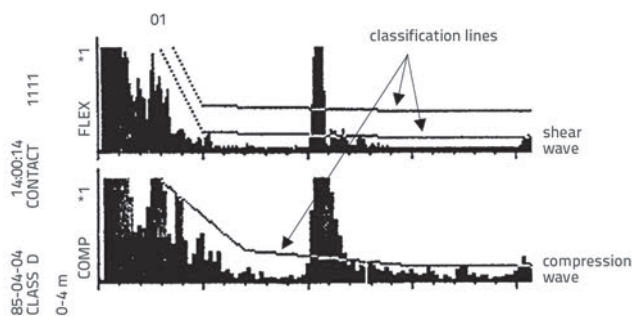


Figure 8. A typical Boltometer result [26]

In 1994, a company developing the Boltometer (Geodynamik) completed the *Rock bolt-reference bank*, which allows comparison of measured signals with the actual grouting condition obtained by rock bolt over-coring. Several drawbacks of the Boltometer were identified, including the significant work on preparing the rock bolt head for proper investigation, limitation of investigations

to 18-32 mm bars and cement-based grout, etc. Additionally, Agnew [27] stated that the Boltometer uses grout as a medium through which the waves pass, taking into account the fact that the wave velocity is lower in the grout than in the steel section and the rock mass. While this assumption may be valid in rock masses with high stiffness, such formulation in soft rock, such as karst rock mass, is questionable [2], since it was shown by Jurić-Kačunić [28] that the stiffness of karst rock mass significantly varies with depth. Agnew [27] conducted further research to overcome some of these limitations whilst Basson [29] concluded that, before finding a test method more suitable than the Boltometer, the quality of rock bolt grouting can only be improved by training people working on its installation.

### 4.2. Future trends: ultrasound guided waves (Rock Bolt Tester)

Beard et al. [30] investigated non-destructive testing of resin-based grouted rock bolts, utilizing a principle of ultrasonic guided waves generated by a frequency-controlled generator, Figure 9a. In this way, propagation of waves through the rock bolt can be analysed for a specific frequency. Appropriate frequencies are identified using a numerical model, laboratory and field testing. The information about the shape of the wave-velocity dispersion curves is used to calculate position of anomalies in grout, and the overall length of the rock bolt.

Compared to the Boltometer, the main advantage arises from the fact that certain frequency shapes are less susceptible to impedance differences between grout and the rock mass. The authors used two frequency tests - low frequency test (30-70 kHz) and high frequency test (2-5 MHz). The general conclusion of the study was that potential grouting defects can be determined using the lower frequency test, while the higher frequency test can be used to determine the rock bolt length. Leakage attenuation is one of main characteristics of ultrasound guided waves, where ultrasound energy has the tendency to leak from grout to the rock mass. Identification of frequency shapes with a relatively low attenuation is therefore a crucial investigation aspect. The modelling of guided waves enabled better insight into their behaviour by looking for a modal solution and calculating modal characteristics. Figure 9b shows a frequency-attenuation graph for different modes. It can be seen from this graph that L(0,1) mode has the lowest

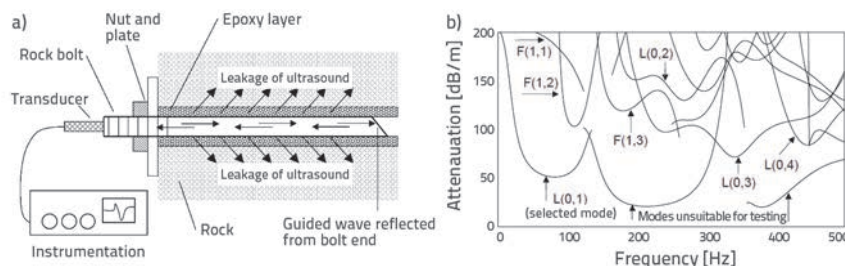


Figure 9. A scheme of rock bolt testing by: a) ultrasound guided waves technique; b) investigation results for different modes of ultrasound guided waves [30]

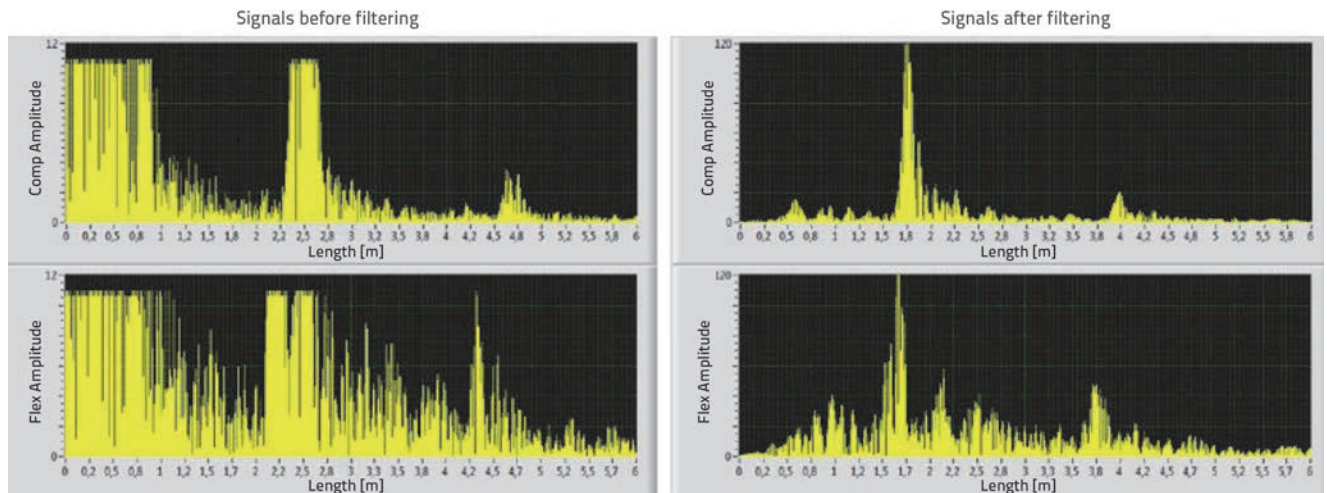


Figure 10. Example of ultrasound echo signals registered by RBT instrument [34]

attenuation at 70 kHz frequency. Several subsequent studies [31–33] focused on complex 3D modelling of ultrasound waves. However, a significant step in the development of a modern and enhanced version of Boltometer was the project initiated by company Geosigma AB [34]. The project was motivated by the needs of companies involved in installation of rock bolts, and the supervising authorities. The enhanced method is based on the research conducted by Beard et al. [30], under the name of Rock Bolt Tester (RBT). The RBT applies guided waves to perform a long-range ultrasound NDT test to determine rock bolt integrity, while the equipment includes modern electronics and signal processing tools. Stepinski et al. [34] state that the problem related to the high signal attenuation in grouted rock bolt was solved by the transmission of high energy via generation of wideband pulse trains. The resulting signals are captured by means of sensitive piezoelectric elements and amplified by high-gain receiver channels. To increase the signal to noise ratio, digital matched filters are applied on the received signal. An example of ultrasound echo signals registered by the RBT instrument is given in Figure 10. Compressional component of signal is in the upper panels, and the flexural components are in lower panels. The experimental validation of the RBT tester was conducted, and the analysis of approximately 3200 tests gave promising results. Andersson [35] states that the RBT is capable of detecting all bolts with either manufactured defects or which are deemed as failed with the Boltometer. The RBT method continues to develop.

#### 4.3. Future trend: analysis of rock bolt frequencies

Several studies were conducted to determine grout quality based on the analysis of frequency spectra resulting from dynamic response of rock bolts. Kovačević et al. [36] analysed the dominant frequency from power density spectra and attempted to link this with the percentage of rock bolt length that is fully grouted. The authors conducted a series of laboratory and field tests, and concluded that the dominant frequency increased with an increase in grout percentage. However, a direct correlation between the dynamic response

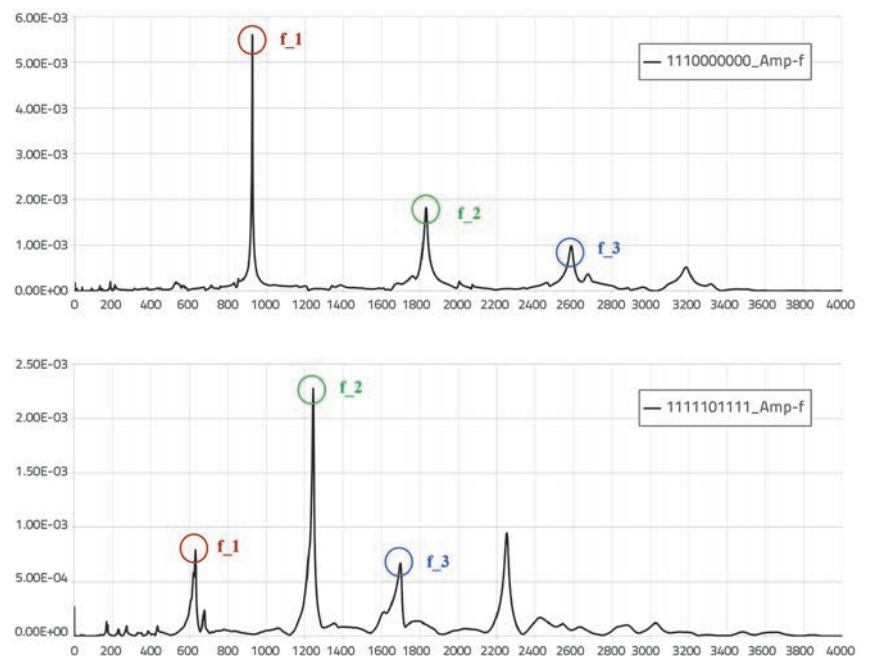


Figure 11. Two frequency spectra with visible peaks representing natural frequencies: a) rock bolt with total of 30% grouted section; b) rock bolt with total of 90% grouted section [2]



and grout quality was not possible. Using more sophisticated equipment, Bačić [2] extended the analysis to consider the first three natural frequencies and linked them with the grouting percentage. Fifty-one rock bolt models representing ninety-four different combinations of grouting defects were tested in the scope of a laboratory study. A custom-made acquisition system was used to generate an impulse on the model head. The received signal was transformed from time domain to frequency domain, and was then further analysed using the developed software. The LabVIEW platform was used as a programming tool. After signal stacking was conducted to increase the signal to noise ratio, distinctive peaks were visible in the frequency spectra (vertical axis – magnitude, horizontal axis – frequency value), pointing to the rock bolt natural frequencies, Figure 11.

By conducting statistical analysis of the first, second and third natural frequencies of a rock bolt, it was shown that a strong correlation exists between the first three natural frequencies and the grout percentage, with the values of each natural frequency increasing with a decrease in grouting percentage. Figure 11 shows higher values of natural frequencies for the rock bolt with a total of 30 % of grouted section (Figure 11a), in comparison to the rock bolt with a total of 90 % of grouted section (Figure 11b). Author further conducted the FEM analysis in order to compare the numerically obtained values with experimental ones. The results demonstrate the potential of vibration based, non-destructive, experimental testing of rock bolt grouting quality, but the method needs to be verified through a subsequent research of rock bolts installed in in-situ conditions.

Hartman et al. [37] also investigated the possibilities of utilizing frequency spectra for the investigation of rock bolts installed in mines throughout Australia. The so-called MODSHOCK system uses an impulse generated in the rock bolt head to obtain the "Mechanical Admittance" response, where the higher frequencies are used to determine resonant harmonics of the rock bolt, while the lower frequencies are used to determine element-head stiffness. The mentioned research efforts clearly demonstrate the potential of using rock bolts frequency response to determine its grouting quality.

#### 4.4. Other approaches

Lee et al. [38] and Cheung et al. [24] give an overview of the rock bolts and soil nails testing methods. According to this research, the electrical resistance method can be used to detect major irregularities in soil nails, but there is a problem of distinguishing anomalies due to the short grouted part and anomalies due to the short steel part. To determine the type of anomaly, the authors recommend using another method to determine the length of the steel part. Consideration of other electrical method, reflectometry of surface wave, analysed in time domain, shows that test results heavily depend on interpretation. Further improvement of the method is required if it is to be used for nail integrity testing. When it comes to electromagnetic methods, Kelly et al. [39] state that it is possibility to detect anomalies using GPR methods if the investigation is conducted carefully. However, although applicable from the theoretical point of view, GPR method has not been applied in practice for rock bolt testing.

#### 5. Conclusion

An overview of non-destructive rock bolt testing methods is given in the paper. Relevant European standards for the design and execution of rock bolts rely on destructive methods only. However, to determine the long-term load level in rock bolt, as well as its integrity from the aspect of grouting quality, non-destructive methods are more effective. Despite the strong theoretical background of these methods, concerns still arise when implementing these methods in practice, probably because of the lack of knowledge on the handling and interpretation of data, or because of poor experience in the past linked with application of older testing instruments. However, the increase of research efforts in this field is evident, where the rock bolt testing has taken a direction towards instrumentation with sensors. Many acoustics-based or vibration-based methods take advantage of modern sensor types such as piezoelectric sensors, optic fibres, etc. Additionally, modern signal processing tools as well as other advanced computing systems, such as neural networks, further open doors to continuous development of non-destructive methods. Modern, reliable and in-situ verified procedures will eventually boost practitioners' confidence in using these innovative testing methods.

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