Sensor techniques to monitor installation and status of rock bolts

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1 Abstract

1.1 Sensor techniques to monitor installation and status of rock bolts

As today’s mining goes deeper than ever before and the in-situ stresses increase, rock reinforcements become increasingly more important to maintain safe and stable underground constructions. There is a great demand to know if the rock reinforcement performs as designed. For example, it can be difficult for a rock engineer to know if the rock bolts are fully grouted, if the rock bolt has broken inside the rock mass or how much elongation has occurred along a dynamic rock bolt inside the rock. To handle these problems, two techniques have been developed.

1.1.1 Quality assurance of the installation

To measure how well the rock bolt is grouted in a borehole, the bolt has been fitted with a plastic tube with small cuts along the length of the bolt. After the bolt is installed, the plastic tube is pressurized to detect cavities and cracks. If there are cavities in the grout, the gas will pass through the plastic tube and fill the cavities, making it possible to calculate their size.

A system called Cavimeter has been developed using this technique, and has been tested on different types of rock bolts. More than 1000 measurements have been made in different types of rock mass at various sites. The results show that the quality of the bolt installation can be investigated using this technique. The Cavimeter is available on the market today.

1.1.2 Monitoring the status of installed rock bolts

Another technique has been developed to monitor for example if a dynamic rock bolt has been broken or if the bolt has been elongated inside the rock mass. A small steel wire is put inside the plastic tube and is fastened at the toe of the rock bolt. By measuring the current loop through the rock bolt and back through the steel wire, the status of broken or not can be determined. Elongation of the rock bolt can be determined by measuring the offset between the thread and the steel wire.

Laboratory tests and preliminary field test show that this technique works. Two types of sensors have been tested. One gives warnings with a blinking red LED if the rock bolt is broken inside the rock and a blinking yellow LED if the elongation of the rock bolt is more than the accepted length. The other sensor can communicate wirelessly with the network of the mine. The data can be displayed on a central computer.

2 Background

As today’s mining goes deeper than ever before and the in-situ stresses increase, rock reinforcements become increasingly more important to maintain safe and stable underground constructions. There is a great demand to know if the rock reinforcement is performing as designed. For example, it can be difficult for a rock engineer to know if the rock bolts are fully grouted, if the rock bolt has broken inside the rock mass or how much elongation has occurred along a dynamic rock bolt inside the rock. To handle these problems two techniques have been developed.

One is to quality-assure the installation of rock bolts by using the Cavimeter method and the other is the Cavisensor program to monitor the elongation and breakage of the installed rock bolts.
3 The Cavimeter method

The rock mass can be reinforced by using rock bolts. Rock reinforcement by means of cement-grouted rock bolts starts by drilling a hole in the rock. Cement slurry is then pumped into the borehole and a rock bolt is inserted. The bolt can be anchored in the bottom of the borehole, using a wedge or expander, before it is tensioned to a certain torque.

In order to be fully functional, the rock bolt must be adequately grouted. If the cement slurry runs out into cracks or cavities in the rock mass, the reinforcement may not carry the intended load. If the borehole is not fully filled with concrete, there is also a risk for corrosion problems because of water and air coming in contact with the steel of the rock bolt.

To measure how well the rock bolt is grouted, the bolt is fitted with a plastic tube with small cuts along the length of the rock bolt. After the bolt is installed, the plastic tube is pressurized to detect cavities and cracks. If there are cavities in the grout, the gas will pass through the plastic tube and fill the cavities, making it possible to calculate their size.

![Figure 1 Principle of the Cavimeter system](image)

A system called Cavimeter, see Fig. 1, has been developed using this technique. It has been tested on different types of rock bolts and wire bolts.

3.1 Field measurements with the Cavimeter

More than 1000 measurements have been made as of today in different types of rock mass at various sites, see Table 1. In Table 1, the size of the cavities are not listed, so they may vary in size.

<table>
<thead>
<tr>
<th>Year</th>
<th>Type of industry</th>
<th>Type of rock bolts</th>
<th>Percentage of rock bolts where cavities were detected</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>2010</td>
<td>Mining</td>
<td>30 static rebar</td>
<td>17% with cavities</td>
<td>Test</td>
</tr>
<tr>
<td>2010</td>
<td>Infrastructure</td>
<td>10 static rebar</td>
<td>20% with cavities</td>
<td>Two were badly grouted on purpose</td>
</tr>
<tr>
<td>2010</td>
<td>Mining</td>
<td>132 static rebar</td>
<td>9% with cavities</td>
<td>Good rock mass</td>
</tr>
<tr>
<td>2010</td>
<td>Mining</td>
<td>235 static rebar</td>
<td>7% with cavities</td>
<td>Good rock mass</td>
</tr>
<tr>
<td>2011</td>
<td>Mining</td>
<td>50 static rebar</td>
<td>33% with cavities</td>
<td>Tunnel</td>
</tr>
<tr>
<td>2011</td>
<td>Infrastructure</td>
<td>20 static rebar</td>
<td>40% with cavities</td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>Mining</td>
<td>150 dynamic bolts</td>
<td>27% with cavities</td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>Mining</td>
<td>150 dynamic bolts</td>
<td>15% with cavities</td>
<td>water</td>
</tr>
<tr>
<td>2012</td>
<td>Mining</td>
<td>10 cable bolts (7m)</td>
<td>10% with cavities</td>
<td>One was badly grouted on purpose</td>
</tr>
<tr>
<td>2012</td>
<td>Infrastructure</td>
<td>55 PC bolts</td>
<td>2% with cavities</td>
<td>Tunnel</td>
</tr>
<tr>
<td>2012</td>
<td>Infrastructure</td>
<td>39 static rebar</td>
<td>15% with cavities</td>
<td>Tunnel</td>
</tr>
</tbody>
</table>
When measurements are made today with the Cavimeter, the filling ratio in % is shown on the handheld presentation unit directly after the measurement is made, see Fig. 2. This data is not noted in Table 1 because this function was implemented after 2013.

![Filling ratio measured with the Cavimeter on a plastic tube to simulate a not fully grouted rock bolt.](image)

The quality of the rock bolt installation can be checked by using this technique. Today the Cavimeter method is patented and the Cavimeter is on the market.

### 3.2 The theory behind the Cavimeter

Static as well as a dynamic mathematic consideration on how the Cavimeter measuring method works are presented here. The static approach is represented with simple calculations.

The mathematical model developed in the dynamic approach are based on Laplace transforms. The mathematical tool used assumes that the system is regarded as linear and that the system is at rest at time $t = 0$. An engineering approach indicates that this approximation is acceptable.

#### 3.2.1 Static approach

Below are some simplified calculations of cavity sizes. Note that only the initial values and final values (typically after 5 seconds) have been taken into account in this simplified calculation.

**Definitions:**

- $P_s$: Initial pressure in the gas cylinder inside the Cavimeter
- $V_s$: volume of the gas cylinder inside the Cavimeter
- $P_e$: final pressure in the gas cylinder inside the Cavimeter
- $V_t$: volume of the plastic tubes
- $V_c$: volume of the cavity in the cement grout
- $V_r$: volume of the rock in the test object
- $V_{tot}$: Total volume consisting of the gas cylinder inside the Cavimeter, plastic tubes and possible cavity

The temperature is presumed constant:

- $P_s V_{tot} = P_e V_t$ and $V_{tot} = V_s + V_t + V_c$ =>
- $V_c = (P_s / P_e) V_t - V_t - V_s = [P_s / P_e - 1] \cdot V_t$
- $V_s = 1 \text{ dm}^3$ and the dimension of the plastic tube, e.g. $V_t$, is known. Then if $P_s$ and $P_e$ are observed the size of possible cavities can be calculated.
3.2.2 **Dynamic approach**

Two cases are illustrated below. The first case indicates the impact of a present cavity in the cement grout. The second case indicates the impact of a present cavity as well as micro cracks in the cement grout and rock. Some simplifications have been assumed:

The system is linear and the starting point is at t=0. We regard the gas cylinder inside the Cavimeter as a capacitor $C_1$ with initial pressure $P_0$ and the cavity in the cement grout as a capacitor $C_2$ not pressurized at t=0.

3.2.3 **Effect of a present cavity**

Laplace transform (s operator) is used to solve the differential equation represented by Fig. 3.

![Simplified model of the Cavimeter measurement on an existing cavity in cement grout and simulation of different sizes of cavities ($C_2$). Pressure $P_1(t)$ in the gas container ($C_1$) inside the Cavimeter as a function of time.](image)

Using the inverse Laplace transform to obtain a time dependent equation on how the pressure in the gas cylinder inside the Cavimeter varies:

$$p_1(t) = \frac{P_0 C_2}{C_1 + C_2} e^{-\frac{C_1+C_2}{R_1 C_1 C_2} t} + \frac{P_0 C_1}{C_1 + C_2} \quad \text{Initial pressure: } p_1(0) = P_0 \quad \text{Asymptote: } p_1(\infty) = \frac{P_0 C_1}{C_1 + C_2}$$

Graphs are plotted for cavities 1, 2, 3, 4 and 5 times the volume of the gas cylinder inside the Cavimeter with initial pressure 3 bar, see Fig. 3.

Practical tests using the Cavimeter on known voids 1, 2, 3, 4 and 5 dl demonstrate almost identical results, see Fig. 4.
3.2.4 **Effect of a present cavity and cracks in the cement grout and rock mass**

A resistor is used to model cracks in the cement grout. The smaller the cracks are, the greater the resistance, see Fig. 5.

Using the same mathematic method on the model represented in Fig. 7 we obtain:

\[ p_1(t) = P_0 \left(1 - \frac{1}{R_1 R_2 C_1 C_2} \left( s_1 s_2 e^{s_1 t} - s_1 e^{s_2 t} + R_2 C_2 (e^{s_1 t} - e^{s_2 t}) \right) \right) s_1 \neq s_2 \]

Where \( s_1 \) and \( s_2 \) are computable real roots of the denominator of the Laplace transform.

Graphs are plotted for cavities with the same volume as the gas container inside the Cavimeter and different numbers of micro cracks, see Fig. 5. Initial pressure is 3 bar.

In order to verify the theoretical simulation, practical tests with the Cavimeter were carried out. An adjustable valve was used to simulate different numbers of micro cracks in the cement grouting and rock mass. The valve was opened step-by-step and measurements were made, see Fig. 6.
Measurements were made with the Cavimeter using different settings of the valve. The valve was adjusted to simulate different numbers of micro cracks. Screen dump of the Cavimeter interface after finished measurements produce almost identical curves shapes.

### 3.2.5 Conclusion

If the graph of the Cavimeter output slopes downward and then levels out, there are cavities present. The change in pressure value is proportional to the volume of the cavities. The more the pressure falls, the bigger the cavities. If the graph slopes but does not level out, there are micro cracks present, see Fig. 7.

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**Figure 6** Measurements were made with the Cavimeter using different settings of the valve. The valve was adjusted to simulate different numbers of micro cracks. Screen dump of the Cavimeter interface after finished measurements produce almost identical curves shapes.

**Figure 7** The principle of how the Cavimeter graphs can be interpreted. In the figure orange = cement grout and green = gas penetrating cavities and micro cracks.
To measure one rock bolt normally don’t take more than 5 seconds. The built in evaluating software will display filling ratio as a percentage of a fully grouted bore hole, on the handheld presentation unit, as seen in Figure 2.

If there are micro cracks present in the cement grout and rock mass the Cavimeter will display “LEAK” instead of a percent number. The input parameters to calculate this are: Bore hole diameter, bore hole length, rock bolt diameter and the length and diameter of the plastic tube between the Cavimeter and the toe of the rock bolt. This data could be typed in using the handheld presentation unit.

4 The Cavisensor program

The development of the patented Cavisensor program started in 2014. One objective was to monitor the elongation of installed dynamic rock bolts. Another objective was to monitor when a rock bolt breaks inside the rock mass. The lineup of the sensor program was:

CaviBasic a simple extensometer mounted on a rock bolt. It consists of a plastic tube with a steel wire inside. The steel wire is fastened at the toe of the rock bolt and is free to move inside the plastic tube. Measurement of elongation and bolt breakage are made by hand using an ohmmeter and a digital caliper.

If the plastic tube is prepared with small cuts along the length of the tube it is possible to use the Cavimeter to check the quality of the rock bolt installation.

CaviLight a sensor screwed on to the thread of a rock bolt. The sensor can indicate bolt breakage and elongation of installed rock bolts. CaviLight is based on CaviBasic and requires that the rock bolt is installed with CaviBasic. Bolt breakage is indicated by a flashing red LED mounted on the sensor. Bolt elongation can be measured by hand or by a fluorescent bead falling down from the sensor when a pre-determined elongation is achieved.

CaviSens a sensor screwed on to the thread of a rock bolt. The sensor can indicate bolt breakage by a flashing red LED and elongation by a flashing yellow LED if an adjustable pre-determined elongation is achieved. CaviSens is based on CaviBasic and requires that the rock bolt is installed with CaviBasic.

CaviCom CaviCom is based on CaviSens and is complemented with an electronic board that can communicate wireless with a gateway. The gateway is implemented with Wi-Fi which enables communication with the mine network and thereby presentation of rock bolt status on a central computer.

The full sensor program has been tested in a laboratory environment with great success. CaviCom was tested together with Mobilaris AB’s presentation system MMI (Mobilaris Mining Intelligence) that is used by LKAB and Boliden as well as other mining companies.

4.1 CaviBasic

CaviBasic can be regarded as a simple and low-cost extensometer point welded at the toe of any mounted rock bolt or wire bolt. It consists of a plastic tube with a steel wire (piano wire) inside. The steel wire is fastened at the toe of the rock bolt and is free to move inside the plastic tube. Measurement of elongation and bolt breakage are made by hand using a caliper and an ohm-meter.

A field test of CaviBasic began in July 2015 at Outokumpu’s mine outside Kemi and is still running. Field tests of the other sensors are planned to start in early spring 2016 and are planned to be completed in autumn 2016.
4.1.1 Principle of CaviBasic operation

A small steel wire is put inside a flexible plastic tube and is fastened at the toe of the rock bolt. By measuring the current loop trough the rock bolt and back through the steel wire, the status broken or not can be determined. Elongation of the rock bolt can be determined by measuring the offset between the thread and the steel wire, see Fig. 8.

![Figure 8 Principle of CaviBasic operation to display elongation of rock bolts.](image)

4.1.2 Field test at Kemi mine

Thirty (30) dynamic rock bolts of type NMX Dynamic M24 were prepared at Nybergs Mechanical Workshop in Kiruna. The bolts were prepared with a plastic tube $\Phi_o$=4.0 mm and $\Phi_i$=2.5 mm. A piano wire $\Phi$=0.7 mm was inserted into the plastic tube and fastened at the toe of the bolt, see Fig. 9.

![Figure 9 Rock bolts prepared with CaviBasic](image)

The Outokumpu’s mine outside Kemi experiences considerable rock movement in certain areas. The idea is to use CaviBasic to measure the progress of these rock movements. A simple and reliable way to do this is to measure the displacement between the rock bolt thread and the free moving piano wire that is attached at the toe of the rock bolt. Moreover, by measuring the resistance between the rock bolt thread and piano wire it is possible to detect bolt breakage inside the rock.

During installation of Cavibasic, the hole nearest the center of the washer is preferable because the measuring tube and piano wire will be more parallel to the rock bolt than if using the outer hole of the washer, see Fig. 10.
Figure 10  An installed rock bolt with CaviBasic

The results up until 2016-01-20 are shown in Fig. 11.

<table>
<thead>
<tr>
<th>Bolt number</th>
<th>Installation 2015-07-29</th>
<th>Read out 2015-10-13</th>
<th>Read out 2015-11-06</th>
<th>Read out 2016-01-20</th>
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<td>8</td>
<td>0</td>
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<td>11</td>
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<tr>
<td>CaviSens 9</td>
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</table>

Figure 11  Test objects at Outokumpu’s mine outside Kemi, Finland (courtesy of Jari Näsö, Outokumpu OY)

4.2  CaviLight

A sensor screwed on to the thread of a rock bolt equipped with CaviBasic. The sensor can indicate bolt breakage and elongation of installed rock bolts. Bolt breakage is indicated by a flashing red LED mounted on the sensor, see Fig. 12. Rock bolt elongation can be measured by hand and/or indicated by a fluorescent bead falling down from the sensor when a pre-determined elongation is achieved.

The theoretical lifespan of the sensor is 5 years if the red LED is not flashing. If the LED is flashing the lifespan is reduced to approximately one week. The sensor is reusable, completely sealed and can operate in a rough environment. A dedicated flashlight can be used to verify that the sensors are in operation.
The CaviLight sensor has been successfully tested in a laboratory environment and field tests are planned to start in early spring 2016.

Figure 12 Three prototypes of CaviLight indicating that the rock bolt has broken. To the right CaviLight with two fluorescent beads. When the beads fall down a pre-determined elongation is achieved.

4.3 CaviSens

CaviSens is sensor screwed on to the thread of a rock bolt. The sensor can indicate bolt breakage by a flashing red LED and elongation by a flashing yellow LED if an adjustable predetermined elongation are achieved. CaviSens are based on CaviBasic and requires that the rock bolt are installed with CaviBasic.

4.3.1 Principle of CaviSens operation

A small steel wire is put inside a flexible plastic tube and is fastened at the toe of the rock bolt. By measuring the current loop trough the rock bolt and back through the steel wire the status of broken or not can be determined.

Elongation of the rock bolt can be determined by measuring the offset between the thread and the steel wire. A built-in potentiometer will produce a voltage proportional to elongation of the rock bolt. By adjusting another potentiometer inside the sensor housing it is possible to adjust at which elongation the yellow LED should start to flash, see Fig. 13.

It is also possible to connect a data logger to the sensor to log data as elongation and bolt breakage as a function of time. This is done in the Kemi mine during field testing of one CaviSens unit.

Figure 13 Principle of the operation of CaviSens
4.3.2 Laboratory test of CaviSens

Laboratory tests of CaviSens were carried out at Nybergs Mechanical Workshop in Kiruna in January 2015. Four test objects were prepared, see Fig. 14.

![Diagram of laboratory test setup](image)

**Figure 14** Preparation of laboratory tests of CaviSens. A) An 8 mm steel bar was prepared with a 400 mm long plastic tube to create a dynamic zone. B) The steel bar was cement-grouted inside two separate steel pipes. C) A reference potentiometer was mounted on the hydraulic jack and fastened on the moving cylinder of the hydraulic jack. D) The actual setup for the tests. To the left an early prototype of the CaviSens.

The signals from the test object were amplified and low pass filtered and captured by an AD converter from National Instruments. Data was saved and displayed on a computer. Figure 15 shows the reference signals of load and elongation as well as output elongation and bolt breakage from the CaviSens prototype.

![Graph of test signals](image)

**Figure 15** Diagram from the performed test. The reference potentiometer was protracted approx. 3 cm when the test started.

4.3.3 Conclusion

The results indicated that measuring the elongation could be done using the technique with a piano wire inside a plastic tube where the wire is fastened at the toe of a rock bolt. It is also possible to indicate if a rock bolt has snapped inside the rock by checking the current loop through the rebar and back through the wire which is isolated by the plastic tube.
4.3.4 **Field test of CaviSens at Kemi mine**

One CaviSens was also tested together with field tests of CaviBasic in Outokumpu’s mine outside Kemi. Rock bolt number 9 was used for that purpose. Instead of flashing red and yellow LED’s, a contact was mounted on the sensor. From the contact a cable was connected to a data logger placed inside a sealed plastic box, see Fig. 16.

![CaviSens and data logger](image)

**Figure 16** CaviSens and data logger

To adjust the signal levels of the sensor to the data logger in order to enhance the performance an amplifier and filter were built and mounted inside the sensor housing. The amplifier had to be battery powered. The battery was placed inside a sealed plastic box together with the data logger.

As seen in Table 2, rock bolt number 9 has had an elongation of 0.83 – 0.53 ≈ 0.3 mm as of 2015-11-06.

<table>
<thead>
<tr>
<th>Bolt number</th>
<th>Readout 2015-07-29 (mm)</th>
<th>Readout 2015-10-13 (mm)</th>
<th>Readout 2015-11-06 (mm)</th>
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<td>9 (test of CaviSens)</td>
<td>0.56</td>
<td>0.63</td>
<td>0.83</td>
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</table>

More field tests are planned to be performed in early spring 2016 at LKAB in Malmberget and SKB (Swedish Nuclear Fuel and Waste Management Co.) in Oskarshamn.

4.4 **CaviCom**

CaviCom is based on CaviSens and is complemented by an electronic board (internet of things) that can communicate wireless with a gateway. The gateway is implemented with Wi-Fi which enables communication with the mine’s network and thereby presentation of rock bolt status on a central computer, see Fig. 17.
The full sensor program has been tested in a laboratory environment with great success. CaviCom was tested together with Mobilaris AB’s MMI (Mobilaris Mining Intelligence) that are used by LKAB and Boliden as well as other mining companies.

Field tests are planned to start early spring 2016 at LKAB in Kiruna.

5 Acknowledgements

Suggestions and support from Jari Näsi (Outokumpu OY) during tests in Kemi are gratefully acknowledged. Comment and suggestions made by Göran Nilsson (GNC AB) on an early draft of this paper are gratefully acknowledged.