

Monitoring of high safety pillars stability in quarry Lipica II – EL beam displacement sensors

Merilni nadzor stabilnosti visokih varnostnih stebrov v kamnolomu Lipica II. – palični merilniki deformacij EL

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Abstract

Underground excavation of natural stone in Lipica II quarry is carried out using the modified room-and-pillar mining method. In order to support and ensure the stability of underground chambers high safety pillars are used. These pillars are made of surrounding stone and therefore intersected by discontinuities. The discontinuities represent high risk to stability of underground facilities and work itself. To monitor stress and strain parameters in pillars we use 2D WV stressmeters (VW – vibrating wire) inside the safety pillars and EL beam sensors on the surface of pillars. In this paper we will present procedures of wedges deformation monitoring in safety pillars with EL beam sensors in the underground natural stone quarry Lipica II.

Key words: EL (electronic level) beam sensor, natural stone, high safety pillar, room and pillar mining method

Izvleček

Podzemno pridobivanje blokov naravnega kamna v kamnolomu Lipica II poteka po modificirani komorno-steborni odkopni metodi. Za podpiranje in zagotavljanje stabilnosti podzemnih prostorov se uporablja samonosilno naravno podporje v obliki visokih varnostnih stebrov. Visoke varnostne stebre sekajo naravne razpoke, ki pomenijo nevarnost pri zagotavljanju stabilnosti podzemnih prostorov in nevarnost pri obratovanju podzemnih delovišč. Za spremljavo napetostnih in deformacijskih parametrov se izvaja merilni nadzor dogajanja na in v varnostnem stebru. Poleg uporabe napetostnih merilnih celic v notranjosti varnostnih stebrov se za spremljavo v podzemnih kamnolomih uporabljajo elektronski palični merilniki deformacij. V prispevku bodo predstavljeni postopki spremljave deformacij klinov v visokih varnostnih stebrih in rezultati spremljave deformacij s paličnimi merilniki deformacij EL visokih varnostnih stebrov pri podzemnem pridobivanju blokov naravnega kamna v kamnolomu Lipica II.

Ključne besede: palični merilnik EL, naravni kamen, visoki varnostni steber, komorno-steborna odkopna metoda

Introduction

Proper monitoring of safety pillars and rock masses can help a mining engineer recognize when the probability of a failure is higher than usual. This pre-failure warning can help the mining engineer in many ways. Not only do safety pillar failures wreak havoc on current production, they are able to seriously damage machine equipment, and in the worst cases, injure workers too close to the point of failure. The objective of safety pillars monitoring is to detect, before failure, possible instabilities to allow the mining engineer to take appropriate remedial measures. The main concern and main purpose of monitoring is the protection of workers and equipment.

In analysis of special phenomena such as failure of structures, pillar wedge stability, etc. requires deformation measurement with specific instruments of high accuracy^[2]. This paper demonstrates two types of measuring instruments, EL beam or tiltmeter and 3 screw open fissures displacement meter. Several types of sensitive tiltmeters have been developed to measure and observe ground deformations^[3,14]. A tiltmeter gives the rotation of a line segment fixed in the rock about a chosen horizontal axis perpendicular to the local gravity vector. An 3 screw dyke-displacement meter measures the change in distance between three points (screws) on the rock which are a finite triangle distance apart^[9]. Both instruments enabled the detection of small deformations that cannot be detected and measured by ordinary surveying instruments. These instruments were used to study the movement of ceiling/roof and walls in underground structures of quarry Lipica. Two tiltmeters and several 3 screws open fissures displacement meters were used in the rock deformations monitoring in quarry Lipica II.

The underground quarry Lipica is situated near village Lipica, at 5.5 km to the southeast of Sežana. In the Lipica II. quarry, the underground excavation blocks of natural stone runs for more than 12 years. One of the important advantages of the underground mining operations is do not affect on the surface above. For the purposes of safe and stable excavation of natural stone in underground structures is required a good knowledge of rock properties in

safety pillars, primary geomechanical conditions in the overburden and discontinuity orientations in the deposition. In addition, during the excavation also monitoring of stress conditions in the safety pillars and ceiling. In the context of in-situ measurements and control of the Room-and-Pillar mining method using stress measurements (2D WV stressmeter device) and deformation measurements (EL beam gauge and 3 screw open fissures displacement meters) in the safety pillars, such as on the ceiling of large open underground spaces. In 2010 we started to use the vertical EL beam gauges with the task of monitoring the wedges movements or the major open cracks at the surface area of high safety pillars.

In situ stresses measurements in quarry Lipica II

All rock masses contain discontinuities such as bedding planes, joints, shear zones and faults. At shallow depth as underground structures in quarry Lipica II, where stresses are low, failure of the intact rock material is minimal and the behaviour of the rock mass is controlled by sliding on the discontinuities. In order to analyse the stability of this system of individual rock blocks, it is necessary to understand the factors that control the shear strength of the discontinuities which separate the blocks.

The weight of the vertical column of rock at a depth h is the product of the depth and the unit weight of the overlying rock mass. Vertical stress σ_v is estimated from the simple relationship

$$\sigma_v = \gamma \cdot h \quad (1)$$

where

γ ... the unit weight of the overlying rock (typically about 0.027 MN/m³)

h ... the depth below surface.

The horizontal stresses acting on an element of rock at a depth z below the surface are much more difficult to estimate than the vertical stresses. Normally, the ratio of the average horizontal stress to the vertical stress is denoted by the letter k such that:

$$\sigma_h = k \cdot \sigma_v = k \cdot \gamma \cdot h \quad (2)$$

k ... the average horizontal stress to the vertical stress.

In-situ measurements of horizontal stresses at mining sites around the world show that the ratio k tends to be high at shallow depth and that it decreases at depth (Brown and Hoek, 1978, Herget, 1988)^[1,6]. Sheorey (1994)^[12] developed an elasto-static thermal stress model of the rock. This model considers curvature of the crust and variation of elastic constants, density and thermal expansion coefficients through the crust and mantle. A simplified equation which can be used for estimating the horizontal to vertical stress ratio k is (Figure 1, left):

$$k = 0.25 + 7 \cdot E_h \cdot \left(0.001 + \frac{1}{h} \right) \quad (3)$$

E_h ... the average deformation modulus of the upper part of the earth's crust measured in a horizontal direction (typically in range from 10–100 GPa).

Horizontal direction of the average deformation modulus measurement is important particularly in layered sedimentary rocks, in which the deformation modulus may be significantly different in different directions. A plot of this equation is given in Figure 1 for a range of deformation moduli. The curves relating k with depth below surface h are similar to those published by Brown and Hoek (1978)^[1], Herget (1988)^[6] and others for measured in situ stresses. Hence equation 3 is considered to provide a reasonable basis for estimating the value of k .

With the background of previous stress measuring studies in literature, Brown and Hoek (1978)^[1] have tabulated in Table 1 a wide range of stress measurement data for depth $h = 0$ –100 m.

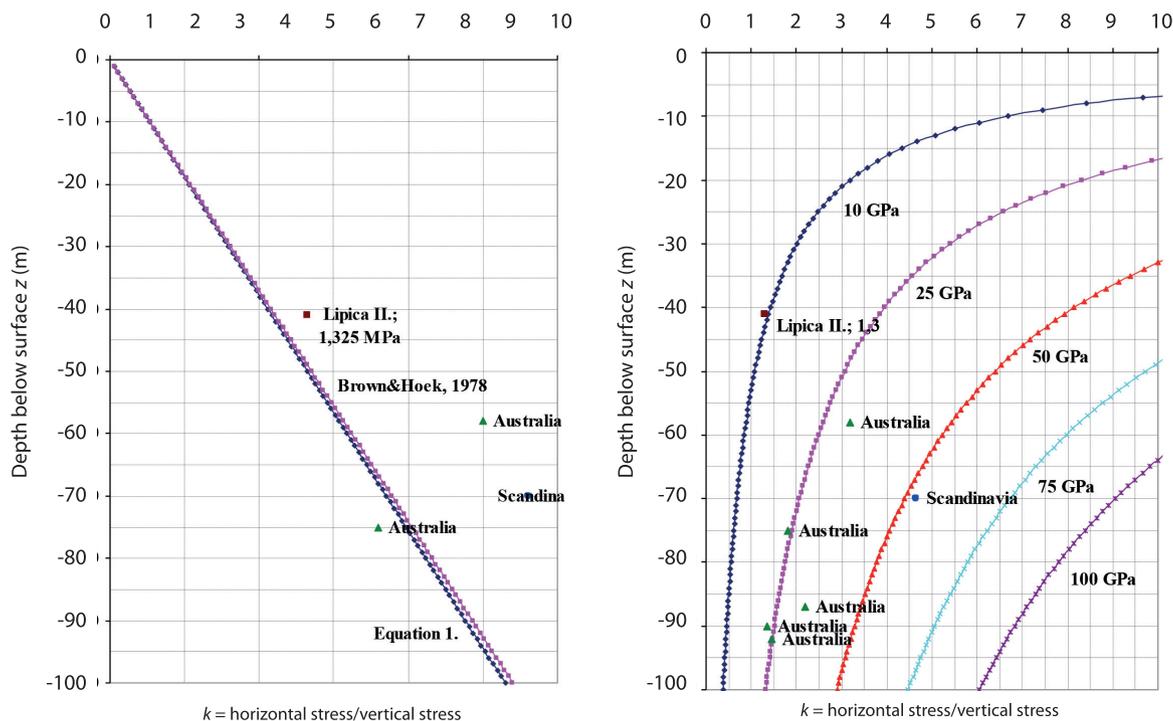


Figure 1: Ratio of horizontal to vertical stress for different deformation moduli base upon Sheorey's equation (Sheorey, 1994)^[12] (left) and calculated vertical stress (Brown and Hoek, 1978)^[1] (right) with measured parameters in the quarry Lipica II. and the world.

Table 1: *In situ stress measurement data (Brown and Hoek, 1978)^[1]*

| No. | Location | Rock type | Depth h/m | σ_v/MPa | $k = \sigma_h/\sigma_v$ | Ref. |
|--------------------|-------------------------------|--------------------------|----------------|----------------|-------------------------|------|
| Australia | | | | | | |
| 1 | Kanmantoo, SA | Black garnet mica schist | 58 | 2.50 | 3.30 | [15] |
| 2 | Mount Charlotte mine, WA | Dolerite | 92 | 11.20 | 1.45 | [15] |
| 3 | Durkin mine, Kambalda, WA | Serpentine | 87 | 7.40 | 2.20 | [15] |
| 4 | Dolphin mine, Kings Is., Tas. | Marble and skarn | 75 | 1.80 | 1.80 | [15] |
| 5 | Cethana, Tas. | Quartzite conglomerate | 90 | 14.00 | 1.35 | [15] |
| Scandinavia | | | | | | |
| 6 | Bidjovagge mine, N. Norway | Pre-Cambrian rocks | 70 | 2.80 | 4.64 | [10] |
| Slovenia | | | | | | |
| 7 | Lipica II. | Limestone | 41 | 1.32 | 1.30 | [9] |

In Figure 1 (right), the vertical stress, σ_v is plotted against depth h , while Figure 1 (left) shows a plot of $k = \sigma_h / \sigma_v$ against depth h . Figure 1 (right) shows that measured vertical stresses generally follow the trend given by the simple relationship;

$$\sigma_v = 0,927 \cdot h \quad (4)$$

At shallow depths (0–100 m), there is considerable scatter in the observed values.

Discontinuities in quarry Lipica II

Discontinuities (open cracks) appearing in the quarry Lipica II. have rough walls and in space variable dip, which is a favorable property regarding the stability of randomly generated wedges. Cracks are mostly empty or filled with heavy mouldable reddish-brown clay (Figure 2). The thickness of clay fillers varies from thin clay trash to few inches thick clay layer. Cracks walls are mostly lined with red calcite incrustation, which is also advantageous feature of the stability of cracks. In cases where cracks have no incrustation, they are wavy to the rough, which means that the unevenness of the cracks surface increases the shear strength of the cracks. Spacing between the cracks is 1–5 m.

This means that the choice of GSI index less than 50 is not appropriate, since this is applicable in the case of smooth cracks filled with clay. Geomechanical parameters of Lipica limestone are reduced by Hoek analysis^[7].

The index GSI (Geological Strength Index) was determined on the basis of engineering-geological mapping of cracks and is 55 ± 5 ^[5]. For $GSI = 55 \pm 5$ is characterized by a block structure with three rock fracture systems and with good merged blocks, whereas the walls of the crack to the flat smooth, with a moist surface. Cracks are closed or open. Open cracks are filled with a compact infill or coarser primary rock particles.

Geotechnical properties of cracks were accurately determined by reverse analysis of the quarry Lipica II. underground structures. Robertson's test of the samples with a crack-free clay showed values of the angle of internal friction $\varphi = 26^\circ$, cohesion $c = 21$ kPa at 100 kPa load and angle of internal friction $\varphi = 16^\circ$, cohesion $c = 50$ kPa at 160 kPa load.

Laboratory and "in-situ" tests have shown the following geomechanical properties of the intact limestone Lipica:

Deposit of natural stone in quarry Lipica is a strong tectonic disrupted with at least seven leading towards discontinuity (casting), which cause the danger of underground mining. The



Figure 2: Open fissures in underground structures of quarry Lipica II.

cracks link together and form in the ceiling and the side of the underground spaces of the dangerous rocky wedge. Precisely because of this, in order to ensure stability and safe working conditions we implement in-situ monitoring and controlling devices. In addition to the stress gauges also use EL beams gauges for rock wedge movement and deformation monitoring.

| | |
|--|-----------------------------|
| E (modulus of elasticity) | 14–37 GPa |
| σ_u (uniaxial compressive strength) | 94–220 MPa (170 MPa) |
| γ (weight) | 26.3–26.8 kN/m ³ |
| ν (poisson's ratio) | 0.33–0.36 (0.15–0.30) |
| T (tensile strength) | 3.8–6.14 MPa |
| φ (angle of internal friction) | 52–54° |
| c (cohesion) | 46.6 MPa |
| c_{res} (residual cohesion) | 11.5 MPa |
| m (Hoek-Brown parameter) | 10.4 |

El beam gauges

The use of the EL beam gauges (also tiltmeter) is an extremely broad, since they used to measure vertical movements, declination or movements on dams, observation of the stability and covergences of banks areas, observation of the tunnels stability, observe of the structures around exploitations areas, etc. EL beam sensors monitor differential movement and rotation in structures. Two types of sensors are used – horizontal and vertical type. Horizontal

beam sensors monitor settlement and heave. Vertical beam sensors monitor lateral displacement and deformation.

Table 2: Technical characteristics of EL beam gauge manufacturer Slope Indicator^[13]

| | Horizontal | Vertical |
|-----------------------|------------------------------|----------|
| Measurement range | $\pm 40'$, (± 11 mm/m) | |
| Accuracy | ± 0.1 mm/m | |
| Operating temperature | –20 to +50 °C | |
| Weight | 210 g | 890 g |

The beam sensor consists of an electrolytic tilt sensor attached to a rigid metal beam. The tilt sensor is a precision bubble-level that is sensed electrically as a resistance bridge. The bridge circuit outputs a voltage proportional to the tilt of the sensor. The beam, which is typically one to two meters long, is mounted on anchor bolts that are set into the structure. Movement of the structure changes the tilt of the beam and the output of the sensor. The voltage reading from the sensor is converted to a tilt reading in mm per meter. Displacements are then calculated by subtracting the initial tilt reading from the current reading and multiplying by the gauge length of the sensor (the distance between anchors). When sensors are linked end to end,

displacement values can be accumulated from anchor to anchor to provide a profile of differential movements or settlement.



Figure 3: Horizontal EL beam gauge^[13].

The metal rods, on which the meters are installed, are very sensitive on temperature changes, which may be (in the underground mining of natural stone) in winter/summer period quite great. Heating and cooling of the air in the underground spaces result of the expansion and contraction of metal roads. It is therefore necessary to take into account in data processing of metal road expansion correction factor.

Calculation of deflection takes place with the help of the following polynomial equations:

$$\frac{mm}{m} = C5 \cdot EL^5 + C4 \cdot EL^4 + C3 \cdot EL^3 + C2 \cdot EL^2 + C1 \cdot EL + C0 \quad (5)$$

where

EL ... measured voltage value

C5 ... C0 ... polynomial coefficients

Reading in mm/m it is necessary to multiply with the length of the bars (in our case, 2 m), which comes out $(2x-1.961) -3.922 \text{ mm}^{[4]}$.

Temperature resistance equation

(6)

$$T = \left[\frac{1}{A + B \cdot (\ln R) + C \cdot (\ln R)^3} \right] - 273.2 \text{ } ^\circ\text{C}$$

where

T ... temperature in °C

lnR ... natural log of termistor resistance

A ... 1.4051×10^{-3}

B ... 2.369×10^{-4}

C ... 1.019×10^{-7}

EL beams in quarry Lipica II

Two EL beams we have built in safety pillar (VS3) at level 359 on the open cracks, both located on the corners of the high safety pillar. Discontinuities with the direction 120°/60° and 110°/75° are open and filled with clay. Both discontinuities cross-cut the safety pillar. In the case of additional compressive load of safety pillar, there could appear a deformation and slip a stone wedge from safety pillar. For a Visual check on the safety pillar also installed a glass seals. Dangerous rock wedges on the security pillar are stabilized with anchors.

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Figure 4. shows a map of the rock discontinuities apparing on sealing of underground structures and locations (green circle) of EL beams gauges instalations in quarry Lipica II.

Table 3: Example of deviation calculation considering calibration test coefficients^[4]

| | Polynomial coefficient | EL reading | Value |
|-----------------------------|-------------------------|------------------------|-----------------------|
| C5 | 1.642 6E ⁻¹ | -0.585 71 ⁵ | -0.113 225 700 0 |
| C4 | -1.583 6E ⁻² | -0.585 71 ⁴ | -0.001 863 700 2 |
| C3 | -2.688 1E ⁻¹ | -0.585 71 ³ | 0.051 012 382 9 |
| C2 | -7.990 4E ⁻² | -0.585 71 ² | -0.027 411 562 9 |
| C1 | 3.509 8 | -0.585 71 ¹ | -2.055 724 958 0 |
| C0 | 8.118 5E ⁻² | -0.585 71 ⁰ | 0.081 185 000 0 |
| deviation d/(mm/m) = | | | -1.961 154 082 |

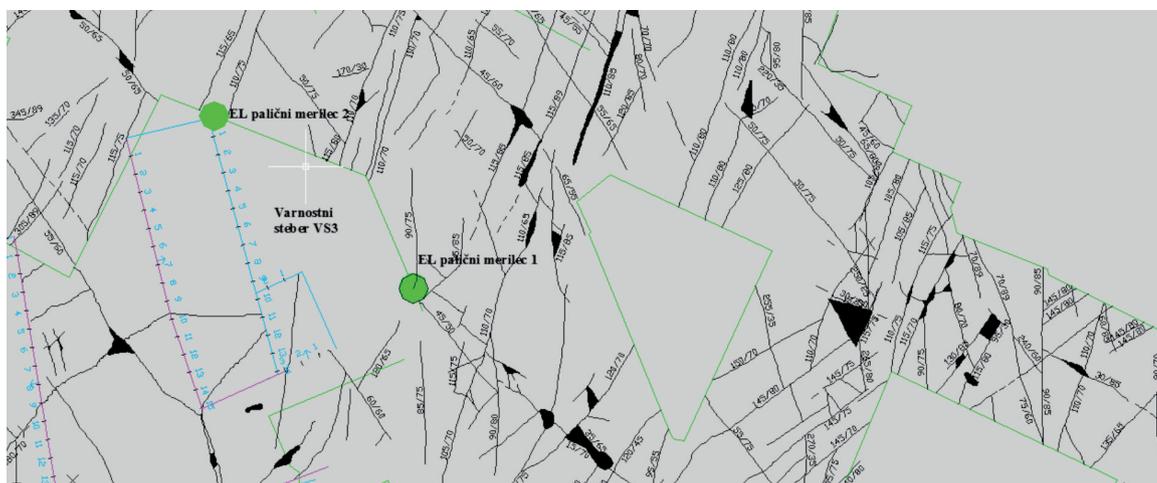


Figure 4: Map of the rock discontinuity orientations and locations (green circle) of EL beams gauges installations in quarry Lipica II^[11].

In quarry Lipica II. EL beam meter manufacturer Slope Indicator is used to measure supervisory convergences in one vertical plane in high safety pillar VS03 (Figure 5). A bar gauge is installed through the cracks, so that there is one screw on the part of the anchor windlass for anchor, such as flexible wedge screw for stable work.



Figure 5: EL beam gauge on the high safety pillar VS3.

According to practical experience, the best indicators of developments are movements in pillar corners. For that reasons we decided to monitor the developments on the safety pillar corner, where the sliding surfaces of the main crack are driving out.

From Figure 6, we can see that in the summer time period El beam rod is stretching in the winter time period EL beam rod is shrinkage.



Figure 6: Vertical EL beam gauge installation on the high safety pillar VS3.

The metal rod, on which there is displacement meter is sensitive to changes in temperature, which may be in the underground extraction during the winter/summer relatively large ($\Delta T/^\circ\text{C}$ in period from 2004/2010 9.24 $^\circ\text{C}$ / 12.2 $^\circ\text{C}$ / 14.07 $^\circ\text{C}$ / 10.52 $^\circ\text{C}$ / 12.19 $^\circ\text{C}$ / 14.7 $^\circ\text{C}$ / 13.55 $^\circ\text{C}$). During heating and cooling of air in underground structures leads to expansion and contraction of metal rods. Therefore, the data processing necessary to consider correction factor of metal rods. In the time period October 2010/March 2012 absolute max. measured displacement was 0.08 mm, which does not threaten the stability of the high safety pillar VS3.

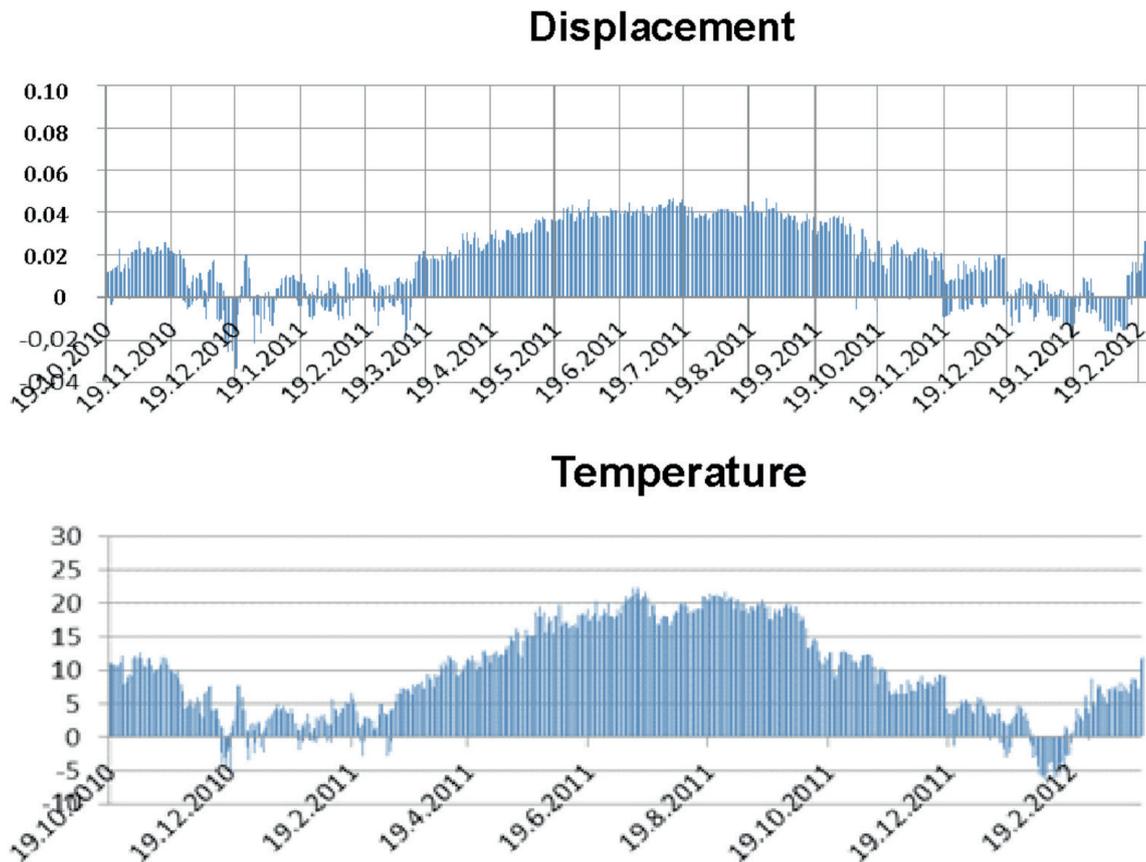


Figure 7: Diagram of the measured EL beam true deflections/movements in mm (above) and temperature in °C (below) in the time period October 2010/March 2012.

Conclusion

Mining engineers have to work with the limitations of available technology. The strength and deformation characteristics of the rock and the discontinuities play a major role in determining suitability as well as the reinforcement and support requirements in underground excavation of natural stone. Efforts to overcome these limitations have resulted in use of the EL beam gauges in quarry Lipica II.

In order to maintain a stable underground structures and the provision of safety and health at work, it is provided constantly monitoring of high safety pillars in quarry Lipica II. Even small changes in strain-stress state in the vicinity of underground structures can mean a potential risk of the wedge failure, if it is not stabilized properly with anchors. EL beam gauges have so far proved to be a reliable tool for high safety pillar stability monitoring. The

advantage of these meters is also that in case of gauge failure, we can easily check the operation of the instrument, supply power cable, etc. and in case of any failure also easily replace or repair (in comparison with VW stressmeter gauge, it is cemented in the borehole and replacement is not possible). An important role is played also the relatively lower price of the EL beam instrument.

Constant monitoring of instability wedges in the pillars hips or in the ceiling of the underground spaces with EL beam gauges will provide more information for the planning of the final dimensions of the new high safety pillars. The experience and results of measurements that are currently passing, we can use in the development and/or modifications of existing monitoring systems and to ensure even greater safety in the underground excavation of natural stone.

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