HIGH SAFETY PILLARS STABILITY CONTROL USING EL BEAM DISPLACEMENT SENSORS IN LIPICA II QUARRY

JOŽE KORTNIK, SUNNY O. NWAUBANI and ANDREJ KOS

about the authors

corresponding author
Jože Kortnik
University of Ljubljana,
Faculty of Natural Sciences and Engineering,
Department of Geotechnology and Mining
Ljubljana, Slovenia
E-mail: joze.kortnik@guest.arnes.si

Sunny O. Nwaubani
Anglia Ruskin University,
Faculty of Sciences and Engineering
Cambridge&Chelmsford, United Kingdom
E-mail: sunny.nwaubani@anglia.ac.uk

Andrej Kos
Marmor Sežana
Sežana, Slovenia
E-mail: kos@marmorsezana.com

Abstract

In underground Lipica II. quarry for the excavation of natural stone, a modified room-and-pillar mining method is used, that is adjusted to the conditions of the site. In order to support and ensure the stability of underground chambers high safety pillars (HSP) are used. These pillars are made of surrounding stone and therefore intersected by discontinuities. The discontinuities represent high risk to the stability of underground facilities and workmen below/itself. To ensure their safety the stress and strain parameters in hight safety pillars are continously monitored using two vibrating wire (WV) stressmeters inside the high safety pillars and two EL (Electronic level) beam sensors on the surface of the high safety pillar VS3. In the time period October 2010/June 2012 absolute max. measured deviation with EL beam sensors were D_1=0.9 mm and D_2=1.1 mm, which does not compromise the stability of the high safety pillar VS3. This paper presents the procedures of wedges deformation monitoring in safety pillars with EL beam sensors in the Lipica II underground natural stone quarry.

keywords

beam sensor, high safety pillar, monitoring, natural stone, room and pillar mining method

1 INTRODUCTION

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 determinating the suitability as well as the reinforcement and support requirements in underground excavation of natural stone. Proper monitoring of safety pillars and rock masses can help a mining engineer recognize when the probability of a failure is higer 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 case injure workers too close to the point of failure [2]. The objective of safety pillars monitoring is to detect, before failure, possible instabilitities to allow the mining engineer to take appropriate remedial masures. The main concern and main purpose of monitoring is the protection of workers and equipment [10].

In analysis of special phenomena such as failure of structures, pillar wedge stability, etc. requires deformation measurement with specific high precition instruments. In various scientific papers demonstrates mostly 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. A tiltmeter gives the rotation of a line segment fixed in the rock about a chosen horizontal axis perpendicular to the local gravity vector [3, 15]. A 3 screw dyke-displacement meter measures the change in distance between three points(screws) on the rock which are a finite triangle distance apart [8, 9]. Both instruments enables the detection of small deformations that cannot be detected and measured by ordinary surveying instruments to be determined. These instruments were used to study the movement of ceiling/roof and walls in underground structures of the Lipica II. quarry.

In the Lipica II. quarry near city Sežana, the underground excavation blocks of natural stone runs for

Figure 1. 3 screw open fissures displacement meter (left) and glass fissures displacement meter/seal (right) for visual monitoring of underground structures stability in Lipica II. quarry.

more than 12 years. One of the important advantages of the underground mining operations is that they do not affect the surface above. For the purposes of safe and stable excavation of natural stone in underground structures a good knowledge of rock properties in high safety pillars, primary geomechanical conditions in the overburden and discountinuity orientations in the deposition is required. In addition, during the excavation careful monitoring of stress conditions in the safety pillars and ceiling is required. In the context of in-situ measurements and control of the room-and-pillar mining method use is made of 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. Use of two vertical EL beam gauges, with the task of monitoring the wedges movements or the major discontinuities (open cracks) displacement at the surface area of high safety pillar VS3 (Figure 6.) the Lipica II. quarry was started in 2010.

Purpose of the study presented in this article is to observe the movement of the rock wedges and the impact on the stability of high safety pillars. Additional several 3 screws open fissure displacement meters, cement and glass seals (Figure 1.) were used for visual monitoring the rock deformations in the Lipica II. quarry.

2 PILLARS WITH JOINTS THEORY

Geological discontinuities such as faults, bedding plane contacts, fractures - "joints" for brevity - that transect pillars may fail even though the pillar proper does not. Joint failure mechanisms as well as strength failure of a pillar therefore need to be examined for pillar design. An appropriate safety factor for joints is [11]

$$FS_j = \frac{\tau_j(strength)}{\left|\tau_j(stress)\right|} \qquad (1)$$

where

$\tau_j(strength)$ … shear strength relate to joint
$\tau_j(stress)$ … shera stress relate to joint.

A Mohr-Coulomb criterion for joint strength is reasonable, so shear strength is given by

$$\tau_j = \sigma_j \tan(\varphi_j) + c_j \qquad (2)$$

where the subscript j refers to the joint.

Joint properties are considered known, but stress analysis is necessary to determine the normal stress acting across the joint and the shear stress acting along the joint.

Flat seam pillars with joints [11]; A simple force equilibrium analysis suffices for the determination of joint stresses that, in fact, are average stresses. With reference to Figure 2, equilibrium in the flat seam case requires

$$\begin{aligned} \sigma_j \cdot A_j &= S_p \cdot A_p \cos(\alpha) \\ \tau_j \cdot A_j &= -S_p \cdot A_p \sin(\alpha) \end{aligned} \qquad (3)$$

where the stresses are indeed averages over the respective areas acted upon. In view of the relationships $A_p = A_j \cdot \cos(\alpha)$,

$$\begin{aligned} \sigma_j &= S_p \cdot \cos^2(\alpha) = S_p \cdot \left(\frac{1+\cos(2\alpha)}{2}\right) \\ \tau_j &= -S_p \cdot \sin(\alpha) \cdot \cos(\alpha) = -\left(\frac{S_p}{2}\right) \cdot \sin(2\alpha) \end{aligned} \qquad (4)$$

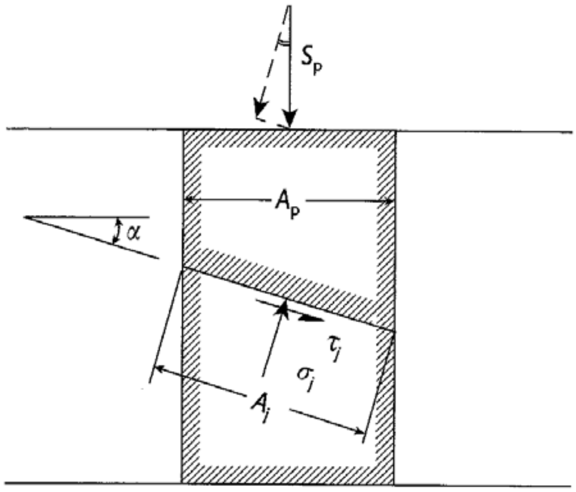

Figure 2. Pillar in a flat seam with a joint [11].

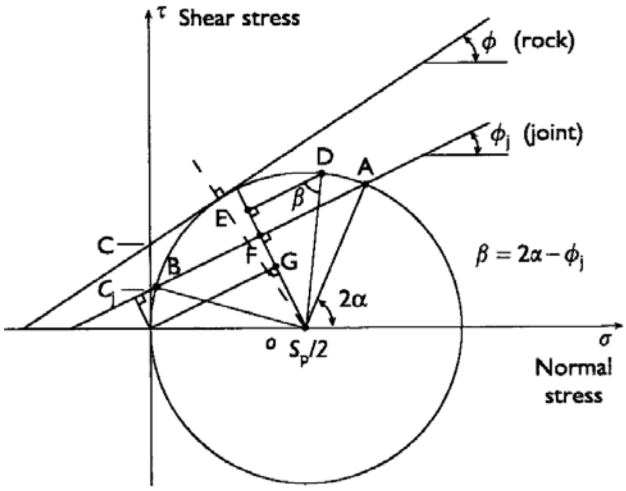

Figure 3. Pillar in a flat seam with a joint [11].

where the negative sign on the shear stress relates to the directions shown in Figure 2. The absolute value is used in the safety factor calculation.

A variation on the question of pillar safety when a joint is present is a question concerning dangerous joint dips. Is there a range of joint dips that are safe? If slip is impending, then

$$\tau_j(stress) = \left(\frac{S_p}{2}\right) \cdot \sin(2\alpha) > \tau_j(strength) = \\ = \left(\frac{S_p}{2}\right) \cdot \left[1 + \cos(2\alpha)\right] \cdot \tan(\varphi_j) + c_j \tag{5}$$

where absolute shear stress value is used. After rearrangement, this criterion is

$$\left(\frac{S_p}{2}\right) \cdot \sin(2\alpha - \varphi_j) > \left(\frac{S_p}{2}\right) \cdot \sin(\varphi_j) + c_j \cdot \cos(\varphi_j) \tag{6}$$

A graphical interpretation of this criterion is shown in Figure 3 that contains Mohr-Coulomb failure criteria for pillar and joint and the Mohr circle that represents the stress state in the pillar. Figure 3 shows that in the range (α_A, α_B) joint slip is possible. This range increases with pillar stress and is maximum when the pillar stress equals pillar unconfined compressive strength, as showu in Figure 3 where the Mohr circle just touches the pillar strength line. Formal solution requires finding the inverse sine of the function containing α in the slip condition. There are actually four solutions because there is symmetry to the problem. This symmetry is graphically represented in the lower half of Mohr's circle where shear stresses and (strengths) are negative. Physically, there is symmetry of dangerous and safe dips about the vertical load axis. Near vertical and near horizontal joints will be safe as one would intuitively suppose [11].

3 DISCONTINUITIES IN LIPICA II. QUARRY

Discontinuities (open craks) appearing in the Lipica II. quarry 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 mouldabe reddish-brown clay (Figure 4.). The thickness of clay fillers varies from thin clay trush 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 and 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 [1,6].

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 ± 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.

Figure 4. Samples of falling rock wedges in underground structures of Lipica II. quarry.

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 $\varphi = 26°$, cohesion $c = 21$ kPa at 100 kPa load and angle of internal friction $\varphi = 16°$, cohesion $c = 50$ kPa at 160 kPa load [5].

Deposit of natural stone in Lipica II. quarry is a strong tectonic disrupted with at least seven leading towards discontinuity (casting) [12], which cause the danger of underground mining. The cracks link together and form in the ceiling and the side of the underground spaces of the dangerous rock wedges (Figure 4.). Precisely because of this, in order to ensure stability and safe working conditions in-situ monitoring and controling devices were implemented. In addition to the stress gauges use were also made of EL beams gauges for rock wedge movement and deformation monitoring.

4 EL BEAM GAUGES

The use of the EL beam gauges (also tiltmeter) is an extremely versatile, since they may be 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. In table 1. is introduced two types of sensors – horizontal and vertical type. Horizontal beam sensors monitor settlement and heave (Figure 5.) and vertical beam sensors monitor lateral displacement and deformation.

Table 1. Technical characteristics of EL beam gauge manufacturer Slope Indicator [14].

	Horizontal	Vertical
Measurement range	± 40 arc min, (± 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.

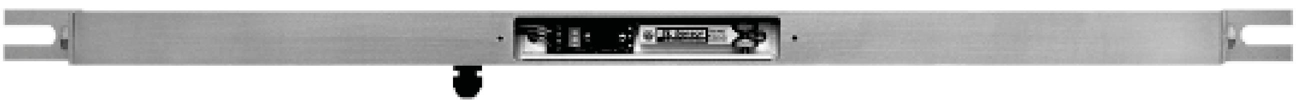

Figure 5. Horizontal EL beam gauge [14].

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

The following polynomial equations is used to calculate the metal beam deflection [4]:

$$\frac{mm}{m} = C5\cdot EL^5 + C4\cdot EL^4 + C3\cdot EL^3 + C2\cdot EL^2 + C1\cdot EL + CO \quad (7)$$

where

EL … measured voltage value
C5…C0 … polynomial coefficients.

Table 1. Example of deviation calculation considering calibration test coefficients - EL beam sensor [4].

	Polynomial coefficient	EL reading	Value
C5	1.6426E^{-1}	-0.585715	-0.1132257000
C4	-1.5836E^{-2}	-0.585714	-0.0018637002
C3	-2.6881E^{-1}	-0.585713	0.0510123829
C2	-7.9904E^{-2}	-0.585712	-0.0274115629
C1	3.5098	-0.585711	-2.0557249580
C0	8.1185E^{-2}	-0.585710	0.0811850000
		mm/m deviation =	-1.961154082

Reading in mm/m it is necessary to multiply with the length of the metal beam (in our case, 2 m), which comes out (2 x -1.961) -3.922 mm.. Due to temperature variations during the period of summer/winter it is necessary to take into account the temperature resistance equation [4]:

$$T = \frac{1}{\left[A + B\cdot(\ln R) + C\cdot(\ln R)^3\right]} - 273.2^\circ C \qquad (8)$$

where

T … temperature in °C
ln *R* … natural log of termistor resistance
A … 1.4051 · 10^{-3}
B … 2.369 · 10^{-4}
C … 1.019 · 10^{-7}

5 APPLICATION OF EL BEAMS IN LIPICA II. QUARRY

Two vertical EL beams were have built in safety pillar (VS3) at level 359 on the open discontinuities, 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 which may cause the slipage of stone wedges from the safety pillars. For a visual check on the safety pillars, cement and glass seals were also installed (Figure 1.). Dangerous rock wedges on the security pillar are stabilized with anchors (Figure 7.).

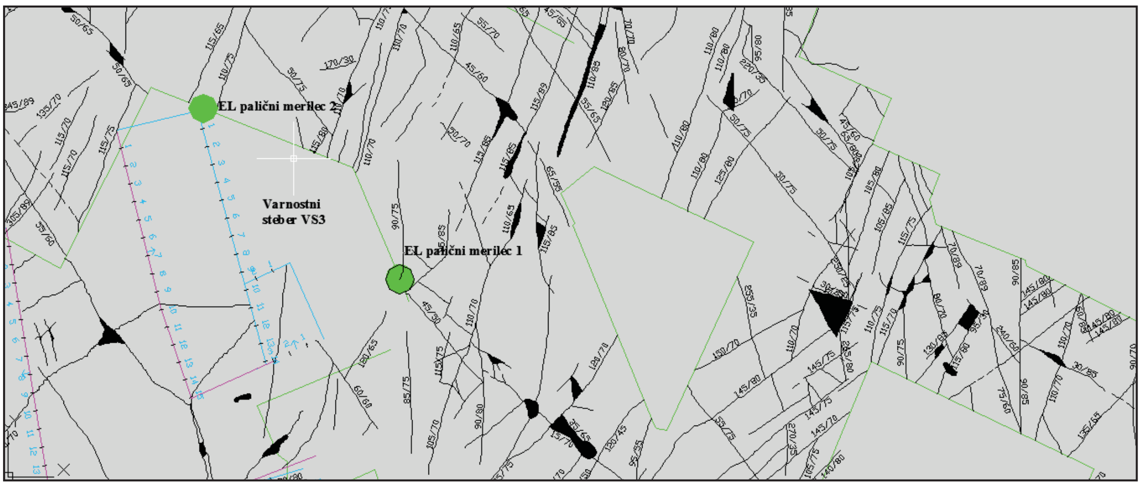

Figure 5. Map of the rock discontinuity orientations and locations (green circle) of two vertical EL beams gauges instalations (safety pillar VS3) in Lipica II. quarry [7, 12].

Figure 7. Datalogger (left) with vertical EL beam gauge (right) instalation on the high safety pillar VS3 stabilized with anchors (middle) in Lipica II. quarry.

Figure 6. shows a map of the rock discontinuities apparing on the sealing of underground structures and locations (green circle) of EL beam gauges instalations in Lipica II. quarry.

In Lipica II. quarry EL beam meter manufacturer Slope Indicator is used to measure supervisory convergences in one vertical plane in high safety pillar VS03 (Figure 7). 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. From practical experience, the best indicators of developments are movements in pillar corners. Consequently, it was decided to monitor the developments on the safety pillar corner, where the sliding surfaces of the main crack are driving out.

6 DISCUSSION

In the time period October 2010/June 2012 absolute max. measured deviation was D_1=0.9 mm and D_2=1.1 mm (see Table 3. and Figure 8.), which does not threaten the stability of the heigh safety pillar VS3. EL beam gauges have so far proved to be a reliable tool for high safety pillar stability monitoring.

As already mentioned the heating and cooling of air in underground structures leads to expansion and contraction of metal rods. Therefore, the data processing involves use of correction factor for metal rods. From Figure 8, we can see that in the summer times, the EL beam rod stretches but in the winter time the EL beam rod shrinks. The metal rod, on which there is displacement meter was observed to be sensitive to changes in temperature, which occurs in the underground extraction during the winter/summer and may be relatively large (ΔT of air in period from 2010/2011 winter -6.4°C / summer 22.3°C).

Problems with rock wedge spalling and pillar stability have been studied to a great extent in the mining industry, but they take a different approach to the safety factor for their underground openings. Localized yield-

Table 3. Data of deviation measurement with EL beam 1 and EL beam 2 [7].

Date	EL beam 1 – deviation [mm]		Date	EL beam 2 – deviation [mm]	
15.11.2010	- 0.09336		03.11.2010	- 0.11903	
19.12.2010		+ 0.31603	19.12.2010		+ 0.53867
27.08.2011	- 0.48343		09.03.2011		+ 0.39831
21.12.2011		+ 0.30086	27.08.2011	- 0.34415	
05.02.2012		+ 0.41547	06.02.2012		+ 0.35279
18.06.2012	- 0.42992		18.06.2012	- 0.57776	
$D_{1max.,min.}$	- 0.48343	+ 0.41547	$D_{2max.,min.}$	- 0.57776	+ 0.53867
D_1	0.89890 mm		D_2	1.11643 mm	

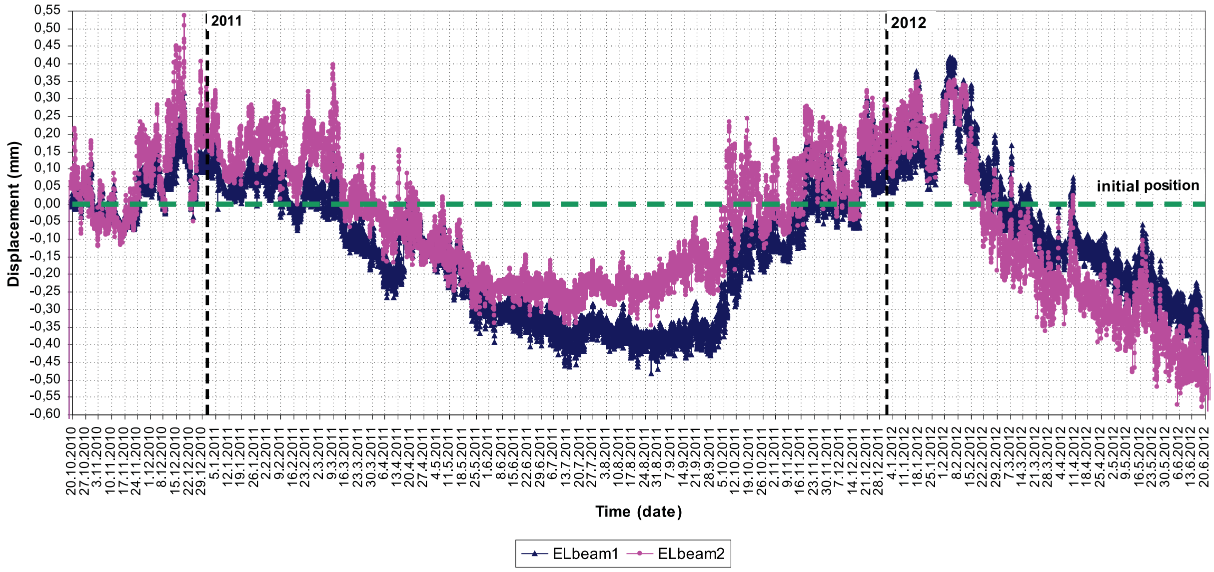

Figure 8. Diagram of the measured EL beam1 and EL beam 2 true deflections/movements in mm in the time period October 2010/June 2012.

ing or failure is a natural part of the process, since the extraction ratio has to be as large as possible. Different empirical methods have been developed, but very few people have taken a more theoretical look at the problem and verified the theories with controlled field experiments. From a high safety pillar stability point of view, these empirical results are just first step to the solution and the problem has to be further studied on a more both empirical and theoretical basis.

7 CONCLUSION

In the underground excavation of natural stone blocks using the room-and-pillar excavation method, special attention needs to be paid to the determination of the appropriate dimensions (width and height) of large open underground spaces (rooms) and high safety pillars, as well as the installation of appropriate systems for continual monitoring and identification of instability phenomena in their ceilings.

Due to large heights (even in excess of 20 m) of such open underground spaces, deepening of the plane renders access to the ceiling for any repair work or the installation of additional supports more difficult or even impossible. In order to maintain a stable underground structure and the provision of safety and health at work, high safety pillars in Lipica II. quarry are constantly monitored. 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 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 by the relatively lower price of the EL beam instrument. Efforts to overcome these limitations have resulted in use of the EL beam gauges in Lipica II quarry.

EL beam gauges when compared with other continuously operating strain gauges, for example, vibrating wire (WV) stressmeters significantly cheaper, simpler to install, the installation of surface rock are readily available to eliminate potential errors / repair and the possibility of multiple use by relocating to the current location of the new measurements of displacements / deformations.

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 gained can be useful in development and/or modifications of existing monitoring systems and to ensure even greater safety in the underground excavation of natural stone.

ACKNOWLEDGEMENT

Special thanks go to Marmor Sežana they enabled not formally funded study with unselfish understanding, attention, a lot of voluntary work and engagement of their human resources, as well as their hardware and software.

REFERENCES

[1] Brown, E.T. and Hoek, E. (1978): Trends in relationships between measured rock in situ stresses and depth. *Int. J. Rock Mech. Min. Sci. & Geomech.* Abstr. 15, pp.211-215.

[2.] Dal Moro, G., Zadro, M. (1998): Subsurface deformations induced by rainfall and atmospheric pressure: tilt/strain measurements in the NE Italy seizmic area. Earth and Planetary Science Letters, vol. 164, no. 1., pp. 193-203.

[3.] D'Oreye, L.N. (1998): Qualification test of a dual-axis bubble type resistive tiltmeter (AGI-700 series): earth tides recorded and analyzed in the undergoud laboratory of Walferdange. Marees Terrestres Bulletin d'Information, 129, pp. 9953-9961.

[4.] EL beam Sensor Manual (2003): Slope Indicator Company 2009/10/12, Standard &SC Versions 56801399, 24 p.

[5.] Fifer-Bizjak, K. (2003): Geotechnical research of Lipica II. quarry underground structures / Geotehnične raziskave za podzemne prostore kamnolom Lipica II.; Nr. P 73/03-750, ZAG, 32 p.

[6.] Hoek, E., Brown, E.T. (1997): Practical estimates or rock mass strength. *Int. J. Rock Mech. & Mining Sci. & Geomechanics Abstracts*. 34 (8), pp. 1165-1186.

[7.] Kos, Andrej, Kortnik, J. (2013): 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. *RMZ - Materials and geoenvironment*, vol. 60, no. 2, pp. 111-119.

[8.] Kortnik, J. (2007): Monitoring and optimization of safety pillars at underground excavation of natural stone / Spremljava in optimiranje varnostnih stebrov pri podzemnem pridobivanju blokov naravnega kamna, 8th conference od mining and geotechnology experts at »40. jump over the leather«, Faculty of Natural Sciences and Engineering, pp. 46-54.

[9.] Kortnik, J. (2009): Optimization of the high safety pillars for the underground excavation of natural stone blocks, *Acta geotechnica Slovenica*, vol. 2009/1, pp. 34-48.

[10.] Likar, J. (2012). Geomechanical effects of operation and closing the Idrija mercury mine on the environment. *Acta geodynamica et geomaterialia*, vol. 9, no. 1, str. 43-55.

[11.] Pariseau, W.G. (2012). Design analysis in rock mechanics, 2nd edition. CRC Press Taylor & Francis Group, pp. 356-360.

[12.] Rijavec, J. (2011): Report about geological research of natural stone Marmor Sežana -2011 / Porocilo o geoloskih raziskavah naravnega kamna na obmocjih kamnolomov druzbe Marmor, Sezana d.d. - leto 2011, archives of Marmor, Sezana d.d., 36 p.

[13.] Sheory, P.R. (1994): A theory for in situ stresses in isotropic and transversely isotropic rock. *Int. J. Rock Mech. Min. Sci. & Geomech. Abstr*. 31(1), pp. 23-34.

[14.] Slope Indicator [cited 20/9/2013] Available on: <http://www.slopeindicator.com/.../tilt-elbeam.html>.

[15.] Teskey, W.F. (1988): Special survey instrumentation for deformation measurements. Journal of Surveying Engineering, ASCE, 114(1), pp. 2-12.