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STABILITY ASSESSMENT OF THE HIGH SAFETY PILLARS IN SLOVENIAN NATURAL STONE MINES

OCENA STABILNOŚCI WYSOKICH FILARÓW BEZPIECZEŃSTWA W KOPALNIACH KAMIENI NATURALNYCH W SŁOWENII

For the first time in Slovenia, the underground excavation of natural stone blocks was introduced on a trial basis at the Hotavlje I colourful limestone quarry in 1993, in 2002 at the Lipica II limestone quarry, in 2008 at the Lipica I limestone quarry and in 2009 also at the Doline limestone quarry. This was primarily because of the geological structure of the site, the quarry's condition, the potentially large amounts of the overburden in the event of an expansion of the surface part of the quarry, and the increasing needs for this raw material, i.e. natural stone.

The underground excavation of natural stone in all locations are done using a modified room-and-pillar excavation method that is adjusted to each site's characteristics, with regularly or irregularly distributed high safety pillars. Since the underground excavation of natural stone blocks is performed at a relatively shallow level under the surface, i.e., at a depth of only 10-40 m, the value of the primary vertical stress state is also relatively low (less than 1.0 MPa).

This significantly increases the risk of wedge-shaped pieces or blocks falling out of the ceiling in open underground spaces. In previous years, special attention was paid to the installation of stress-strain systems for controlling the planned dimensions (width and height) of large, open, underground spaces (rooms) and the dimensions of the high safety pillars, along with continual monitoring and identification of the instability phenomena in the ceiling and sides of the large open spaces (rooms).

The paper presents the methods and devices used for the optimization and the safety monitoring of high safety pillars for the underground excavation of natural stone blocks in Slovenian natural stone mines.

Keywords: high safety pillar, natural stone, stability assessment, quarry, underground mining

Wydobycie naturalnych bloków skalnych ze złóż podziemnych rozpoczęło się w Słowenii w roku 1993 w kamieniołomach wapieni kolorowych w Hotavlje I (etap próbny). W 2002 uruchomiono kamieniołom Lipica II (wapień), w 2008 kamieniołom Lipica I (wapień), w roku 2009 wapień pozyskiwać także zaczęto z kamieniołomu w Dolinie. Działo się to głównie z uwagi na strukturę geologiczną w tych miejscach, warunki geologiczne kamieniołomów, potencjalnie grube warstwy nadkładu w przypadku rozszerzania działalności w części odkrywkowej kamieniołomu, a także rosnący popyt na te surowce (kamień naturalny).

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Podziemne wydobycie kamieni naturalnych we wszystkich tych lokalizacjach odbywa się za pomocą zmodyfikowanej metody filarowo- komorowej, dostosowanej do uwarunkowań poszczególnych lokalizacji, z wykorzystaniem układu mniej lub bardziej regularnie rozmieszczonych filarów zabezpieczających. Ponieważ podziemne wydobycie naturalnych bloków skalnych odbywa się stosunkowo płytko pod powierzchnią, (na głębokościach rzędu 10-40 m), to wartości pierwotnego naprężenia pionowego są stosunkowo niewielkie (poniżej 1.0 MPa).

Wskutek tego powstaje poważne ryzyko odrywania się od stropu bloków skalnych w kształcie klinów, zwłaszcza w dużych, otwartych komorach podziemnych. W latach ubiegłych instalowano układy monitorujące stan naprężeń i odkształceń, wykorzystywane przy planowaniu wymiarów (szerokości i wysokości) dużych, otwartych, przestrzennych komór podziemnych oraz wymiarów filarów zabezpieczających, a także układy zapewniające stałą kontrolę i wykrywanie niestabilności w obrębie stropu oraz w ścianach bocznych komór.

Niniejsza praca zawiera przegląd metod i urządzeń wykorzystywanych do optymalizacji i bezpieczeństwa monitorowania stanu filarów zabezpieczających w podziemnych kopalniach kamieni naturalnych w Słowenii.

Słowa kluczowe: filary zabezpieczające, kamienie naturalne, ocena stabilności, kamieniołom, górnictwo podziemne

1. Introduction

in Slovenia, the underground excavation of natural stone blocks was first introduced on a trial basis at the Hotavlje I colourful limestone quarry in 1993, in 2002 at the Lipica II limestone quarry and in 2008 it was also implemented at the Lipica II limestone quarry (Bajzelj et al., 1999).

The Marmor Hotavlje, as one of the leading Slovenian stone-cutting companies, began the organized excavation of natural stone at the Hotavlje I quarry in 1948, but the actual beginnings of the excavation of natural stone blocks at the Hotavlje I quarry date back to the 1800's. The natural stone found here, the so-called "Hotaveljčan" limestone (Fig. 1), is colourful (grey, red, pink, and sometimes almost black) and has white calcite veins as well as the remnants of individual corals and algae (Marmor Hotavlje, 2013). The Marmor Hotavlje management decided to introduce underground excavation, primarily due to the geological structure of the site, the

Fig. 1. The Hotavlje I quarry (situation 2011), limestone so-called "Hotaveljčan" (grey, pink, red)

condition of the quarry, the large amounts of the overburden in the event of an expansion of the surface part of the quarry, and the increasing needs for natural stone as a raw material.

Marmor Sežana, which has been the leading stone-cutting company in the Karst region for over half a century, began its excavation of natural stone at the Lipica I quarry in 1960 and at the Lipica II quarry in 1986 (Fig. 2). In Lipica quarries excavates two types of natural stone, which were named by the Karst stone-cutters as "Lipica Unito" (homogenous stone) and "Lipica Fiorito" (rose stone) (Marmor Sezana, 2013). In terms of size, the Lipica II quarry ranks among the largest Slovenian natural stone quarries. For similar reasons to the case of the Hotavlje I quarry, in the Lipica II quarry also decided on a trial underground excavation of natural stone blocks in 2001 and introduced it in 2002 (Lipica I, 2008 and Doline, 2009).

Fig. 2. The Lipica II (left-front) and Lipica I quarry (left-behind), "Lipica Unito" (right-up homogenous stone) and "Lipica Fiorito" (right-down rose stone)

In all quarries, the underground excavation of natural stone blocks is done using the modified room-and-pillar excavation method, which is adjusted to the characteristics of the sites with irregularly spaced safety pillars (Kortnik & Bajželj, 2005). Since in both cases the underground excavation is done at a relatively shallow depth from 20 to 40 m, the value of the primary vertical stress state is relatively low (< 1.0 MPa). This significantly increases the risk that wedge-shaped pieces or blocks may fall out of the ceiling in open underground spaces. When planning the underground excavation, special attention therefore had to be paid to the engineering-geological mapping, which was initially done for the external surfaces of the future area of the underground spaces (i.e., galleries, transverse roads and niches, and, after deepening, also the rooms) and the structure of the productive layer. On the basis of these data, the predominant dike systems, which are important for the stability and consequentially also the safety of the underground spaces, were determined. However, this issue will not be addressed in greater detail in the paper.

2. The planning and design of high safety pillars

The strength of safety pillars has been studied for decades by many researchers. The majority of studies in the past were focused on the research of safety pillars in coal mines, but some were also applied to rocks. As a result of these studies, it was found that the strength of a safety pillar is proportional to the strength of the rock in which it is located, and inversely proportional to its thickness: the thinner the pillar, the smaller is its load-carrying capacity. Among the methods used for planning safety pillars, the following two groups predominate:

Analytical methods, which are based on the mathematical principles of the mechanical behaviour of rocks and are computationally less difficult to execute. However, in spite of the possibility of fostering a better understanding of the mechanics of safety pillars, these methods have not been widely used in practice. Their primary disadvantage lies in the use of certain prescribed values (constants), which are difficult or almost impossible to determine in practical work.

Numerical methods, which use modern, numerical techniques and are computationally more demanding, are intended for modelling the loads on safety pillars and presenting changes in the rock's stress and strain states. Furthermore, they enable the modelling of special conditions by taking into account the faults and dikes, as well as the inclusion and assessment of the effect of weakened areas on the overall stability. Nowadays, numerical models play a very important role in the planning of safety pillars for special conditions.

3.1. Analytical method for determining the largest span of open spaces (rooms) between safety pillars

Analytical investigations are usually based on a determination of the static equilibrium of the rock. In such analyses, the average stress state is first determined within the support elements (i.e., the safety pillars) and is then compared to the average value of the rock's strength (see Fig. 3).

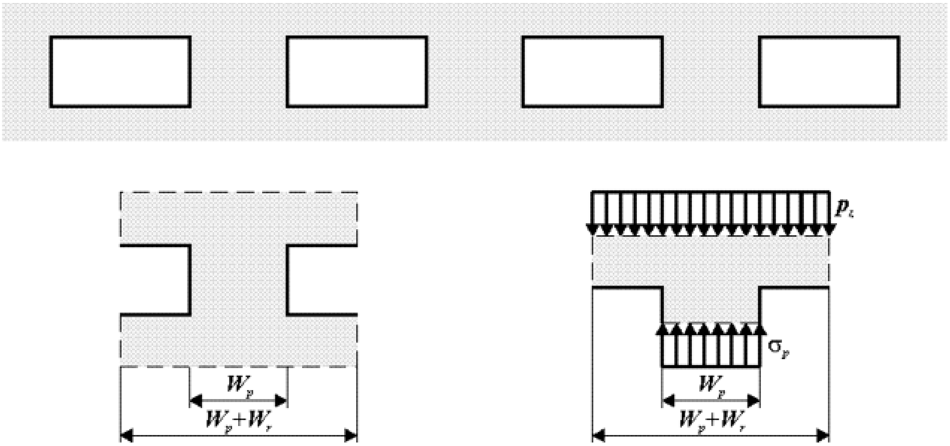

Fig. 3. Cross-section over a horizontally positioned productive layer of uniform thickness, which is excavated by forming long rooms with a width of W_r and intermediary pillars with a width of W_p (Brady & Brown, 1985)

Generally, stone pillars are less stable if the overburden is substantial because of the higher stress. Pillars are also less stable as the width-to-height ratio decreases, for example in benching operations. The stress levels within pillars can be approximated by using the tributary area theory (Brady & Brown, 1985). The average axial pillar stress level σ_p (Wagner & Frömmer, 2004);

$$\sigma_p = \rho \cdot g \cdot H \cdot \frac{\left(W_{r1} + W_{p1}\right) \cdot \left(W_{r2} + W_{p2}\right)}{\left(W_{p1} \cdot W_{p2}\right)} = p_z \cdot \frac{\left(W_{r1} + W_{p1}\right) \cdot \left(W_{r2} + W_{p2}\right)}{\left(W_{p1} \cdot W_{p2}\right)} \tag{1}$$

where

W_{p1} — the pillar's width, [m],
W_{p2} — the pillar's length, [m],
W_{r1} — the room's width (gallery, crosscut, niche, room, etc.), [m],
W_{r2} — the room's length (gallery, crosscut, niche, room, etc.), [m],
ρ — the density of overburden strata, [kg/m^3],
g — the acceleration due to gravity, [m/s^2],
H — the thickness of the overburden, [m],
p_z — the vertical normal component of the pre-mining stress field, [MPa].

The pillar's stress levels are affected by the overburden and the relationship between the area supported by the pillar and the area of the pillar. The relationship is illustrated by comparing the post-mining vertical stress levels as the overburden and the extraction ratio increase.

The most generally accepted techniques for determining pillar strength, defined as the ultimate load per unit area of a pillar, use empirical equations based on survey data from actual mining conditions. The failings of the empirical method stems from an inability to extend these equations beyond the specific material properties, sizes, shapes and overburdens found in the survey data. Bieniawski (Bieniawski, 1984) wrote that the strength of safety pillars is depends upon three elements:

- the size or volume effect (strength reduction from a small laboratory specimen of rock to the full size safety pillars),
- the effect of the pillar's geometry (shape effect),
- the properties of the pillar's material.

For non-coal pillars (Hoek & Brown, 1997), empirical formulas have largely been derived from some form of the following power equation for the safety pillar's strength S_p,

$$S_p = \sigma_c \cdot \frac{W_p^a}{h^b} \tag{2}$$

where

S_p — the pillar's strength, [MPa],
σ_c — the pillar's rock uniaxial compressive strength, [MPa],
h — the pillar's height, [m],
a, b — the exponents determining the pillar's strength from its volume and shape, [/].

This equation considers both the material's strength and the safety pillar's shape (Table 1) to calculate the pillar's strength.

TABLE 1

Exponents determining the pillar's strength from its volume and shape (see Equation 2)

Subject medium	*a*	*b*	Source
Quartzite pillars; Uranium mines near Elliot Lake, Canada; for $w/h < 4.5$	0.5	0.75	(Hedley & Grant, 1972)
Rock pillars	0.5	0.70	(Stacey & Page, 1986)

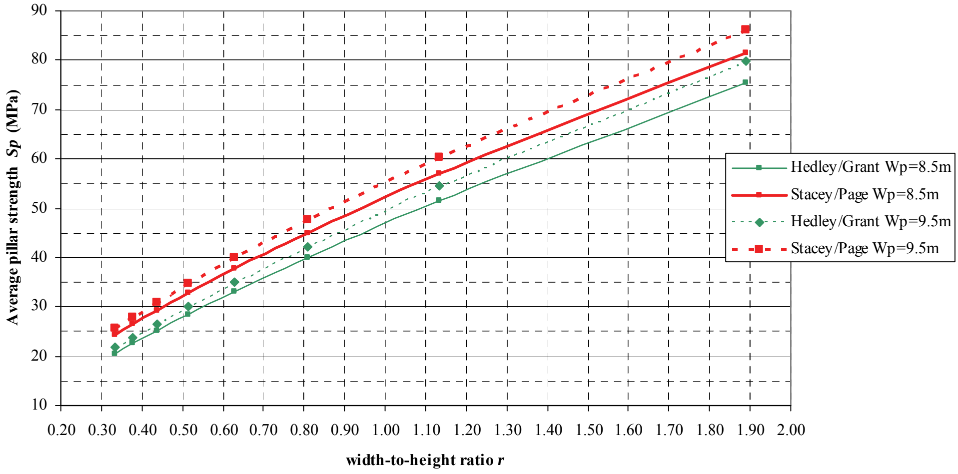

Fig. 4. Comparison between the pillar's width-to-height ratio and the average pillar strength for several different empirical equations (Table 2) based on a power function (Rock uniaxial compressive strength $\sigma_c = 80$ MPa)

In the planning of underground excavations of natural stone blocks using the room-and-pillar method, cautious use of the results of the empirical equation 2 is required. At low width-to-height ratios ($r < 1$), the pillar's strength rises rapidly. At higher width-to-height ratios ($r > 1$), strength increases occur at diminishing rates (Iannacchione, 1999). In other words, at some point the pillar would begin to display some plastic behaviour (Barron, 1984). Pillar stability is most endangered at low width-to-height ratios (see Fig. 4). As typical stone safety pillars reach a width-to-height ratio of $r > 1.5$ (Iannacchione, 1999), they begin to exhibit an almost indestructible character.

Factor of safety F_s,

$$F_s = \frac{S_p}{\sigma_p} \geq 1.6 \tag{3}$$

The low factor of safety provided by this prospective layout indicates that a redesign is necessary to achieve the required factor of 1.6 (Brady & Brown, 1985). The options are to reduce the room span, thereby reducing the pillar's stress level, to increase the pillar's width, or to reduce the pillar's (and mining) height. The selection of an appropriate safety factor can be based on a subjective assessment of the pillar's performance or a statistical analysis of the failed and stable cases. As the F_s decreases, the probability of failure of the pillars can be expected to increase. In practical terms, if one or more pillars are observed to be failed in a layout, it is an indication that the pillar stress is approaching the average pillar strength, causing the weaker pillars to fail. The relationship between F_s and the failure probability, however, depends on the uncertainty and variability of the system under consideration. The value of the factor of safety F_s was calculated using Equation 3 for different values of the width-to-height ratio *r* and for different values of the uniaxial compressive strength σ_c of the pillar rock at a depth of 40 m below the surface. This is presented in Figure 5.

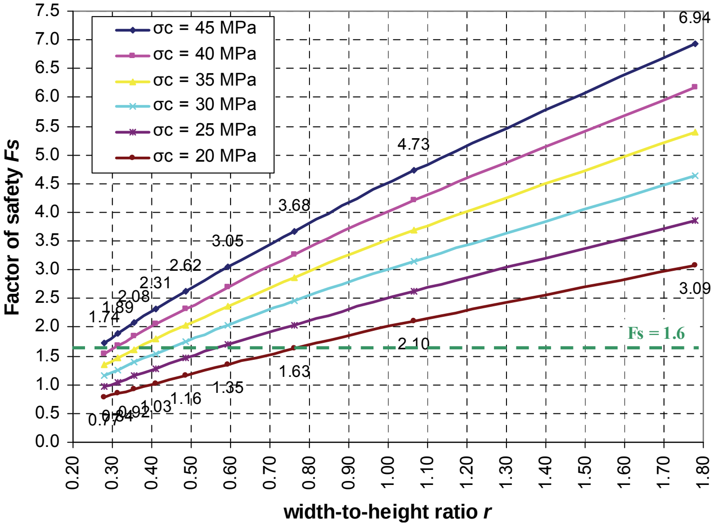

Fig. 5. Safety factor for shallow underground excavation spaces
(thickness of overburden $H = 40$ m, room's width $W_r = 12.0$ m, pillar's width $W_p = 8.5$ m)

3.2. Numerical analysis of the stability of safety pillars and ceiling in open underground spaces

Nowadays, various program packages are available for the numerical analyses of the stability of safety pillars and ceilings of open underground spaces (FLAC 2D, FLAC 3D, PLAXIS, etc.). They are based on the finite-element method (FEM), finite difference method (FDM), the distinct-element method (DEM), etc. The Fast Lagrangian Analysis of Continua (FLAC 2D) is a two-dimensional explicit finite-diference method (FDM). FLAC is well accepted by social mining and rock mechanics engineering. The main advantage of this method is the integration of the surrounding roof and floor conditions on the stone safety pillar strength (Anon, 1998).

For the numerical analysis, the FLAC 3.3 software package was used. The purpose of the numerical analysis was to determine the stability of the planned dimensions of the underground rooms, to make a comparison between the deepening of the levels in monolithic rock without failure and in rock that has failed because it had cracks and dikes (Fig. 6), and to provide the geotechnical foundations for the planning dimensions in an underground excavation, along with continued surface excavation at the Lipica II quarry.

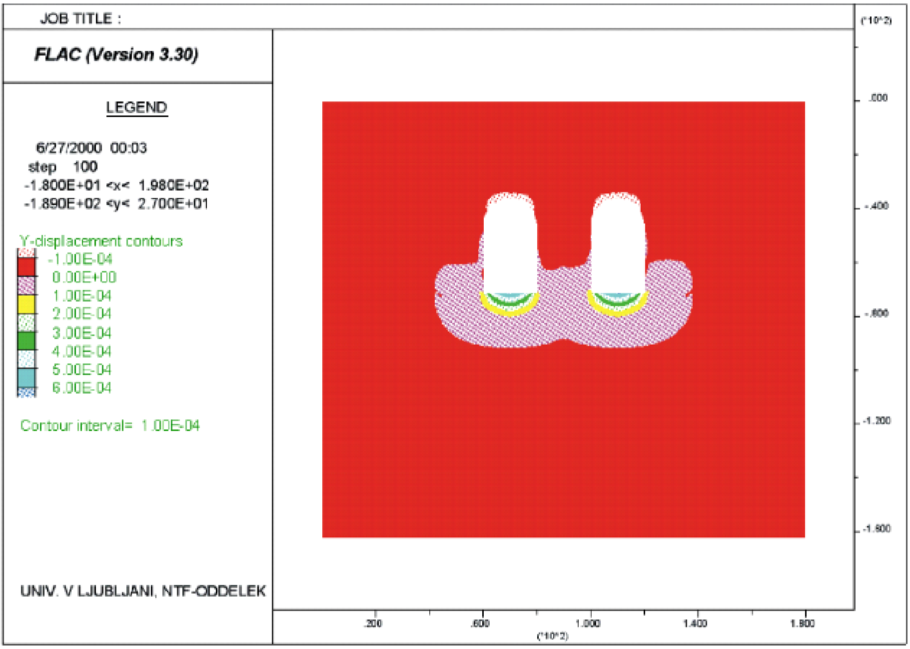

Fig. 6. Stability analysis of the safety pillars using the FLAC 2D software package

According to data from the literature, the ratio of the horizontal to the vertical component of the primary stress state varies widely in the area close to the surface. For underground room depths of up to about 100 m, the value of the coefficient k ($k = \sigma_h/\sigma_v$) is between 1.3 and 3.5. In the majority of cases close to the surface, the value of the horizontal stress σ_h is greater than that of the vertical stress σ_v (Hoek & Brown, 1997). Underground rooms at the Lipica II and Hotavlje I quarries are located close to the surface, and the lowest height of the overburden is 39 m or 36 m. The value of the coefficient $k = 1.3$ was therefore used in the numerical analysis.

On the basis of previously presented data, several models were made to present the deepening of a pair of galleries-rooms with widths of 13 m, 15 m, 16 m and 20 m in compact and failed limestone. Table 2 shows the geomechanical properties used in the numerical analysis.

TABLE 2

The following geomechanical properties were used in the models (Kortnik, 2009)

Parameters	**Compact limestone Model 3.**	**Fractured limestone Model 1. in 2.**	**Very fractured limestone**
E Module of Elasticity	14.7 GPa	9.8 GPa	5.6 GPa
γ Density	26.3 kN/m^3	26.3 kN/m^3	26.3 kN/m^3
ν Poisson's ratio	0,3	0,3	0.3
T Tensile strength	1.0 MPa	0.5 MPa	0.5 MPa
φ Angle of internal friction	52°	35°	29°
c Cohesion	1.8 MPa	1.2 MPa	0.7 MPa

Based on the modelling results, it was concluded that:

- A gallery-room with a width of up to 13 m is stable up to a width-to-height ratio of r = 0.28 if the geomechanical properties of compact limestone are used; if those of failed limestone are taken into account, then up to a width-to-height ratio of r = 0.48,
- A gallery-room with a width of 15 m is stable up to a width-to-height ratio of r = 0.36 if the geomechanical properties of compact limestone are used; if those of failed limestone are taken into account, then up to a width-to-height ratio of r = 0.76,
- A gallery-room with a width of 20 m is stable up to a width-to-height ratio of r = 1.78 if the geomechanical properties of compact limestone are used;
- The models showed that galleries-rooms with a width of 13 m, 15 m or 20 m can be deepened up to a width-to-height ratio of r = 0.28 by using support measures in the form of local anchoring of the lower half of gallery-room sides.

Galleries-rooms with a flat ceiling remain stable even if a factor of safety of F_s = 1.6 is used. The factor of safety is taken into account in the model so that the geomechanical properties of limestone are reduced by the corresponding percentage of the safety factor.

4. In-situ measurements

In-situ control measurements for the room-and-pillar mining method include measurements of the stress state (2D stressmeter) as well as the strains (EL-beam sensors, multipoint extensometer, meter for determining the displacement of open dikes) within safety pillars and in ceilings of large, open, underground spaces. Only the results of in-situ control measurements done at the Lipica II quarry are shown below due to more intense excavation of natural stone blocks and the longer monitoring of these measurements.

To perform control measurements of the changes in the stress state of high safety pillars, a 2D stressmeter (VW (vibrating wire) biaxial stressmeter model 4350-1) manufactured by Geokon was used to monitor the main stresses in a single vertical plane perpendicular to the axis of the drill hole (Fig. 7). Measurements of the main stresses are enabled by three VW sensors, which are oriented at 60° angles within the probe. The stressmeter also has a sensor for temperature measurements. The stressmeter body is made of a steel cylinder with a maximum external diameter of 57.1 mm (Kortnik, 2009).

TABLE 3

Technical characteristics of 2D stressmeter (Model 4350 BX)

Standard stressmeter range	70 MPa
Resolution[1]	14 do 70 kPa
Accuracy	±0.1% F.S.
Temperature range	(253…353 K) –20°C to +80°C
Borehole diameter	BX (60 mm)

[1] Depends on rock modulus

For transferring data from the stressmeter, a memory unit (datalogger CR10 module, AVW1, SC32B) is used for the data capture, along with the appropriate software (the PC200W software

Fig. 7. VW01 Biaxial Stressmeter and its position in the borehole

package). The data capture is done automatically, using the time interval set in the program (1 min, 60 min or 240 min).

The VW1 stressmeter used to monitor the changes in the primary stresses in the vertical plane perpendicular to the axis of the drill hole was installed in the SP02 safety pillar (22.10.2003; drill-hole L-14/03 at the depth 3.00 m) see Figure 11. The site of the stressmeter installation corresponds to the site of monitoring the primary stresses in the numerical model for the case of deepening of the gallery pairs. The results of the measurements of the stress state in the SP02 safety pillar are shown in Table 4.

TABLE 4

Average measured values of the main stresses in the SP02 safety pillar

VW1 stressmeter width-to-height ratio *r*	**Temperature [°C]**	**Sig_1 [MPa]**	**Sig_2 [MPa]**	***k* [/]**
1.80	5.4/14.5	–2.60	–2.09	1.24
1.10	3.0/15.1	–3.03	–2.29	1.32
0.80	2.7/15.6	–3.62	–2.67	1.35

With deepening of the gallery/safety pillars (see Fig. 8) or reduction of the width-to-height ratio *r*, the ratio of the vertical to horizontal components of the primary stresses in the safety pillar is within the range of 1.24 to 1.35 (1.30).

The EL beam gauges (also tiltmeter) are used to measure vertical movements, declination or movements on dams, observation of the stability and convergences 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.

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 struc-

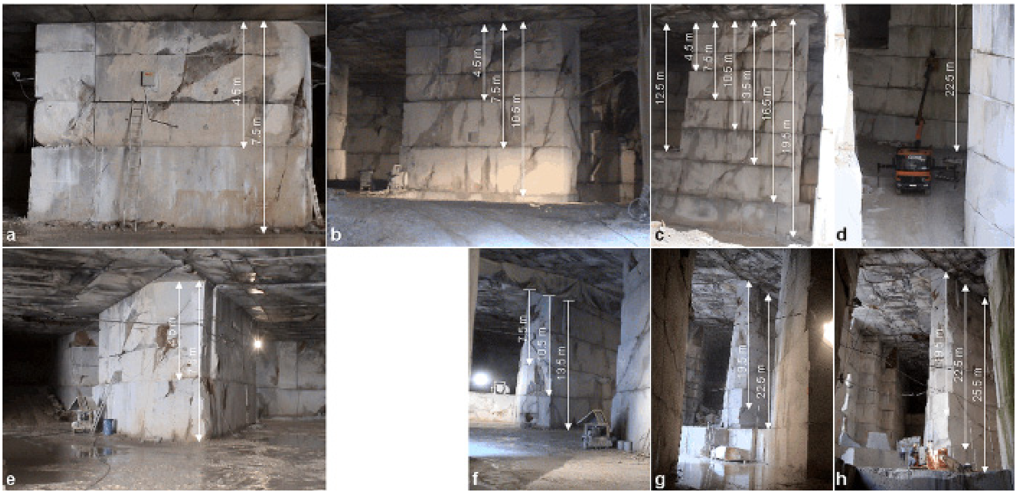

Fig. 8. Deepening (from 4.5 m (a) to 25,5 m (h)) of the heigh safety pillar SP02 (cross-section area 72 m^2) in Lipica II. quarry

ture 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.

TABLE 5

Technical characteristics of EL beam gauge manufacturer Slope Indicator (Slope indicator, 2013)

	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

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.

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 6), which does not threaten the stability of the heigh safety pillar VS3.

If open dikes appear in a safety pillar, relatively simple dike displacement meters are additionally installed in order to monitor the sliding surfaces within the dikes (Fig. 10).

Fig. 9. Vertical EL beam gauge installation on the high safety pillar VS3 in Lipica II. quarry

Fig. 10. Visual (cement seal) and manual (three screw system) measurement of the displacements of open dikes within safety pillars

TABLE 6

Data of deviation measurement with EL beam 1 and EL beam 2

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	
$D1_{\text{max., min.}}$	**–0.48343**	**+0.41547**	**$D2_{\text{max., min.}}$**	**–0.57776**	**+0.53867**
$D1$	**0.89890 mm**		**$D2$**	**1.11643 mm**	

A dike-displacement meter consists of three screws system installed along a dike and arranged in the form of a equilateral triangle (see Fig. 10). The measurements of dike displacements are done manually with an adjustable gauge, by measuring the changes in the distance between the screws. At the Lipica II quarry, three dike displacement meters are installed: one in the P2 to SP02 line, one on the right-hand side of the G2 gallery and the third one on the right-hand side of the G1 gallery (see Fig. 11). Because of difficult access to the meters after the first deepening, the measurements of dike displacements were done periodically. The results of the measurements for the relative displacements of open dikes in safety pillars SP02 to SP04 did not show any active displacements of the sliding surfaces in the pillars.

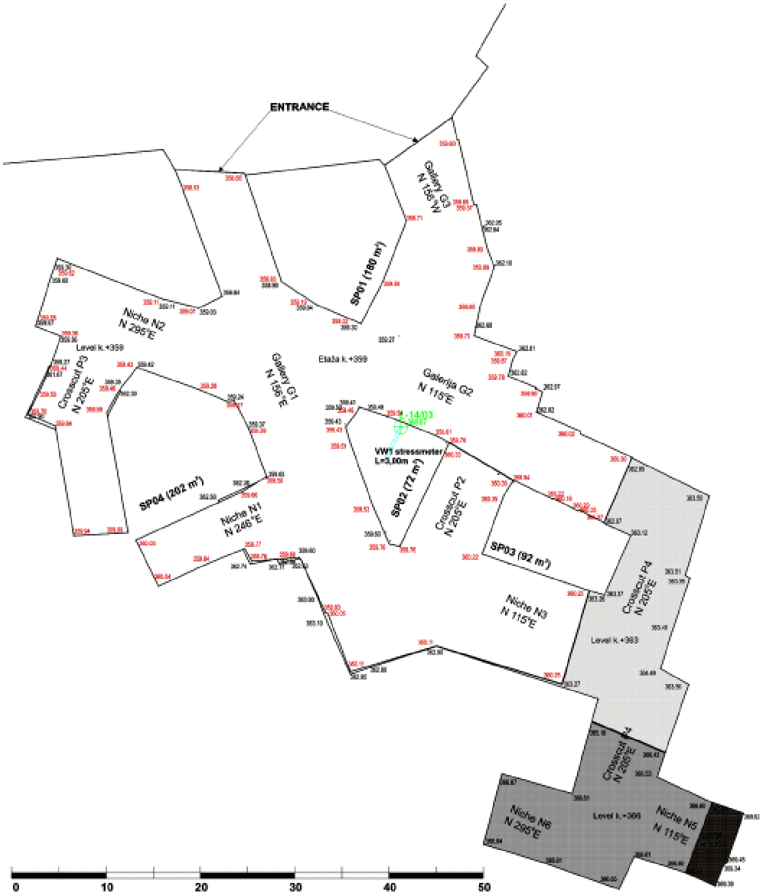

Fig. 11. Plain view of the Lipica II underground quarry (VW1 – vibrating wire stressmeter, safety pillars SP01 to SP04)

5. Conclusions

In the planning of an 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 the instability phenomena in their ceilings. Due to the 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.

The results of analytical calculations and numerical modelling showed that in the case when the geomechanical properties of the compact limestone were taken, a gallery-room with a width of up to 13 m is stable up to a width-to-height ratio of $r = 0.28$ without having to employ any additional support measures. If the geomechanical properties of failed limestone were used, then such a gallery-room is stable up to a width-to-height ratio of $r = 0.48$. On the basis of the modelling results, the width of the portal portion of the pillar was also estimated (along the cross-section that is perpendicular to the surface levels), which had to be greater than 13 m. The results of in-situ measurements of the stress state at the Lipica II quarry in the SP02 safety pillar have confirmed the results of the numerical modelling. The measurements of the dike displacements also do not indicate any displacements of the sliding surfaces in the area of open dikes in the safety pillars SP02 to SP04.

In order to maintain a stable underground structure and the provision of safety and health at work, high safety pillars as in the case of Lipica II quarry, should be 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. In-situ control measurements (2D stressmeter, EL-beam sensors, multipoint extensometer, meter for determining the displacement of open dikes) have so far proved to be a reliable tool for high safety pillar stability monitoring.

For the time being, no methodology is available for dimensioning high safety rock pillars with a low width-to-height ratio for underground quarries of natural and technical stone. The experience and results of measurements currently obtained in both Slovenian quarries that employ the underground excavation of natural stone will be beneficially used in the development of a new methodology for the implementation of this underground excavation method in other natural stone quarries that are suitable for its use. The pillar-design guidelines developed throught, the observational, analytical and numerical simulations discussed above will require further field confirmation. This approach can help to form a part of the comprehensive pro-active mine safety ground-control plan for underground natural stone mines.

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