HIGH SAFETY PILLARS STABILITY ASSESSMENT IN DEBELA GRIZA DIMENSION STONE QUARRY

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ABSTRACT
Underground excavation of natural stone in Slovenia is carried out on five quarry locations (Hotavlje I, Lipica II, Lipica I, Doline and Debela Griža) using the modified room-and-pillar mining method, which is adjusted to the characteristics of the sites with irregularly spaced high safety pillars. Since in all cases the underground excavation is done at a relatively shallow depth (from the surface) from about 15÷34 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 rooms. When designing the special attention therefore had to be paid also 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. In order to support and ensure the stability of underground rooms the high safety pillars are used. These pillars are made of surrounding rock and therefore intersected by discontinuities. The discontinuities represent high risk to stability of underground facilities and work itself. To monitor stress and strain parameters of high safety pillars we use 2D WV stressmeters (VW – vibrating wire) inside the safety pillars and EL beam sensors on the surface of pillars. In paper will be presented procedures of designing and stress-deformation monitoring of safety pillars in the Debela Griža underground dimension stone quarry.
Key words: *EL beam sensor, dimension stone, high safety pillar, room and pillar mining method, VW stressmeter.*

1. INTRODUCTION

In Slovenia, we started introducing underground extraction of dimension stone blocks in 1993, first in the quarry of limestone Hotavlje I and then in 2002 in the Lipica limestone quarry. We continued with the introduction of underground mining in 2009, first in the Doline limestone quarry and then in the Lipica quarry. limestone Lipica I. In 2014, we started to introduce underground extraction of dimension stone blocks in the quarry of limestone Debela Griža, which will be presented in more detail.

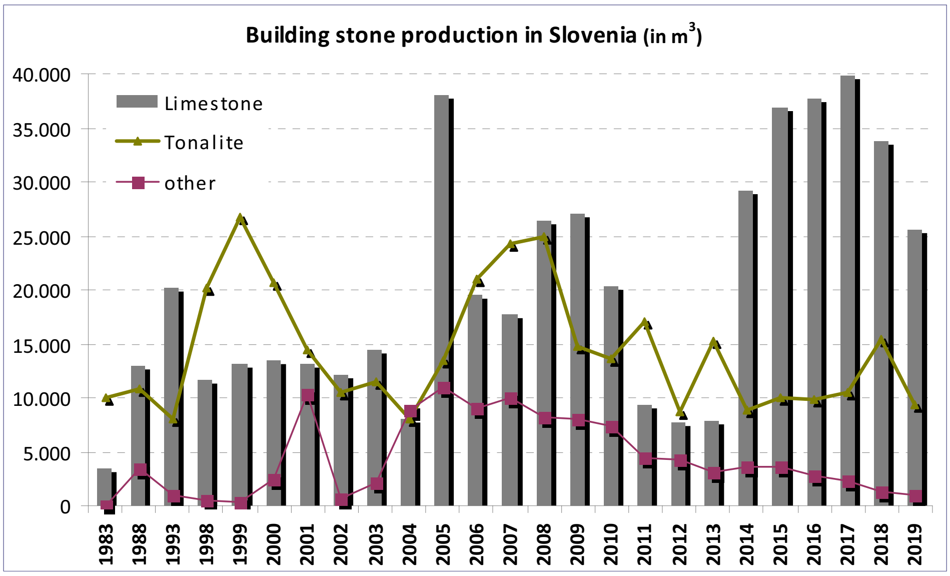

Figure 1.: *Excavated quantities of building stone in Slovenia from 1983 to 2019 [**2**].*

In Slovenia, the extraction of dimensional-building stone - limestone was constantly growing until 2009 (27,000 m^3), followed because of the global financial crisis of 2007-2008 by a marked decline in production until 2012 (7,780 m^3), after which extraction began to grow sharply again - in 2017 it reached almost 40,000 m^3. After 2017, the extraction of dimensional stone blocks declined again due to falling raw material prices and lower demand in domestic and foreign building industry.
The rapid growth of building stone - limestone extraction after 2004 (2013) was mostly enabled (see Figure 1) because of the introduction of underground mining in the previously mentioned dimension stone quarries.

2. DEBELA GRIŽA QUARRY

The Debela Griža limestone quarry is exploited by the Kamnoseštvo Tavčar [**6**], a family business company, since 1985. Natural stone, the so-called "Repen" stone, is a high-quality crystallized gray limestone rich in fossil shells (Figure 2). It has good physico-chemical properties, is compact and colorful, has a pleasant appearance, is very durable and therefore also suitable for outdoor use. The Repen limestone from the Debela Griža quarry (Figure 2. right) and the Doline quarry is about 93 million years old.
Mechanical properties of dimension stone are determined in accordance with the standard SIST EN 12058: 2004 (Natural stone - Slabs for floors and stairs - Requirements). The geo-mechanical properties of different color variants of a natural decorative stone called Repen from the Dolina quarry and the Debela Griža quarry are shown in Table 1.

Table 1.: *Comparison of geo-mechanical properties of similar natural stone Repen Doline and Repen Debela Griža.*

		Doline	Debela Griža	
Characteristic	Unit	Repen	Repen bright	Repen dark
Density without pores and caverns	$t\ m^{-3}$	2.72	2.79	2.78
Density	$t\ m^{-3}$	2.70	2.68	2.68
Density coefficient		0.99	0.96	0.96
Porosity	%	0.70	4.10	3.60
Water absorption	%	0.17	0.23	0.11
Abrasion wear	$cm^3\ 50cm^{-2}$	18.4	23.9	18.0
Modulus of elasticity	GPa	82.7	-	-
Angle of internal friction	°	34.0	-	-
Average compressive strength:				
- dry	MPa	210.0	206.0	221.0
- wet	MPa	190.0	190.0	212.0
- after 25 freeze/thaw cycles	MPa	172.0	197.0	223.0

The introduction of underground extraction of dimension stone blocks in the Debela Griža quarry is mainly due to the geological structure of the deposit, the surface condition of the quarry's and the potential large quantities of overburden in the case of expansion of the quarry's surface part into the eastern side of the extraction area. Figure 2 shows a high portal wall with an entrance to the G1 gallery with a ceiling height of approx. 12 m (right) and top left entrance to the G2 gallery current roof height approx. 6 m. In the case of the expansion of surface extraction, it would be necessary to first remove the overburden at the stated heights and deposit it, which has a strong impact on the economy of extraction.


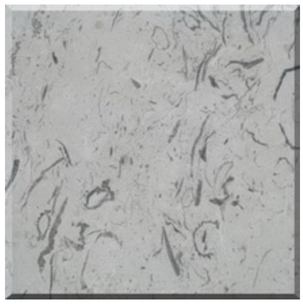

Figure 2.: *High portal wall with entrance into the underground Debela Griža quarry (left), "Repen" limestone sample (right) [6].*

Since the underground extraction in the Debela Griža quarry is carried out relatively shallow below the surface of approx. 24 m, the value of the primary vertical stress state is relatively low (<1.0 MPa) and thus significantly increased the possibility of failure of the wedges/blocks from the roof into open underground spaces. When planning underground extraction, it was therefore necessary to pay special attention to engineering-geological mapping, first of the outer surfaces of the future area of underground spaces (galleries, cross-cuts and niches, and after galleries floor deepening also chambers) and structural structure of the productive layer. On the basis of these data, the predominant crack systems, which are important for the stability and consequently the safety of underground open spaces, have been identified. The following are some important elements of planning the underground extraction of dimension stone blocks.

3. PLANNING AND OPTIMIZATION OF UNDERGROUND EXPLOITATION

In underground mines of dimension and technical stone, the room-and-pillar mining method adapted to the conditions of the deposit with correctly or incorrectly arranged safety pillars with a greater or lesser coefficient of the width-to-height ratio is mainly used. The mining method allows the use of self-supporting rock as a supporting element in the form of safety pillars of appropriate dimensions, which must ensure the stability of the hanging-wall in the open spaces ceiling and allow the required span of open spaces between them for safe access and operation of underground sites. When planning the dimensions (area, width and height) of safety pillars and the span of open spaces (chambers) between the safety pillars, the designer must usually decide between the request of the owner of the mining right or the mining company management after the maximum possible extraction ratio of dimension stone blocks and the requirement to ensure adequate safety. Due to the limited quantities of natural stone in the deposit, the larger the volume of dimension stone blocks, the larger the dimensions of underground spaces and the smallest possible dimensions of safety pillars, which in turn reduces the safety in underground spaces. By reducing the floor plan dimensions of the safety pillars, their strength decreases, and conversely, the load and the possibility of overloading the safety pillars increases [**8**].

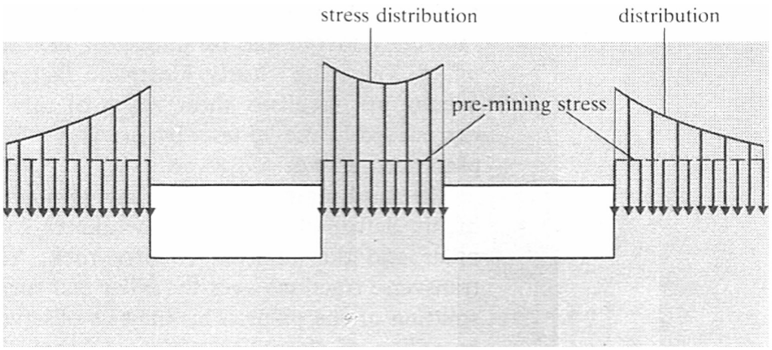

Figure 3.: *The stress redistribution after the construction of underground open spaces [**3, 4**].*

The stability of the ceiling of large underground spaces and safety pillars depends mainly on the quality of the geomechanical properties of the rock and the intensity of tectonic activities in the deposit. The differences are due to the different volumetric masses of the rock, the different overburden loads and the different tectonic activities, which requires detailed extraction planning and appropriate support measures to ensure safe working conditions. Therefore, for the needs of safe and stable extraction of natural stone blocks, it is necessary to know well the geomechanical properties of the rock, the primary stress state in the hanging-wall p_z and the tectonics of the deposit.

3.1 Design of high safety pillars with a small width-to-height ratio

The load-bearing capacity (strength) of the safety pillar depends mainly on the rock strength and the value of the safety pillar ratio of the width-to-height. Any reduction in the width-to-height ratio can lead to a reduction in the overall strength of the safety pillar.

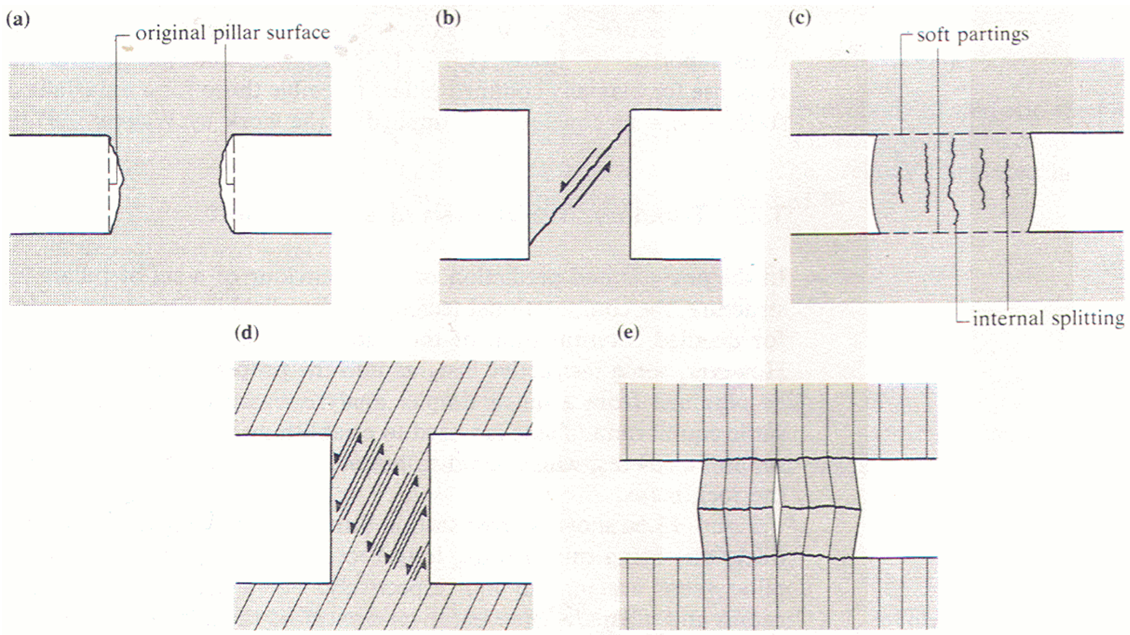

Figure 4.: *The predominant ways of damaging safety stone pillars include; (a) peeling of the stone pillar surface, (b) shear fracture over the stone pillar, (c) transverse expansion (barrel), (d) parallel cracks, (e) budding [**3, 4**].*

The following common features (recommendations) were observed in the existing underground mines of natural and technical stone with regard to safety pillar with a low value of the width-to-height ratio:

- The initial heights of the safety pillars are usually 4.5 m to 7.6 m, which increase with the deepening of underground spaces and in some places reach heights of 18.0 m and even more. Already slender safety pillars are usually further weakened with each deepening of the base floor due to a reduction in the basic horizontal cross section and can collapse in the event of a decrease in the limit allowable strength due to a decrease in the value of the width-to-height ratio.
- Initially stable safety pillars can become unstable as the basement deepens. In many underground mines of natural and technical stone, deepening was abandoned precisely because of the deteriorating mountain conditions of the deepened floors.
- Weakening or. failure of one safety pillars can cause a chain reaction or. overloading of adjacent safety pillars and thus settling of the entire roof area above them. This danger is especially great in the case of slender safety pillars.
- Safety pillars, which gradually reduce the width-to-height ratio, are particularly sensitive to impairments due to transversely or vertically intersecting discontinuities (cracks or slides). Underground mines of dimension and technical building stone usually have very good geomechanical conditions, which can deteriorate rapidly due to the unexpected occurrence of discontinuities, especially in the case of slender safety pillars.

3.2 Determining the dimensions of the underground open spaces

The demand of mining companies management is that due to the growing demand for raw materials and lower extraction costs, they consequently demand an increase in the spans of open underground spaces. Due to different geological conditions in the deposits of natural and technical stone, the surface of the ceiling of a large open space usually represents one or more layers (layers) of rock, which are parallel or inclined to the ceiling. The stability of the open space ceiling depends mainly on the geomechanical properties of the rock, the load of the roof on the ceiling (vault) and the tectonic conditions in the deposit. The spans of open spaces in underground mines of dimension and technical building stone are usually up to 13 m, exceptionally up to a maximum of 18 m. Increasing the span reduces the stability of the open space ceiling and can occur:

- Occurrence of bending stresses, which causes bending and bending of the ceiling and the formation of shear cracks in the ceiling,
- Increase in bending and shear stresses in the ceiling, which can cause critical damage to the intact rock or. ceiling collapse,
- In all probability, the occurrence of an unfavorable crack that crosses the ceiling of the underground space.

As in the planning of the dimensions of safety pillars, the practical experience of already used ceiling spans of existing underground spaces is most often transferred or trial-and-error approach. The methods on the basis of which, for different locally rock geo-mechanic characteristic and for different stress conditions, the appropriate spans of the ceiling of underground spaces in natural and technical stone mines could be determined, are still in their infancy. Today, methods have been used to plan the dimensions of underground spaces, which were developed mainly for the needs of planning coal mines and metal mines and only indirectly take into account the needs and conditions of underground extraction of dimension and technical building stone.
When planning the underground extraction of dimension stone blocks with the room-and-pillar mining method, additional attention should be paid to determining the appropriate dimensions (width and height) of large open spaces (galleries, cross-cuts, niches and chambers), dimensions of high safety pillars to achieve optimal utilization of natural stone. Table 2 shows the efficiency percentages for different dimensions of pillar and open spaces. In practice, given the mechanical properties of rocks in the case of high safety pillars, a ratio of 1: 4.4 proved to be optimal.

Table 2.: *Determining the optimal share of dimension stone efficiency in different layouts of safety pillars on the underground Debela Griža quarry.*

Pillar width a [m]	Pillar depth b [m]	Gallery width c [m]	Pillar surface axb 'A' [m²]	'Tributary area' 'B' [m²]	Ratio 'A': 'B'
16,8	16,8	16,8	282,24	846,72	1 : 3,0
16,8	14,0	16,8	235,20	799,68	1 : 3,4
14,0	**14,0**	**16,8**	**196,00**	**752,64**	**1 : 3,8**
14,0	14,0	14,0	196,00	588,00	1 : 3,0
14,0	11,2	14,0	156,80	548,80	1 : 3,5
11,2	**11,2**	**14,0**	**125,44**	**509,60**	**1 : 4,1**
11,2	11,2	11,2	125,44	376,32	1 : 3,0
11,2	8,4	11,2	94,08	344,96	1 : 3,7
8,4	**8,4**	**11,2**	**70,56**	**313,60**	**1 : 4,4**
8,4	8,4	8,4	70,56	211,68	1 : 3,0
8,4	5,6	8,4	47,04	188,16	1 : 4,0
5,6	5,6	8,4	31,36	164,64	1 : 5,3
5,6	5,6	5,6	31,36	94,08	1 : 3,0

For the needs of geotechnical analyzes of the stability of high safety pillars and ceilings of open underground spaces, various software packages (FLAC 2D, FLAC 3D, PLAXIS, Phase2, etc.) are available today, based on different methods of numerical analysis (finite elements, finite differences, etc.).

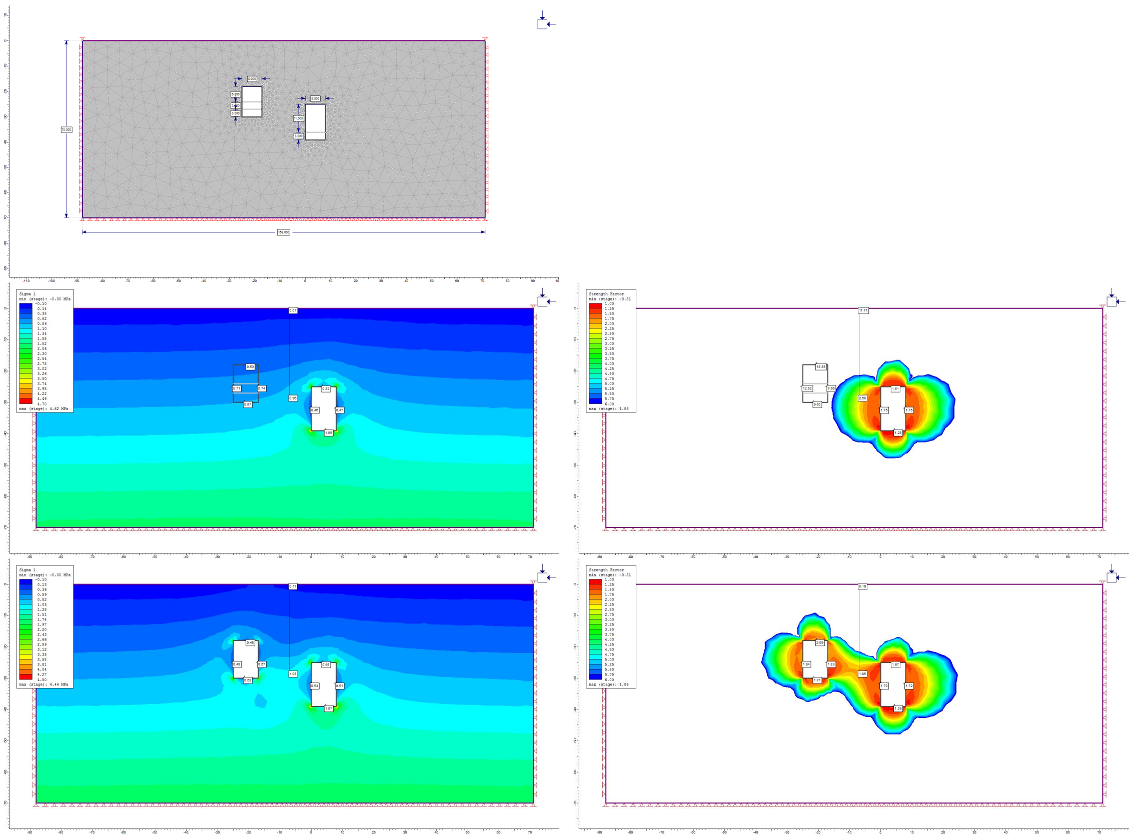

Figure 6.: *Modeling of stress/deformation changes Sig 1 (left) and calculation of safety factor (right) in the vicinity of underground Debela Griža galleries G1 and G2 after deepening both galleries floor by Phase2 software.*

For the optimization of the underground spaces dimensions in the Debela Griža quarry, we used the software package Phase2, stress/deformation modeling is shown in Figure 6. In the model, we also simulated the installation of geotechnical monitoring devices. Today, in the underground spaces of the Debela Griža quarry, we perform geotechnical monitoring in two high safety pillars with stress measurements (VW stress meter, Fig. 8 left) and in one profile with measurements of vertical deformations / ceiling settlements (EL bar gauge with open cracks). in the safety pillars as well as in the ceiling of large open underground spaces, and we compare the in-situ measured values with the model calculated values.

4. IN-SITU GEOTECHNICAL MONITORING AND STRESS ASSESSMENT

As part of the in-situ geotechnical monitoring and stress assessment of the room-and-pilar mining method, measurements of stress state (2D stress meter) and deformations (EL beam meter, multi-point extensometer, open crack displacement meter) are planned both in high safety pillars and in the ceiling of underground open spaces (galleries, cross-cuts, niches and chambers).
For visual observation of displacements at open cracks, as shown in Figures 7, glass and cement seals are used, which are installed at the place of occurrence of the open crack in the ceiling or side of open underground spaces.

Figure 7.: *Visual inspection of open cracks (glass and cement seals) on the ceiling (left) and side of the underground gallery G1 (right).*

To perform measurements of stress changes in high safety pillars, we installed a 2D stress meter (VW (vibrating wire) biaxial stressmeter model 4350-1) manufactured by Geokon (Figure 8). By installing in the safety pillar, we monitor changes in the main stresses in one vertical plane, perpendicular to the axis of the pillar. Measurements of the main stresses are enabled by three VW sensors, which are oriented in the probe with an angular offset of 60°. The body of the stress meter is made of a steel cylinder with a maximum outer diameter of 57.1 mm [**5**]. A memory unit (datalogger CR10 module, AVW1, SC32B) for data acquisition and software (software package PC200W) are used to extract data from the stress meter (see Figure 8. right). Data acquisition is performed automatically according to the program set time interval (1 min, 60 min or 240 min).

Figure 8.: *2D stress meter (VW biaxial stressmeter 4350BX) (left) and location of installation in the borehole ϕ60mm in the G1 gallery (right).*

***Table 3.:** Technical characteristics of the 2D stress meter (Model 4350 BX) [**5**].*

Standard measuring range	70 MPa
Sensitivity[1]	14 to 70 kPa
Accuracy	±0,1% F.S.
Operating temperature range	-20°C to +80°C
Required borehole diameter	BX (60 mm)

[1] depending on the rock Modulus of Elasticity

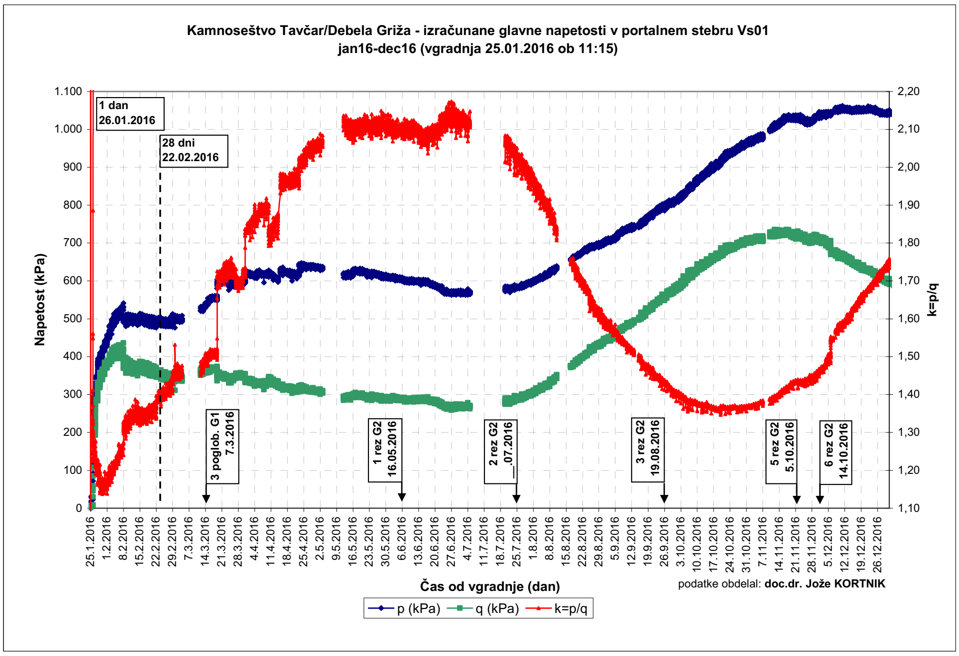

***Figure 9.:** Measurements of the stresses in the portal pillar between galleries G1 and G2 in the Debela Griža quarry in the period Jan / Dec 2016*

The results of stress measurements with 2D stress meters in the portal safety pillar (Vw01) are shown in the graph in Figure 8. The measured main vertical stress is shown in blue and the main horizontal stress in the portal safety pillar is measured in green between galleries G1 and G2. The ratio k between the measured horizontal and vertical stresses is shown in red. With in-situ measurements of horizontal stresses, we want to further confirm the assumption of Hoek and Brown (1997) that the value of the coefficient k is higher near the surface and decreases with depth [**3**].

The possibility of expanding underground mining to the southern part of the Debela Griža quarry is indicated by newly obtained geological data, data on discontinuous areas and especially data from the existing geotechnical monitoring in the portal pillar between galleries G1 and G2 in the eastern part of the Debela Griža quarry. Underground extraction with the chamber column excavation method is expected to take place with three parallel and transverse galleries G5, G4 and G6 up to 19 m high between the angles k. + 469 and k. + 450 and the total volume of underground spaces around 40,000 m^3.

5. CONCLUSIONS

When planning the underground extraction of dimension/building stone blocks with the room-and-pillar mining method in the Debela Griža quarry, special attention was paid to determining the appropriate dimensions (width and height) of large open underground spaces (chambers), dimensions of high safety pillars and installation of appropriate monitoring systems and the identification of phenomena of instability in the ceiling of large open spaces (chambers). Due to the large height of the final open underground spaces (planned height

up to 16 m), access to the ceiling for the implementation of possible rehabilitation works or. the installation of additional support measures after deepening is severely hampered or even prevented.
To date, no appropriate methodology has been developed for the dimensioning of high safety pillars with a low width-to-height ratio for the needs of underground mines of dimension and technical building stone. The experience and results of measurements that are currently being obtained in all five Slovenian quarries with underground extraction of dimension stone blocks can be usefully used in the development of the methodology for introducing the underground method of extraction into others, suitable for this method of extraction of dimension stone blocks.

6. LITERATURE

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