OPTIMIZATION OF THE HIGH SAFETY PILLARS FOR THE UNDERGROUND EXCAVATION OF NATURAL STONE BLOCKS

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Abstract

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, and in 2002 also at the Lipica II 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. Underground The underground excavation of natural stone blocks is 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 (<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 procedures for the planning, optimization and monitoring of high safety pillars for the underground excavation of natural stone blocks.

Keywords

natural stone, high safety pillars, room-and-pillar mining method, underground mining, quarry

1 INTRODUCTION

The underground excavation of natural stone blocks is not an idea generated by the modern information society; it dates back to the times of the ancient Romans. Evidence found in South East Britain, in the county of Devon [11], i.e., in the now abandoned Beer quarry, which has been converted into a museum, shows us that the underground excavation of natural stone blocks was done here, even B.C., by the ancient Romans. In Europe, the underground excavation of natural stone blocks is nowadays mostly done in several quarries in Italy (Carrara, the Apuan Alps, Bolzano, etc.), Great Britain (Avon, Somerset, Dorset, etc. [2, 13]), Greece (Dionysos - Athens), Portugal (Solubema - Lisbon), Croatia (Kanfanar - Pazin), etc.

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, and in 2002 it was also implemented at the Lipica II limestone quarry.

The Marmor Hotavlje (MH) company, 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 1800s. Natural The natural stone found here, the so-called “Hotaveljčan” limestone, is colourful (grey, red, pink, and sometimes almost black) and has white calcite veins as well as the remnants of individual corals and algae [14]. The MH management decided to introduce underground excavation, primarily due to the geological structure of the site, the 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 II quarry in 1986. The Lipica II quarry excavates two types of natural stone, which were named by the

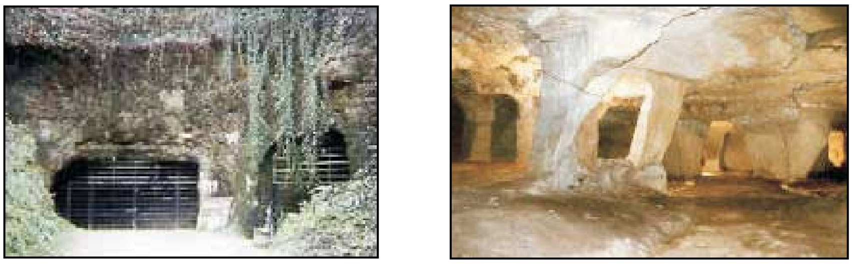

Figure 1., 2. Underground excavation of natural stone at the old Beer quarry [11].

Karst stone-cutters as “Lipica Unito” (homogenous stone) and “Lipica Fiorito” (rose stone) [15]. 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, the Lipica II quarry also decided on a trial underground excavation of natural stone blocks in 2001 and introduced it in 2002.

In both 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. Since in both cases the underground excavation is done at a relatively shallow depth of about 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 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.

Figure 3., 4., 5. The Hotavlje I quarry, limestone so-called “Hotaveljčan” (grey, pink, red).

Figure 6., 7., 8. The Lipica II quarry, “Lipica Unito” (homogenous stone) and “Lipica Fiorito” (rose stone).

2 PLANNING AND OPTIMIZATION OF THE ROOM-AND-PILLAR MINING METHOD

In many underground quarries for the excavation of natural and technical stone, a modified room-and-pillar method is used, which is adjusted to the conditions of the site. It employs regularly (Figure 9) or irregularly spaced safety pillars that have as small as possible width-to-height ratios r [6]. This type of mining method enables the use of self-supporting rock as the support element, which is achieved by forming safety pillars of the appropriate dimensions during the excavation in order to ensure the stability of the hanging wall on the ceiling and the required span of open spaces between these pillars for safe access and operation of an underground excavation site. In planning the dimensions (the surface area and the height) of the safety pillars as well as the span of the open spaces (rooms) between them, mining engineers usually have to strike a balance between the requirements of the mining rights' owner, i.e., the client who has commissioned the excavation project, and the demands for the maximum possible yield of natural stone blocks, on the one hand, and the need to ensure a certain level of safety that is still adequate, on the other [9]. This is because, due to the limited amount of natural stone available at any site, the largest possible dimensions of open underground spaces and the smallest dimensions of the safety pillars are needed in order to obtain the maximum volume of natural stone blocks, although this also tends to reduce the safety of the underground spaces in an inverse proportional manner. By reducing the base dimensions of the safety pillars, their strength is reduced as well, while the loads and the risk of overloading the safety pillars increase in an inversely proportional manner [10].

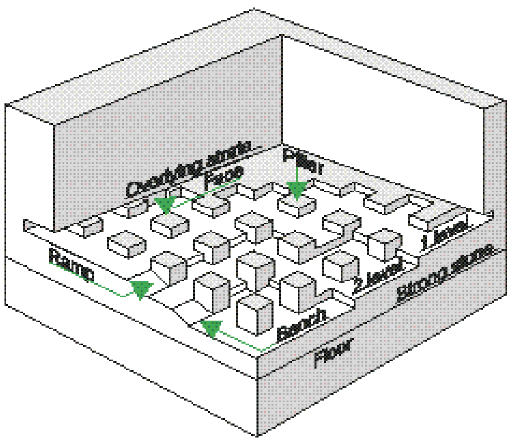

Figure 9. Typical room-and-pillar layout with regularly spaced pillars for non-metal (stone) mines.

The stability of the ceiling of large underground spaces and the safety pillars in them depend primarily on the quality of the geomechanical properties of the rock and the intensity of the tectonic activity at the site. Differences in stability occur due to the different mass mass-to to-volume ratios of the rock, the different loads created by the overburden and the different tectonic activities. This necessitates detailed planning of the excavation and the implementation of appropriate support measures in order to ensure safe working conditions. Therefore, the geomechanical properties of the rock, the primary stress state pz of the hanging wall and the tectonics of the site need to be known in detail in order to ensure the safe and stable excavation of natural stone blocks.

In the case of the underground excavation of natural stone blocks at the Lipica II and Hotavlje I quarries, the use of a modified room-and-pillar method adapted to the two sites is planned, with irregularly distributed high safety pillars and a width-to-height of $r < 1$ ($r = W_p/h$).

2.1 DETERMINING THE DIMENSIONS OF HIGH SAFETY PILLARS WITH LOW WIDTH WIDTH-TO TO-HEIGHT RATIOS

The strength of the safety pillars primarily depends on the strength of the rock and the value of a pillar's width-to-height ratio. Any reduction in the width-to-height ratio may cause a reduction in the total strength of a safety pillar. In existing underground mines of natural and technical stone, including the Lipica II and Hotavlje I quarries, the following common characteristics have been observed concerning safety pillars with a low width-to-height ratio (recommendations) [16]. The initial height of the safety pillars usually amounts to 4.5 m, but with deepening of the underground spaces it increases (3.0 m); in places it may reach values of up to 18.0 m or even more. Already, thin safety pillars are usually further weakened by each deepening of the basic level due to a reduction of their basic horizontal cross-section; they may collapse if the strength is reduced below the respective permissible limit due to a reduction in the value of the pillar's width-to-height ratio *r*. High safety pillars are those in which the value of the width-to-height ratio is $r < 1$.

Initially, the stable safety pillars may become unstable with a gradual deepening of the basic panel. In many underground mines of natural and technical stone, deepening of the panel was stopped exactly because of the worsening of the condition of the rock in the deepened panels. The weakening or collapse of a single safety pillar may cause a chain reaction because it overloads the neighboringneighbouring safety pillars and leads to

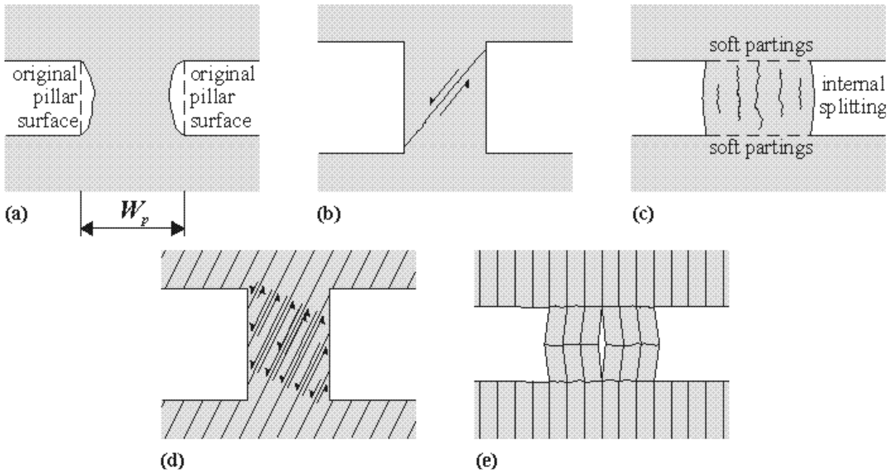

Figure 10. The dominant safety-pillar rupture mode involves; (a) spalling from the pillar surfaces, (b) shear fractures transecting the pillar, (c) lateral bulging or barrelingbarrelling of the pillar surface, (d) a pillar with set of natural transgressive fractures, (e) a pillar with a developed foliation or schistosity parallel to the principal axis of loading (formation of kink bands) [5].

settlement of the entire area of hanging rock above the pillars. This risk is especially high with thin safety pillars.

Safety pillars whose width-to-height ratio is gradually reduced during excavation are especially sensitive to being weakened by transverse or vertical discontinuities (cracks or fractures). The geomechanical conditions in underground mines for natural and technical stone are normally very good, but they may quickly deteriorate because of an unexpected appearance of discontinuities, especially in the case of thin safety pillars (see figure 10).

2.2 DETERMINING THE LARGEST SPAN OF OPEN SPACES (ROOMS) BETWEEN SAFETY PILLARS

Due to the increasing needs for raw materials and the desire to lower the excavation costs, mining companies tend to require an increase in the span of open, underground spaces. Because of the different geological conditions in individual quarries of natural and technical stone, the ceilings of large open rooms are most often composed of one or several layers of rock that may be parallel or inclined with respect to the surface. The stability of the ceilings in open spaces primarily depends on the geomechanical properties of the rock, the loading of the ceiling caused by the overburden (arch), and the tectonic conditions at the site. The usual spans of the open spaces in underground quarries of natural and technical stone amount to about 13.0 m, but they may be as high as 18.0 m. They also depend on the minimum dimensions of the excavation equipment (primarily the diamond diamond-belt sawing machine and the recommended dimensions of the natural stone blocks required for further processing [12]. With an increase in the span, the stability of the ceiling in an underground open space decreases because:

- the bending stresses cause bending and twisting of the ceiling and lead to the appearance of shear cracks,
- an increase in the bending and shear stresses within the ceiling may also cause critical damage to the intact rock or lead to the ceiling's collapse,
- there is a higher probability that the ceiling of an underground space will be perforated by open dikes.

As is the case with the planning of the dimensions of safety pillars, here as well one relies on practical experience acquired with the already-used ceiling spans in existing underground spaces, i.e., the trial-and-error approach. Methods to determine the appropriate spans of the ceiling of the underground spaces in quarries of natural and technical stone for various locally specific rock conditions and stress states are still in their initial stages of development. The methods most often used nowadays are, therefore, those which have been developed for coal mines and metal mines, while the actual conditions applying to the underground excavation of natural and technical stone are taken into account only indirectly.

In the planning of the underground excavation of natural stone blocks using the room-and-pillar excavation method, it is also important to determine the

Table 1. Calculation of the natural stone yield for the correct distribution of the predicted safety pillars for the Hotavlje I and the Lipica II quarry.

W_{p1} [m]	W_{p2} [m]	2Dmodel W^*_{p1} [m]	W_{r12} [m]	Pillar 'A' area [m²]	Tributary area [m²]	Extraction/ Yield ratio [/]	Width-to-height ratio *r* h=4.5m/7.5m/10.5m [/]
16.8	16.8	8.4	16.8	282.24	846.72	1 : 3.0	3.73/2.24/1.60
16.8	14.0	7.6	16.8	235.20	799.68	1 : 3.4	3.73/2.24/1.60
14.0	14.0	6.4	16.8	196.00	752.64	1 : 3.8	3.11/1.87/1.33
14.0	14.0	7.0	14.0	196.00	588.00	1 : 3.0	3.11/1.87/1.33
14.0	11.2	6.2	14.0	156.80	548.80	1 : 3.5	3.11/1.87/1.33
11.2	11.2	5.0	14.0	125.44	509.60	1 : 4.1	2.49/1.49/1.07
11.2	11.2	5.6	11.2	125.44	376.32	1 : 3.0	2.49/1.49/1.07
11.2	8.4	4.8	11.2	94.08	344.96	1 : 3.7	2.49/1.49/1.07
8.4	8.4	3.6	11.2	70.56	313.60	1 : 4.4	1.87/1.12/0.80
8.4	8.4	4.2	8.4	70.56	211.68	1 : 3.0	1.87/1.12/0.80
8.4	5.6	3.4	8.4	47.04	188.16	1 : 4.0	1.87/1.12/0.80
5.6	5.6	2.2	8.4	31.36	164.64	1 : 5.3	1.24/0.75/0,53
5.6	5.6	2.8	5.6	31.36	94.08	1 : 3.0	1.24/0.75/0,53

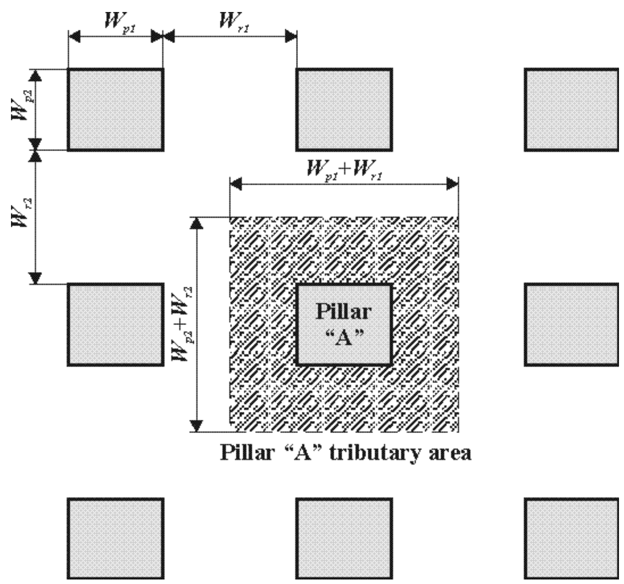

Figure 11. Regular distribution of safety pillars [5].

appropriate dimensions (width and height) of the large open spaces (galleries, transverse roads/crosscuts, niches and rooms) and the high safety pillars (see Figure 11) in order to achieve the optimal natural stone yield ratio (utility value). Table 1 presents the yields for different dimensions of pillars and open spaces. In practice, the yield ratios of 1 : 4.4 and 1 : 4.1 were found to be potentially the best for high safety pillars with respect to the mechanical properties of the rock.

3 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 then compared to the average value of the rock's strength (see Figure 12).

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 [5]. The average axial pillar stress level σ_p [19];

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

where

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

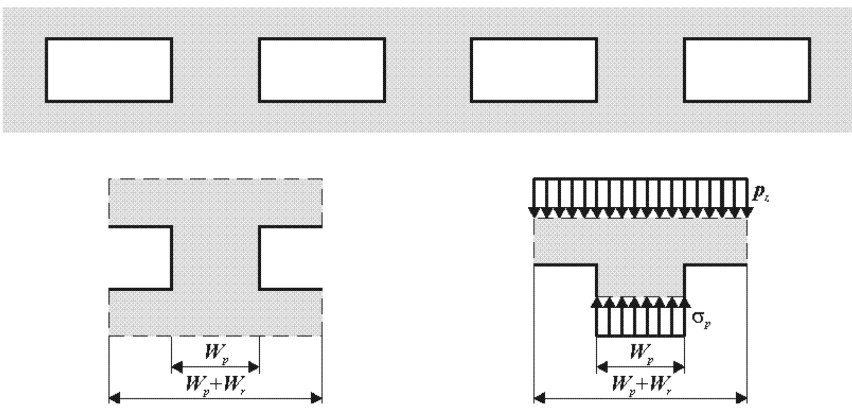

Figure 12. Cross-section over a horizontally positioned productive layer of uniform thickness, which is excavated by forming long rooms with a width of W_r and intermediary pillars with a width of W_p [5].

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 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 stem from an inability to extend these equations beyond the specific material properties, sizes, shapes and overburdens found in the survey data. Bieniawski wrote that the strength of safety pillars depends upon three elements [4]:

- 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 [8], empirical formulas have largely been derived from some form of the following power equation for the safety pillar's strength S_p,

$$S_p = \sigma_c \cdot \frac{W_p^a}{h^b} \qquad (2)$$

where

S_p	[MPa]	the pillar's strength
σ_c	[MPa]	the pillar rock's uniaxial compressive strength
h	[m]	the pillar's height
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 to calculate the pillar's strength.

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

Source	a	b	Subject medium
Hedley and Grant (1972) [7]	0.5	0.75	Quartzite pillars; Uranium mines near Elliot Lake, Canada; for w/h < 4.5
Stacey and Page (1986) [18]	0.5	0.70	

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 is required (2). 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 [9]. In other words, at some point the pillar would begin to display some plastic behaviour [3]. Pillar stability is most endangered at low width-to-height ratios. As typical stone safety pillars reach a width-to-height ratio of $r > 1.5$ [9], they begin to exhibit an almost indestructible character.

Factor of safety F_s,

$$F_s = \frac{S_p}{\sigma_p} \geq 1{,}6 \qquad (3)$$

The low factor of safety provided by this prospective layout indicates that a redesign is necessary to achieve the required factor of 1.6 [5]. 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 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 of the pillar rock at a depth of 40 m below the surface. This is presented in Figure 14 (see next page).

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 finite-element method (FEM), difference method (FDM), the distinct distinct-element method (DEM), etc. The Fast Lagrangian Analysis of Continua (FLAC 2D) is a two-dimensional explicit finite finite-diferencedifference 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 [1].

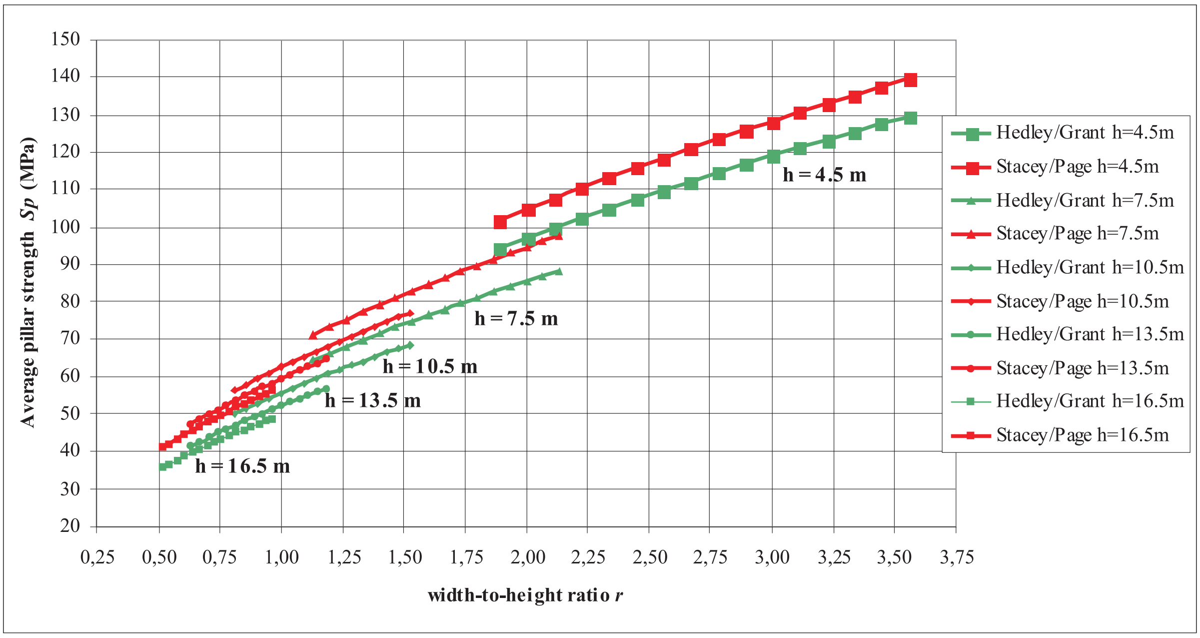

Figure 13. Comparison between the pillar's width-to-height ratio and the average pillar strength for several different empirical equations (table 2. on previous page) based on a power function (Rock uniaxial compressive strength σ_c=100 MPa).

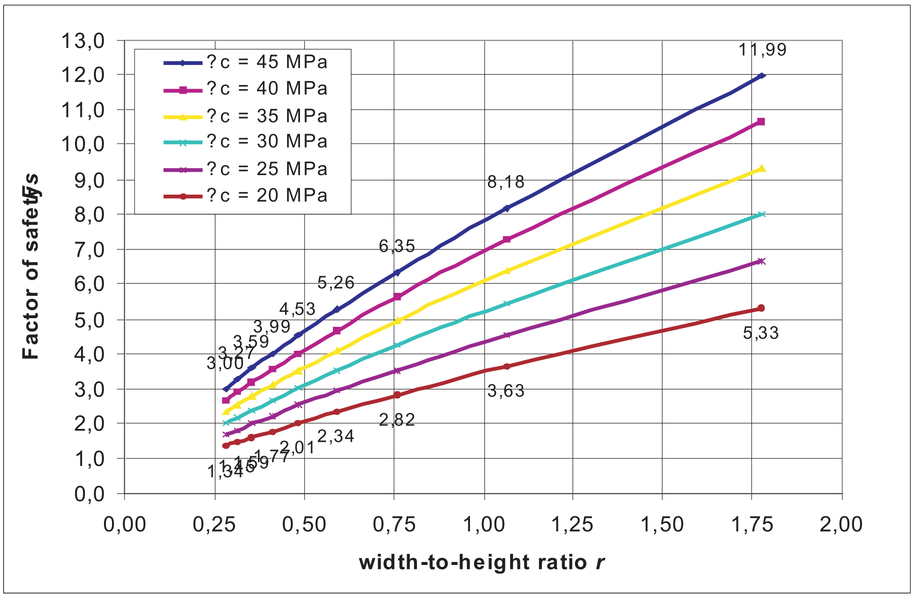

Figure 14. Factor of safety for shallow underground excavation spaces (thickness of overburden *H*=40 m, pillar width W_p=12m).

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, and to provide the geotechnical foundations for the planning dimensions in an underground excavation, along with continued surface excavation at the Lipica II quarry.

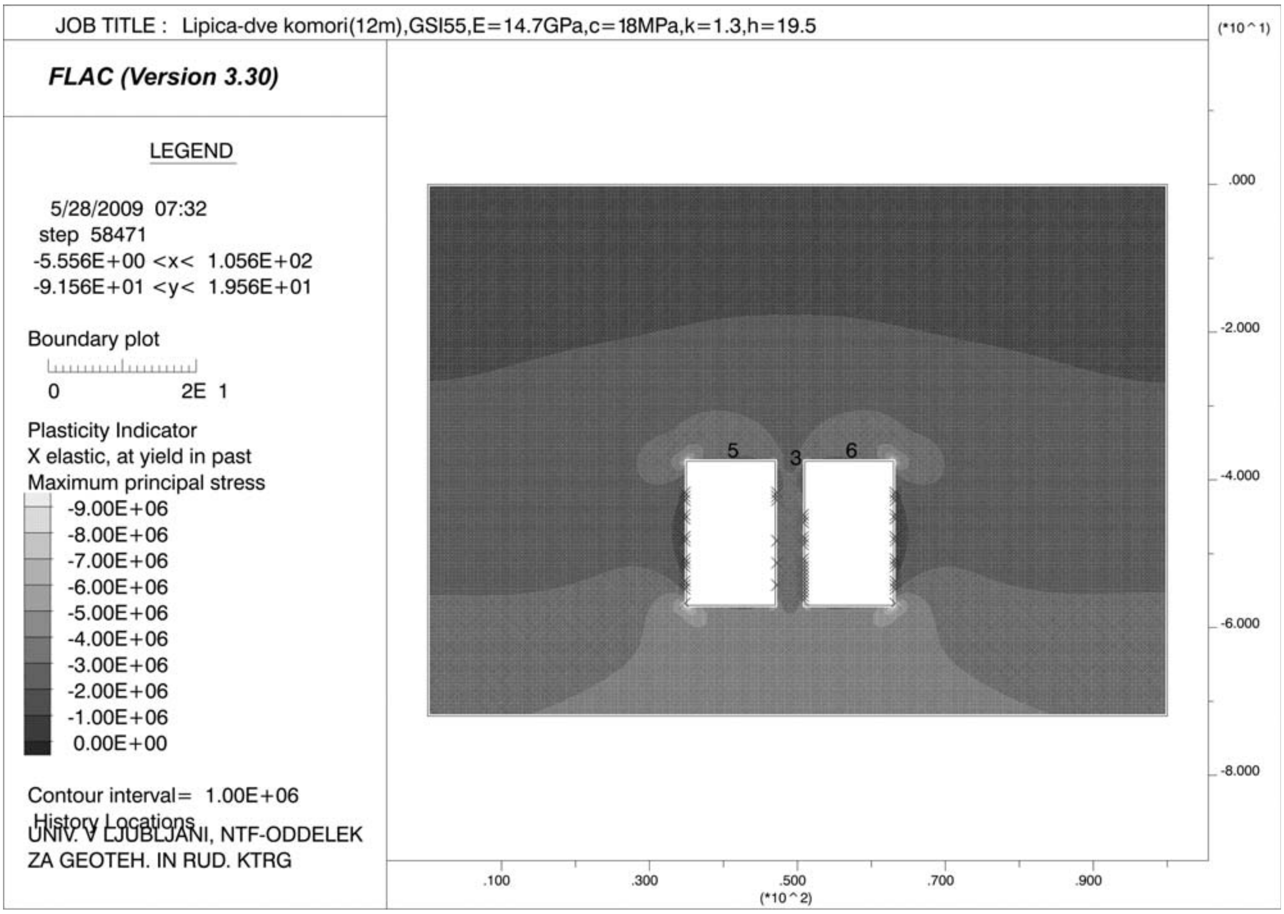

Figure 15. Stability analysis of the safety pillars using the FLAC 2D software package.

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 [8]. 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.

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 $F_s = 1.6$ 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.

Table 4. The following geomechanical properties were used in the models:

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 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

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 the 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. 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 [17].

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

Figure 16., 17. VW Biaxial Stressmeter and its position in the borehole.

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. 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 5.

Table 5. 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

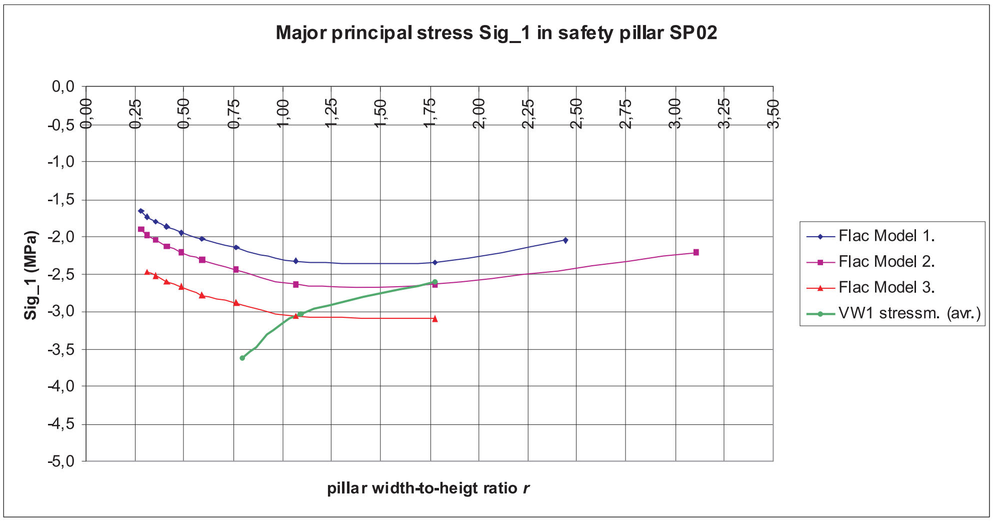

Figure 18. Comparison of measured and calculated (with the aid of numerical modelling) values of the primary vertical stresses Sig_1 in the SP02 safety pillar.

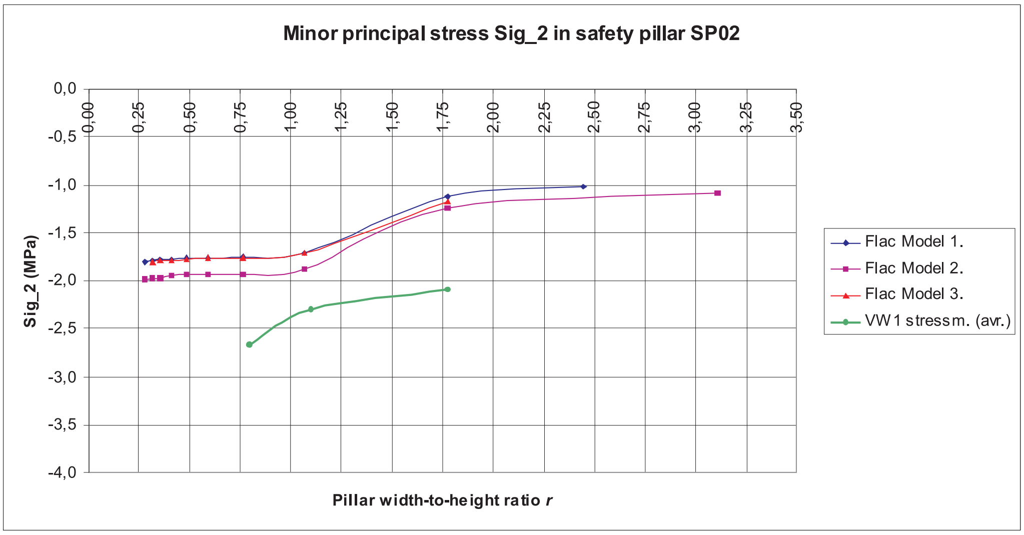

Figure 19. Comparison of measured and calculated (with the aid of numerical modelling) values of the primary horizontal stresses Sig_2 in the SP02 safety pillar.

With the reduction of the width-to-height ratio *r*, in-situ measurements of the stress state exhibit a trend of increase in the primary stresses. Even at the same width-to-height ratio *r*, the primary stresses in the SP02 safety pillar oscillate slightly due to temperature changes in the rock (summer/winter). The values measured in situ are within the range of the results obtained with analytical calculations and numerical modelling, while the results for the primary horizontal stresses deviate slightly. Up to a width-to-height ratio *r* = 1, the results of the in in-situ measurements of the stress state shown in Figures 18 and 19 remain within the range of the results obtained with numerical modelling. With the continued deepening, i.e., a reduction of the width-to-height ratio *r* < 1, in-situ measurements indicate a trend of greater increase of the primary stresses than were calculated during the numerical modelling. This necessitates additional analyses and prompt monitoring of the in-situ measurements during the continued deepening, i.e., a reduction of the width-to-height ratio *r*.

With a 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).

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 (Figure 21).

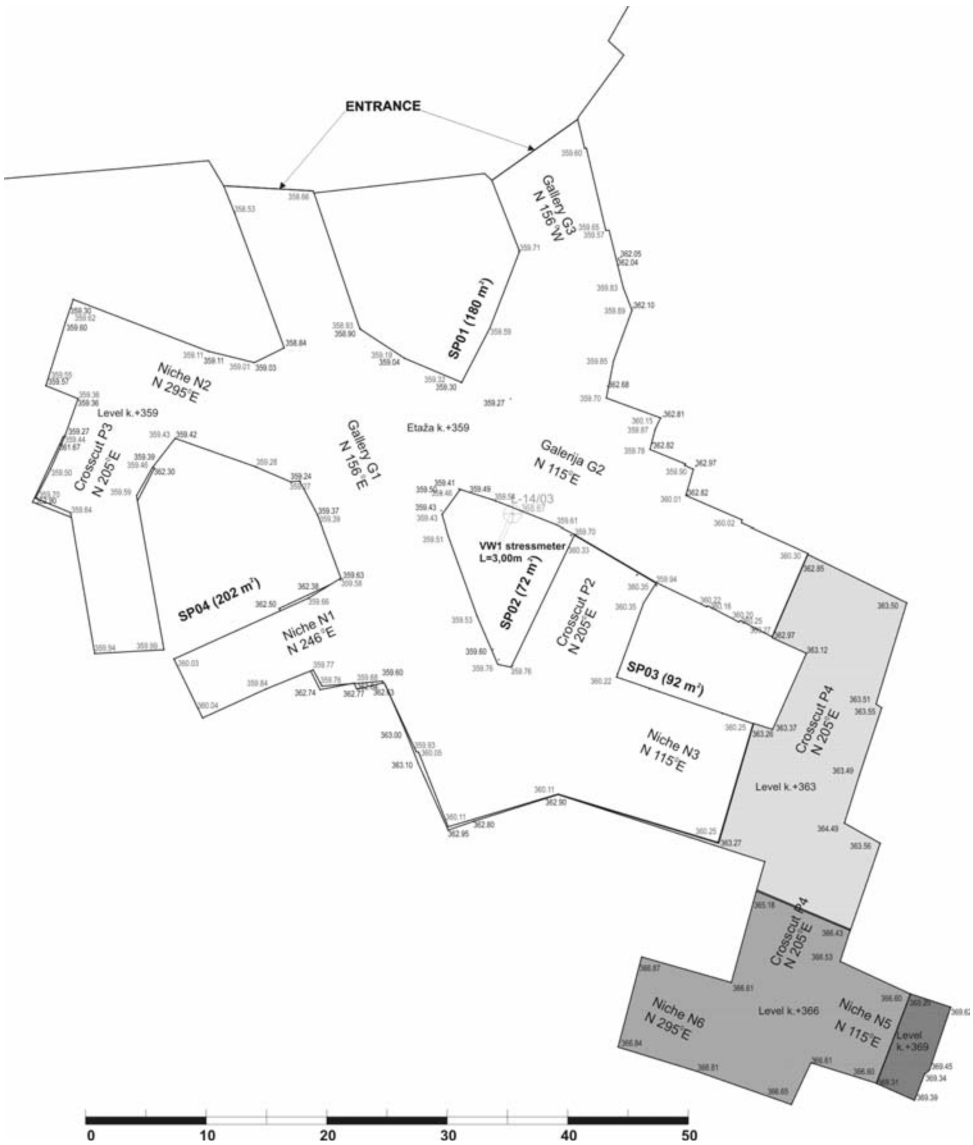

Figure 20. Plain view of the Lipica II underground quarry (VW1 – vibrating wire stressmeter, safety pillars SP01 to SP04).

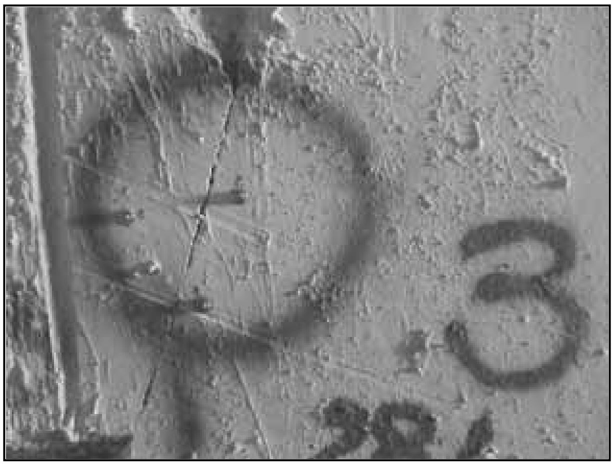

Figure 21. Manual measurement of the displacements of open dikes within safety pillars.

A dike dike-displacement meter consists of three screws installed along a dike and arranged in the form of a equilateral triangle (see Figure 20). 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 P2-to 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 Figure 20).

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.

5 CONCLUSIONS AND FUTURE PERSPECTIVES

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 quar ry in the SP02 safety pillar 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.

For the time being, no methodology is available for dimensioning high safety 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 beneficial 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 through the observational, analiticalanalytical 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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