Journal of Civil Engineering and Construction Technology Vol. 3(6), pp. 179-188, June 2012
Available online at http://www.academicjournals.org/JCECT
DOI: 10.5897/JCECT12.054
ISSN 2141-2634 ©2012 Academic Journals

Review

High safety pillars design for underground excavation of natural stone blocks

Joze Kortnik

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

Accepted 22 June, 2012

In existing underground mines of dimensional (natural) stone in Slovenia, including the Lipica II and Hotavlje I quarry, the geomechanical characteristics have been observed concerning safety pillars with a low width-to-height ratio. The initial height of safety pillars usually amounts to 4.5 m, but with deepening of underground spaces it increases by 3.0 m; in places, it may reach values of up to 25.0 m or even higher. 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 high safety pillars, along with continual monitoring and identification of instability phenomena in the ceiling and sides of large open spaces (rooms). The paper presents procedures for the planning, optimization and monitoring of high safety pillars for underground excavation of natural stone blocks.

Key words: Natural stone, high safety pillars, room-and-pillar mining method, underground mining, quarry.

INTRODUCTION

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

The Marmor Hotavlje (MH) Company as one of leading Slovene stone-cutting companies began organized excavation of natural stone at the Hotavlje I quarry in 1948, but the actual beginnings of excavation of natural stone blocks at the Hotavlje I quarry date back to the 1800's. Natural stone found here, the so-called "Hotaveljcan" limestone, is colourful (red, gray, pink, and sometimes almost black (Figure1b and c) and has white calcite veins as well as remnants of individual corals and algae (Hotavlje, 2008). The MH management decided to introduce underground excavation (Figure 1a) primarily due to the geological structure of the site, the condition of the quarry, large amounts of the overburden in the event of expansion of the surface part of the quarry, and increasing needs for natural stone as a raw material (Kortnik and Bajzelj, 2005).

Marmor Sezana, 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 (Figure 2a). The Lipica II quarry excavates two types of natural stone that were named by Karst stone-cutters as "Lipica Unito" [homogenous stone (Figure 2b)] and "Lipica Fiorito" [rose stone (Figure 2c)] (Sezana, 2008). In terms of size, the Lipica II quarry ranks among the largest Slovene natural stone quarries. For similar reasons as in the Hotavlje I quarry, the Lipica II quarry also decided on trial underground excavation of natural stone blocks in 2001 and introduced it in 2002.

In both quarries, underground excavation of natural stone blocks is done using the modified room-and-pillar excavation method that is adjusted to the characteristics of the sites with irregularly spaced safety pillars. Since in both cases 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. In planning of underground excavation, special attention therefore had to be paid to engineering-geological mapping, which was initially done for the external surfaces of the future area of underground spaces (that is, galleries, transverse roads and niches, and after deepening also rooms) and the structure of the

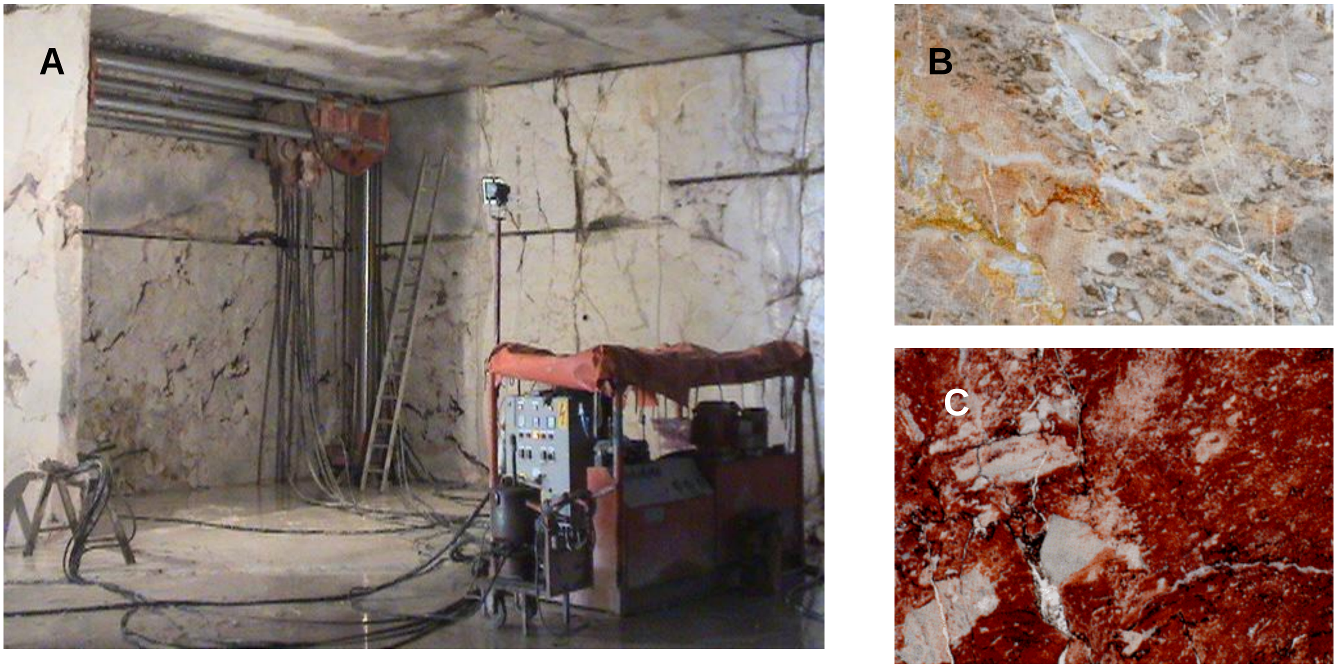

Figure 1. The Hotavlje I quarry (a), limestone so-called “Hotaveljcan” (gray, pink, red) (b and c).

Figure 2. The Lipica II quarry (a), “Lipica Unito” (homogenous stone) (b) and “Lipica Fiorito” (rose stone) (c).

productive layer. On the basis of these data, the predominant dike systems, which are important for the stability and consequentially also the safety of underground spaces, were determined.

HIGH SAFETY PILLARS WITH LOW WIDTH TO HEIGHT RATIOS

In the case of 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 $r < 1$ ($r = W_p/h$).

The strength of 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 quarry, the following common characteristics have been observed concerning safety pillars with a low width-to-height ratio (recommendations) (Mine Safety and Health Administration, 2005). The initial height of safety pillars usually amounts to 4.5 m, but with deepening of underground spaces it increases (3.0 m); in places, it may reach values of up to 18.0 m or even higher. Already thin safety pillars are usually further weakened by each deepening of the basic level due to the reduction of their basic horizontal cross-section; they may collapse if the strength is reduced below the respective permissible limit due to the 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 stable safety pillars may become unstable with the gradual deepening of the basic panel. In many underground mines of natural and technical stones, deepening of the panel was stopped exactly because of worsening of the condition of rock in deepened panels. The weakening or collapse of a single safety pillar may cause a chain reaction because it overloads the neighboring safety pillars and leads to 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 of 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 (Brady and Brown, 1985).

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 oriented into the research of safety pillars in coal mines, and 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 thinness. The thinner the pillar, the smaller its load-carrying capacity. Among methods used for planning safety pillars, the following two groups predominate:

Analytical methods: These are based on the mathematical principles of mechanical behavior of rocks and are computationally less difficult to execute. However, in spite of the possibility of fostering 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: These use modern numerical techniques and are computationally more demanding, are intended for modeling loads on safety pillars and presenting changes in rock stress and strain states. Furthermore, they enable the modeling of special conditions by taking into account faults and dikes, as well as the inclusion and assessment of the effect of weakened areas on overall stability. Nowadays, numerical models play a very important role in the planning of safety pillars for special conditions.

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

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

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

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

Where, W_{p1} [m]: pillar width; W_{p2} [m]: pillar length; W_{r1} [m]: gallery width; W_{r2} [m]: gallery length; ρ [kg/m^3]: density of overburden strata; G [m/s^2]: gravitational acceleration; H [m]: thickness of overburden; p_z [MPa]: vertical normal component of the pre-mining stress field.

Pillar 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

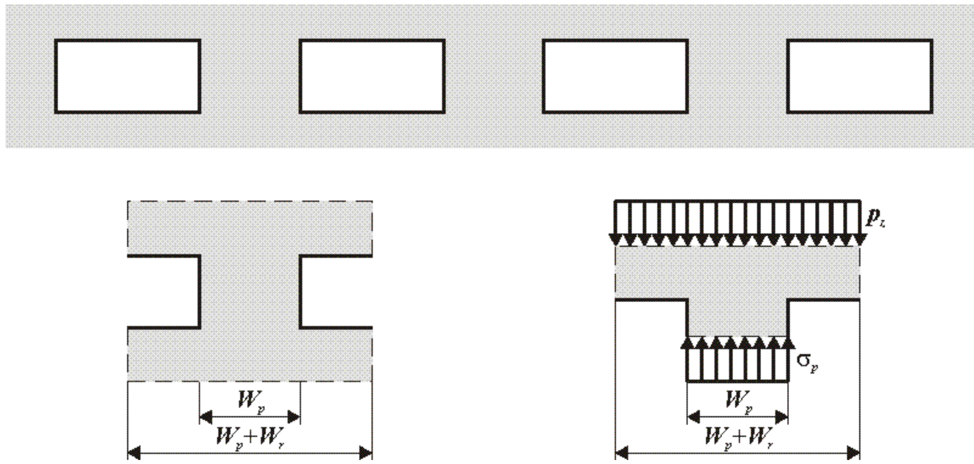

Figure 3. Cross-section over a horizontally positioned productive layer of uniform thickness, which is excavated by forming long rooms with a width of W_r and intermediary pillars with a width of W_p (Brady and Brown, 1985).

Table 1. Exponents determining pillar strength from its volume and shape (Equation 2).

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

these equations beyond the specific material properties, sizes, shapes and overburdens found in the survey data. Bieniawski wrote that the strength of safety pillars is depended upon three elements (Bieniawski, 1984):

1. the size or volume effect (strength reduction from a small laboratory specimen of rock to full size safety pillars).
2. the effect of pillar geometry (shape effect).
3. the properties of the pillar material.

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

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

where, S_p [MPa]: pillar strength; σ_c [MPa] pillar rock uniaxial compressive strength; H [m]: pillar height; *a, b* [/]: exponents determining pillar strength from its volume and shape (Table 1). This equation considers both material strength and safety pillar shape to calculate pillar strength.

In planning of underground excavation of natural stone blocks using the room-and-pillar method, cautious use of the results of empirical equation is required Bajzelj et al., 1999). At low width-to-height ratios ($r < 1$), pillar strength rises rapidly (Figure 4). At higher width-to-height ratios ($r > 1$), strength increases occur at diminishing rates (Esterhuizen et al., 2008; Iannacchione, 1999; Iannacchione and Prosser, 1997). 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. As typical stone safety pillars reach a width-to-height ratio of $r > 1.5$ (Iannacchione, 1999; Iannacchione and Prosser, 1997), 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 redesign is necessary to achieve the required factor of 1.6 (Brady and Brown, 1985). The options are to reduce the room span, thereby reducing the pillar stress level, to increase the pillar width, or to reduce the pillar (and mining) height. The selection of an appropriate safety factor can be based on a subjective assessment of pillar performance or statistical analysis of 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

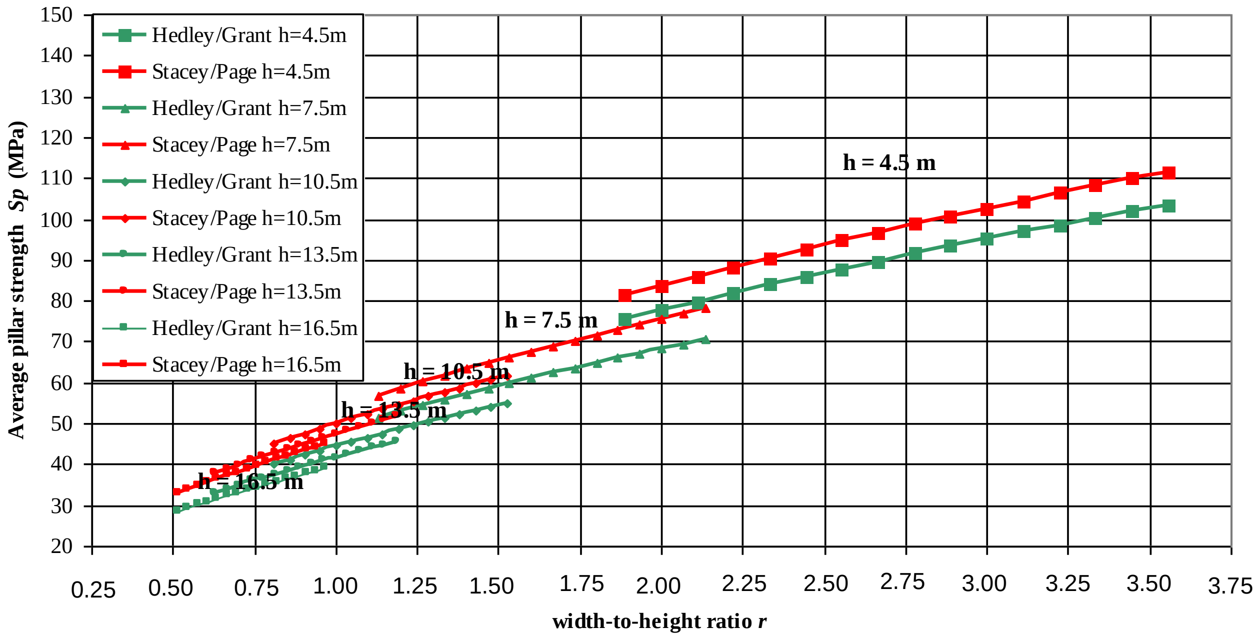

Figure 4. Comparison between pillar width-to-height ratio and average pillar strength for several different empirical equations (Table 1) based on a power function (rock uniaxial compressive strength σ_c = 100 MPa).

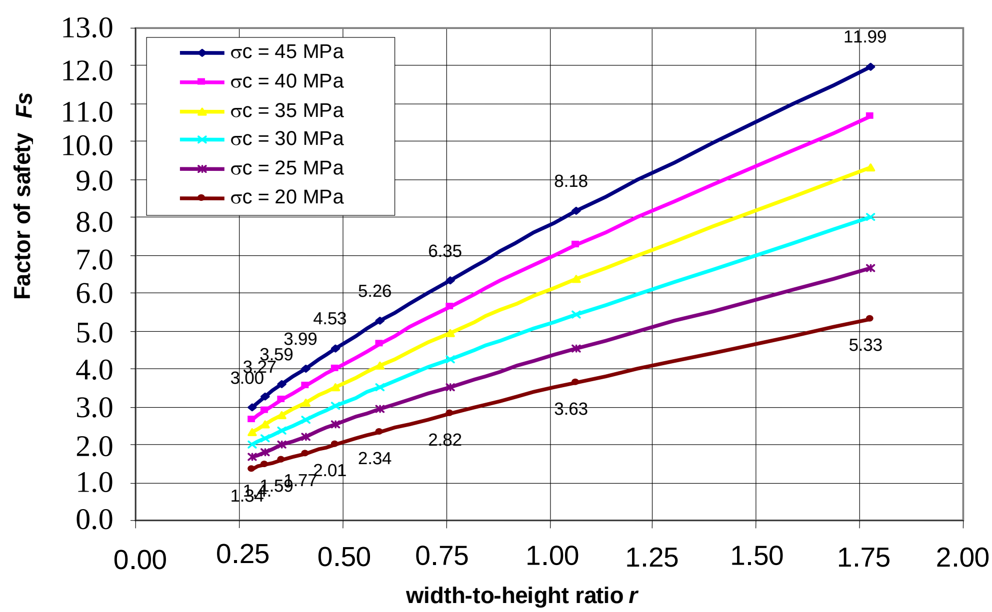

Figure 5. Factor of safety for shallow underground excavation spaces (thickness of overburden H = 40 m, pillar width W_p = 12 m).

relationship between F_s and 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 uniaxial compressive strength of the pillar rock at a depth of 40 m below the surface and it is presented in Figure 5.

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

Nowadays, various program packages are available for

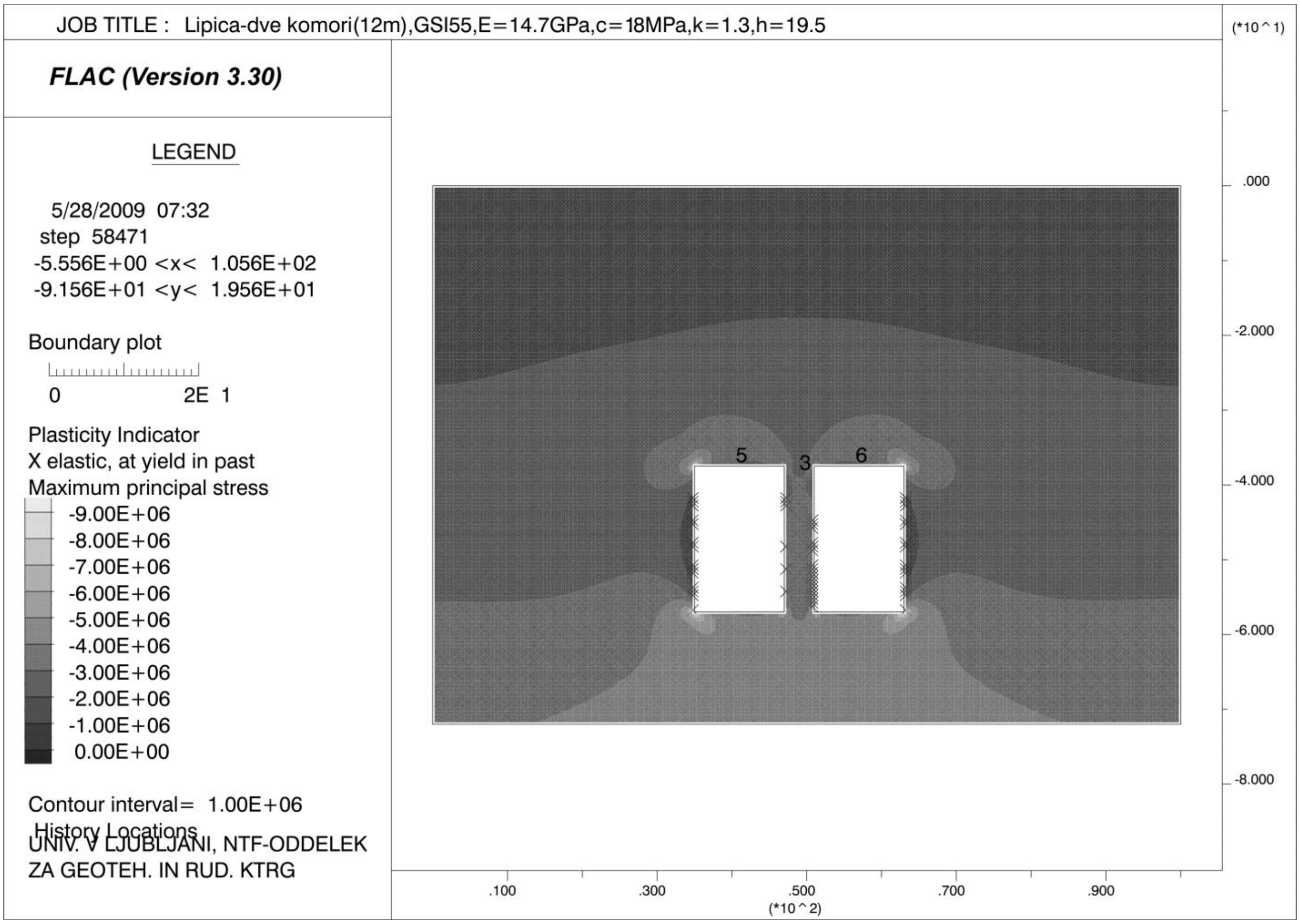

Figure 6. Stability analysis of safety pillars using the FLAC 2D software package.

numerical analyses of the stability of safety pillars and ceilings of open underground spaces (FLAC 2D, FLAC 3D, PLAXIS, itd). They are based on the finite element method (FEM), finite difference method (FDM), 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 surrounding roof and floor conditions on stone safety pillar strength (Anon, 1998).

For numerical analysis, the FLAC 3.3 software package was used. The purpose of numerical analysis was to determine the stability of planned dimensions of underground rooms, to make a comparison between 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 planning dimensions in underground excavation, along with continued surface excavation at the Lipica II quarry (Figure 6).

According to data from literature, the ratio of the horizontal to 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 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 horizontal stress σ_h is greater than that of vertical stress σ_v (Hoek and 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 or 36 m. The value of 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, 15, 16 and 20 m in compact and failed limestone. Geomechanical properties used in the models are presented in Table 2.

Based on the modelling results, it was concluded that:

1. 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

Table 2. The following geomechanical properties were used in the models.

Parameter	Compact limestone Model	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

Figure 7. VW biaxial stressmeter.

properties of compact limestone are used; if those of failed limestone are taken into account, then up to the width-to-height ratio of *r* = 0.48.

2. 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 the width-to-height ratio of *r* = 0.76.

3. 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.

4. The models showed that galleries-rooms with a width of 13, 15 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 the 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.

IN-SITU CONTROL MEASUREMENTS

In-situ control measurements for the room-and-pillar mining method include measurements of the stress state as well as the strains within safety pillars and in ceilings of large open underground spaces. To perform control measurements of changes in the stress state of high safety pillars, a 2D stressmeter (VW (vibrating wire) biaxial stressmeter model 4350-1 (Figure 7) manufactured by Geokon was used to monitor the main stresses in a single vertical plane perpendicular to the axis of the drill hole (Figure 8). 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 the maximum external diameter of 57.1 mm (Instruction manual Model 4350BX Biaxial stressmeter, 2008).

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

Figure 8. VW biaxial stressmeter position in the drill hole.

Table 3. Average measured values of the main stresses in the Lipica II quarry 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

(the PC200W software package). Data capture is done automatically, using the time interval set in the program (1, 60 or 240 min).

The VW1 stressmeter used to monitor the changes in primary stresses in the vertical plane perpendicular to the axis of the drill hole was installed in the Lipica II quarry safety pillar SP02. The site of stressmeter installation corresponds to the site of monitoring the primary stresses in the numerical model for the case of deepening of gallery pairs. The results of measurements of the stress state in the Lipica II quarry safety pillar are shown in Table 3.

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 Lipica II quarry 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 by analytical calculations and numerical modelling, while the results for the primary horizontal stresses deviate slightly. Up to the width-to-height ratio *r* = 1, the results of *in situ* measurements of the stress state shown in Figure 9 remain within the range of the results obtained by numerical modelling. With continued deepening, that is, 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 numerical modelling. These necessitates additional analyses and prompt monitoring of *in situ* measurements during continued deepening, that is, reduction of the width-to-height ratio *r*.

With a reduction of the width-to-height ratio *r,* the ratio of vertical to horizontal components of the primary stresses in the safety pillar is within the range of 1.24 to 1.35 (1.30).

CONCLUSIONS

In the planning of 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.

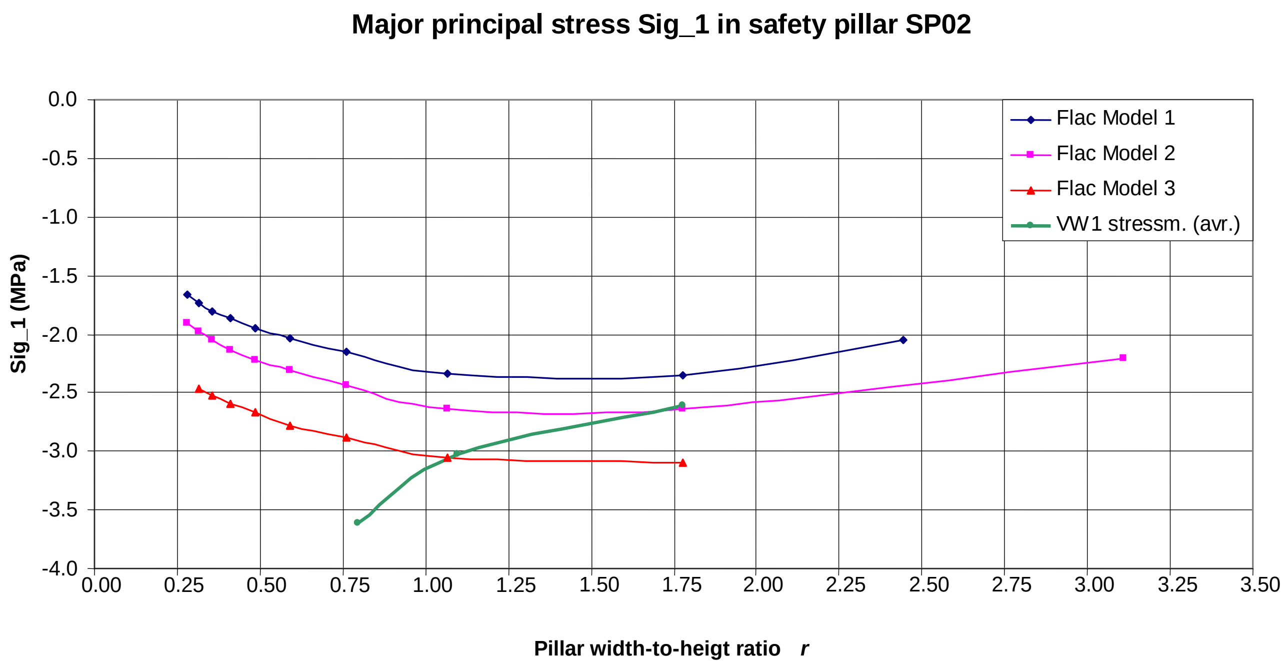

Figure 9. Comparison of measured and calculated (with the aid of numerical modelling) values of primary vertical stresses Sig_1 in the Lipica II quarry safety pillar SP02.

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 (Kortnik, 2009).

The results of analytical calculation and numerical modelling showed that in the case when the geomechanical properties of compact limestone were taken, a gallery-room with a width of up to 13 m is stable up to the 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 the 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 numerical modelling. The measurements of dike displacements also do not indicate any displacements of the sliding surfaces in the area of open dikes in the Lipica II quarry safety pillars.

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 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 which are suitable for its use. The pillar design guidelines developed throught the observational, analitical and numerical simulations discussed above will require further field confirmation. This approach can help to form a part of comprehensive pro-active mine safety ground control plan for underground natural stone mines.

REFERENCES

Anon (1998). FLAC: Fast Lagrangian Analysis of Continua User's Guide. Itasca Consulting Group, Inc., Minneapolis.

Bajzelj U, Kortnik J, Petkovsek B, Fifer K, Begus T (1999). Okolju prijazno podzemno pridobivanje naravnega kamna. RMZ 46/2, pp. 203-214.

Barron K (1984). An Analytical Approach to the Design of Coal Pillars, CIM Bull. 77(868):37-44.

Bieniawski ZT (1984). Rock Mechanics Design in Mining and Tunneling, Balkema, Rotterdam, pp. 193-209.

Brady BHG, Brown ET (1985). Rock Mechanics for Underground Mining, George Allien&Unwin (Publisher) Ltd., pp. 316-350.

Esterhuizen GS, Dolinar DR, Ellenberger JL (2008). Pillar Strength and Design Methodology for Stone Mines, Proceedings of the 27th International Conference on Ground Control in Mining, Morgantown, West Virginia University, pp. 241-253.

Hedley DGF, Grant F (1972). Stope-and-Pillar Design for the Elliot Lake Uranium Mines. CIM Transaction, 75: 121-128.

Hoek E, Brown ET (1997). Practical Estimation of Rock Mass. Int. J. Rock Mech. 34(8):1165-1186.

Iannacchione AT (1999). Pillar Design Issues for Underground Stone Mines, Proceedings of the 18th International Conference on Ground Control in Mining, Morgantown, West Virginia University, pp. 271-281.

Iannacchione AT, Prosser LJ (1997). Roof and Rib Hazard Assessment for Underground Stone Mines. SME Preprint 97-113, SME Annual

Meeting, Denver, CO, p. 5.
Instruction manual Model 4350BX Biaxial stressmeter (2008). http://www.geokon.com/.
Kortnik J (2009). Optimization of the high safety pillars for the underground excavation of natural stone blocks, Acta Geotechnica Slovenica, 1: 34-48.
Kortnik J, Bajzelj U (2005). Underground mining of natural stone in Slovenia, 20th World Mining Congress 2005, Iran, Tehran, pp. 277-286.
Hotavlje M (2008). web page: http://www.marmor-hotavlje.si/.
Sezana M (2008). web page: http://www.marmorsezana.com/.
Mine Safety and Health Administration (2005). web page: http://www.msha.gov/stats/.
Stacey TR, Page CH (1986). Practical Handbook for Underground Rock Mechanics, Series on Rock and Soil Mechanics, Trans Tech Publications, 12: 53-63.
Wagner H, Frömmer T (2004). Changing the Mining Method in an Austrian Magnesite Mine, Proceedings of the 20th World Mining Congress, Tehran, Iran, pp. 211-215.