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STRESSES AND DEFORMABILITY OF ROCK MASS UPON OPEN PIT EXPLOITATION OF DIMENSION STONE

Siniša DUNDA, Petar HRŽENJAK and Trpimir KUJUNDŽIĆ

Faculty of Mining, Geology and Petroleum Engineering, University of Zagreb, Pierottijeva 6, HR-10000 Zagreb, Croatia

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Sažetak

Pojava pojačanih naprezanja i deformacija stijenske mase u kamenolomu Zečevo (eksploatacijsko polje Selca - Brač) prouzročila je izrazito smanjenje iskoristivosti mineralne sirovine što je dovelo u pitanje opstanak kopa. Zbog toga je provedeno istraživanje i mjerenje stanja naprezanja i deformabilnosti stijenske mase unutar ležišta. Osim detaljnih laboratorijskih ispitivanja (ispitivanja na malim uzorcima), provedena su i probna istražna in-situ ispitivanja na velikim uzorcima, te odgovarajuće numeričke analize. Eksploatacija arhitektonsko-građevnog kamena s piljenjem pravilno oblikovanih pravokutnih blokova pokazala se pogodnom za in-situ ispitivanje čvrstoće na savijanje. U radu se prikazuju rezultati provedenih laboratorijskih ispitivanja, in-situ ispitivanja čvrstoće na savijanje uz mjerenje deformacija nakon izrade rezova, te numeričke analize pomoću kojih je utvrđen mogući raspon horizontalnih naprezanja. Budući da za slučaj masivnih stijena, za koje se primjenjuje koncepcija kontinuuma u praksi ne postoje posebno razrađene metode korekcija, prikazana je moguća relacija za korekciju vrijednosti ulaznih veličina, koja se temelji na provedenim laboratorijskim i in-situ ispitivanjima.

Key-words: Dimension stone, Quarrying, Stresses

Abstract

The appearance of increased stresses and deformability of rock mass in the quarry of Zečevo (exploitation field of Selca – island of Brač) has caused a considerable decrease of usability of mineral raw materials, which put into question the survival of the pit. Therefore the research and measurements of the state of stresses and deformability of rock mass within the pit were carried out. Besides detailed laboratory testings (testings on small samples) performed were trial in-situ testings on large samples including the corresponding numerical analyses. The exploitation of dimension stone by sowing regularly shaped rectangular blocks has been proved to be appropriate for in-situ testing of bending strength. The paper presents the results of carried out laboratory testings, in-situ testings of bending strength including measuring of deformations after sowing cuts and numerical analyses by which the possible range of horizontal stresses was determined. Since for the case of massive rocks, for which the continuum concept is applied, there are no specifically defined methods of corrections, presented is a possible relation for correction of input size values based on the carried out laboratory and in-situ testings.

Introduction

Final product of natural stone (dimension stone) excavations is a block i.e. regularly shaped rectangular parallelepiped monolith. Therefore, natural stone beds must have such a discontinuity fabric by which the gaps between tectonic discontinuities in rock mass are big and approximately parallel and vertical to each other. Rock masses are, as real geological setting, heterogeneous and cracked i.e. discontinuous. Cracked systems in rock mass are caused by singenetic, diagenetic and postgenetic processes, which cannot be influenced. Increased discontinuity resulting in increased quantity of excavated waste is often a consequence of inappropriate opening and development of a quarry or inappropriate selection of excavation technology. This is the reason why opening and development of a quarry and choice of excavation technology should be adapted to the discontinuity fabric of the bed to the maximum. However, even upon maximum adjustment of quarry development and site orientation to the natural discontinuity fabric it is possible that in a bed appear increased stresses, additional discontinuities and additional damages caused by exploitation, resulting in additional excavation waste. The appearance of uncontrolled development of cracks within rock mass upon open-pit exploitation of deeper bed parts of dimension stone in the quarry of Zečevo resulted in a number of technological problems, decreased utilisation of mineral raw materials and efficiency, which brought in the question of profitability of production and survival of the quarry. In order to find out the causes of the increased stresses and deformations of rock mass thorough laboratory testings, trial in-situ testings and corresponding numerical analyses were carried out.

Starting consideration

Dimension stone - rudist limestone of Upper Cretaceous Age, known under commercial name as San Giorgio, is excavated in open-pit in the quarry of Zečevo. The quarry has been opened and developed as hillside multi-bench quarry. The general principle of excavations is based on development of the quarry from top to bottom with successive advancement from upper to lower benches (Dunda et al., 1995). However, through frontal advancement on the upper benches the rock mass with thick intercalation of dolomite was penetrated. These layers present "rotten" rock mass, which is not regarded as natural stone. Therefore the exploitations in cracked and dolomite rock mass in the upper parts of the bed were stopped and the excavations were continued under the main working plateau containing quality rock without dolomites. This means that hillside excavations were replaced by pit excavations. Descending into the lowest bed parts without previous widening and complete development of the upper benches increased the “pressures of the hill” on these bed parts, causing larger stresses in the rock followed by its cracking, which do not enable the extraction of large quality blocks and increase the quantity of excavation waste. Therefore the research and measurements of the stress state and deformability of rock mass were carried out within the bed of Zečevo (Dunda et al., 2001). The aim of the research was to find the solution of state of stresses i.e. to determine the reasons of rock mass cracking in order to design a more useful working-out of bed and to apply the exploitation method which will enable better preservation and usability of rock mass. The research comprised: detailed laboratory testings, trial in-situ testings and corresponding numerical analyses.

Laboratory testings

The initial laboratory testings, conducted at the Faculty of Mining, Geology and Petroleum Engineering, comprised those of uniaxial compressive strength, tensile strength and the strength in triaxial stress condition. There were additional testings of bending strength. These results were later used for comparison with in-situ measurements with the goal to correct the input data. Testings were performed on two sets of samples with a vertical axis to the layers and on the set with a parallel axis to the layers. Each set included three testings of uniaxial compressive strength, three testings of strength in triaxial condition, five testings of tensile strength and five testings of bending strength.

Since in the quarry of Zečevo the conditions in the bed are complicated it was necessary to perform a detailed mineralogical and petrographical analysis of stone and testing of fracture toughness i.e. testing of rock resistance to creation and widening of cracks. All the testings were made according to the suggested

Table 1. Average results of laboratory testings
Tablica 1. Prosječni rezultati laboratorijskih ispitivanja

Type of testing	Axis of the sample vertical to the layers			Axis of the sample parallel to the layers		
	Medium value	Standard deviation	Variance	Medium value	Standard deviation	Variance
Uniaxial compressive strength and deformability of material						
Density (kg/m^3)	2614	3.682	13.556	2635	9.202	84.667
Uniaxial compressive strength (MPa)	85.230	5.746	33.014	118.216	21.314	454.279
Elasticity modulus (GPa)	58.259	7.414	54.973	68.580	8.690	75.512
Poisson's ratio	0.356	0.002	0.000	0.340	0.029	0.001
Tensile strength by the Brazil test						
Tensile strength (MPa)	8.840	1.509	2.278	8.583	1.396	1.948
Bending strength						
Bending strength (MPa)	19.105	0.846	0.716	20.761	1.032	1.065
Fracture toughness						
Fracture toughness (first level) ($MN/m^{1,5}$)	1.74	0.05	0.0026	1.80	0.01	0.0002
Fracture toughness (second level) ($MN/m^{1,5}$)	1.99	0.13	0.017	2.18	0.09	0.0087
Maximum force (first level) (kN)	2.53	0.09	0.0086	2.62	0.03	0.0011
Force by which fracture toughness is determined (second level) (kN)	2.38	0.10	0.0096	2.55	0.04	0.0015
Co-efficient of non-linearity	0.18	0.08	0.0069	0.22	0.04	0.0015
Elasticity modulus (GPa)	45.96	1.93	3.71	45.13	2.75	7.57
Resistance to crack widening (J/m^2)	77.99	8.63	74.44	92.60	6.96	48.43

methods of the International Society of Rock Mechanics (ISRM, 1985, 1988). The procedure of fracture toughness testing was conducted on two levels on specifically prepared samples (Kujundžić, 1997).

The first level of fracture toughness testings comprises the observation of maximum force, which appears in the moment of cracking and is used for the calculation of stress intensity coefficient, i.e. fracture toughness. The second level of testings comprises continuous measuring (observation) of force anddeflection and shifts up to and after appearance of the maximum force. If the deflection is not controlled, after application of the maximum force the crack in the sample begins to widen without control and the test becomes unstable. The testing of fracture toughness on both levels provided, besides fracture toughness, the modulus of elasticity upon bending and resistance to the widening of cracks, which was very important for understanding material behaviour.

The average results of testings of uniaxial compressive strength and deformability of material, tensile and bending strength are presented in Tab. 1. The same table includes the average results of fracture toughness, whereas the results of triaxial testings are presented in the Tab. 2.

Table 2. Results of laboratory triaxial testing
Tablica 2. Rezultati laboratorijskog troosnog ispitivanja

Density (kg/m^3)	Confining pressure (MPa)	Axial stress (MPa)
Axis of the sample vertical to the layers		
2611	3.932	162.286
2610	5.884	105.416
2609	7.845	174.769
Axis of the sample parallel to the layers		
2625	3.932	141.702
2639	5.884	185.866
2625	7.845	198.660

The obtained results of the testings showed some differences for variously oriented axis of the samples in relation to the layers. For instance, the largest difference was observed at uniaxial compressive strength, resistance to widening of cracks and modulus of elasticity. It is interesting that considerably higher values were obtained for the samples with their axis parallel to the layers. The largest difference between the results referring to the variance and standard deviation was observed in uniaxial compressive strength, resistance to crack widening and modulus of elasticity, acquired by uniaxial testing. Having compared the obtained results with the characteristics of other rocks (Ouchterlony et al., 1991) it was concluded that the stone in the quarry of Zečevo has a relatively high value of fracture toughness, which points to the large resistance of widening of cracks. Observed was also a relatively high value of elasticity modulus whereas uniaxial compressive strength had average values for limestones.

Trial in-situ testings

In order to get the best insight into the characteristics and behaviour of rock mass the crack systems were thoroughly analysed on excavation surfaces. Trial in-situ testings included testing of bending strength of the sewn blocks in rock mass and measuring of deformations after creation of cuts. The trial in-situ testing comprised similar procedures as those applied earlier in underground excavations in the quarry of Kanfanar (Hrženjak, 2001). This calculation is based on the console – block principle (Fig. 1), on which stress is applied aimed at breaking the final unsown side.

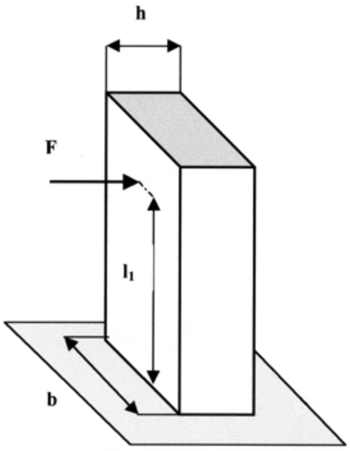

Figure 1. Principle of in-situ testing

Slika 1. Princip in-situ ispitivanja

The stress was made by means of water (stain) pillows, which are usually used upon dimension stone exploitations. After the cuts were sown by means of a chain saw, the dimensions of blocks and the position of the pillow were precisely determined and the pressures were realised upon which the breakage appeared. The active surface area of the pillow, which affects the block, is determined on the basis of its starting dimension and width of the cut, from which the sizes for forces were obtained. On the basis of the measured dimensions of blocks and strains the value of bending strength was calculated by the following formula (1):

$$S = \sigma_{\max} = \frac{M_{\max}}{W} = \frac{F \cdot l_1}{\frac{b \cdot h^2}{6}} = \frac{6 \cdot F \cdot l_1}{b \cdot h^2} \qquad (1)$$

In the quarry of Zečevo testings were performed on the blocks located on the main working plateau (Fig. 2, and 3), whereby the sides of the console base were approximately placed east-west or north-south.

Four blocks were sown with the total of 6 vertical cuts (Fig. 4) so that vertical blocks-console had dimensions 1.2x1.2x1.8 m.

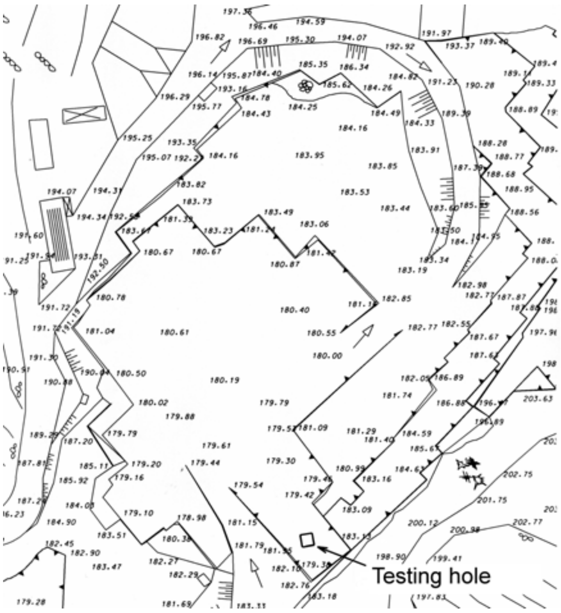

Figure 2. Position of in-situ testing

Slika 2. Položaj in-situ ispitivanja

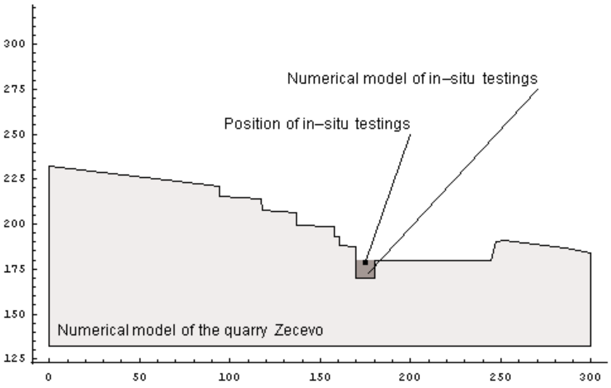

Figure 3. Position of in-situ testing and numercal models

Slika 3. Položaj in-situ ispitivanja i numeričkih modela

Besides, observation points for deformation measurements were placed on 8 locations, from which four (Z1/1, Z2/1, Z3/1, Z4/1) were measuring displacements on the walls of cuts and the remaining four (Z1/2, Z2/2, Z3/2, Z4/2) were measuring deformations of material within the block. The observation points were placed in the spans of 285 mm.

The observation measurements were conducted twice – two times on the starting position and two times after formation of the cuts. The results of deformation measurements after formation of vertical cuts are presented in Tab. 3.

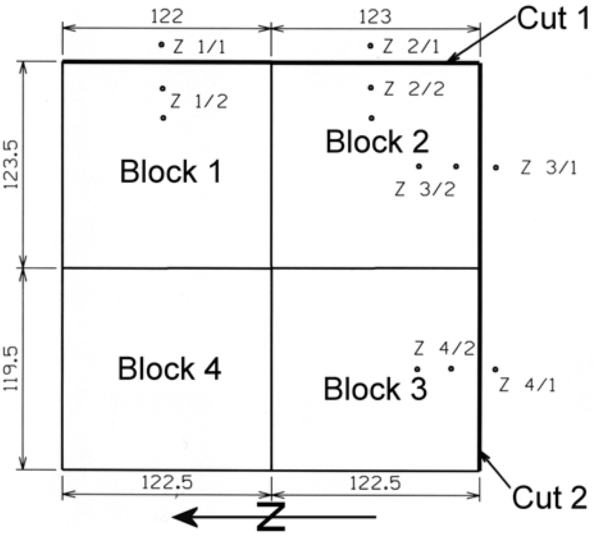

Figure 4. Setting of in-situ testing

Slika 4. Postava in-situ ispitivanja

Table 3. Results of the deformation measurements
Tablica 3. Rezultati mjerenja deformacija

Place of measuring	Measured horizontal displacement (mm)	Place of measuring	Measured horizontal deformation (mm)
Cut 1			
Z1/1	0.960	Z1/2	- 0.050
Z2/1	0.940	Z2/2	- 0.040
Average	0.950	Average	- 0.045
Cut 2.			
Z3/1	0.580	Z3/2	- 0.010
Z4/1	0.230	Z4/2	-0.010
Average	0.404	Average	- 0.010

Positive values refer to the figures of span decrease between the observation points compared to the set span, whereas the negative values refer to the span increase.

The presented results show that average closing of 0.95 mm appeared on the cut 1 and 0.405 mm on the cut 2. Since the measured deformations were twice bigger in direction vertical to the cut 1 (direction east-west) than in direction vertical to the cut 2, it is presumed that values of stresses within rock mass in those directions are in the same ratio.

Model selection and adjustment of input data

For block massive rocks with separate crack systems there are no specific correction methods of obtaining completely realistic values of input data. Therefore it was necessary to investigate possible relations for value adjustment of input data. In this process the importance of the values received in laboratory testings was realised. Finally, the reduction coefficient was proposed, defined by the ratio between in-situ acquired values and values acquired in laboratory testings (Hrženjak, 2001). Thus, the ratio comprised the values of bending strength, acquired in laboratory testings, and the values from in-situ measurements upon breaking of blocks. The obtained average value of in-situ bending strength amounted to 2.893 MPa. Since the obtained average value of laboratory testings amounted to 19.933 MPa the reduction coefficient of 0.145 was calculated.

$$k_r = \frac{S_{insitu}}{S_{lab}} = \frac{2{,}893}{19{,}933} = 0{,}145 \qquad (2)$$

whereby:
S_{insitu} - bending strength from in-situ testings
S_{lab} - bending strength from laboratory testings

During the testing of the blocks 2 and 3 they cracked upon very low applied force, under 0.3 MN. When the blocks were being extracted the reason of this breakage was found, which appeared due to natural crack, along which the block separated without breaking. The relatively low values of bending strength for the blocks 1 and 4 were achieved due to the same reason.

Numerical analyses

Numerical analyses were carried out for three separate cases. Firstly, numerical analyses were performed for the condition upon in-situ testings aimed at determination of approximate horizontal stresses in rock mass and approximate values of rock mass characteristics. The second analyses were performed for the entire condition in the quarry aimed at determination of optimum technological exploitation quantities. The third numerical analyses were performed for the condition upon opening i.e. unburdening of the bed aimed at obtaining optimum dimensions and crack advancement.

Numerical analyses of state of initial stress and deformation of the rock mass at in-situ testing

Taking into consideration a small number of data acquired in in-situ testings, the obtained values were not considered as real average values for rock mass, so that numerical analyses were carried out with different reduction values in the amounts of 0.145, then 0.3 and 1.0. The adjustments were not applied only on density and Poisson's ratio. Cohesion and the angle of internal friction were calculated by the Hoek-Brown strength criterion (Hoek, 1997). The adjusted values are presented in the Tab. 4.

Table 4. Adjusted values of input data
Tablica 4. Korigirane vrijednosti ulaznih podataka

Input data	Model 1 k=0.145	Model 2 k=0.3	Model 3 k=1
Density (kg/m^3)	2622	2622	2622
Uniaxial compressive strength (MPa)	14.749	35.475	101.723
Tensile strength (MPa)	1.263	2.322	8.711
Module of Elasticity (MPa)	9195	19025	63419
Poisson's ratio	0.348	0.348	0.348
Cohesion (MPa)	3.859	7.984	26.613
Angle of internal friction (°)	44.5	44.5	44.5

Numerical calculations by means of FLAC program (Itasca, 1998) were carried out numerical model 20×9 m to simulate the situation upon in-situ measurements on the cuts, on which displacements were measured (Fig. 5).

The total of nine analyses were performed. For each of the three models of material three cases were monitored with presumed initial horizontal stresses of 1MPa, 3MPa and 5MPa. Results of the numerical calculations are presented in the graph in the Fig. 6.

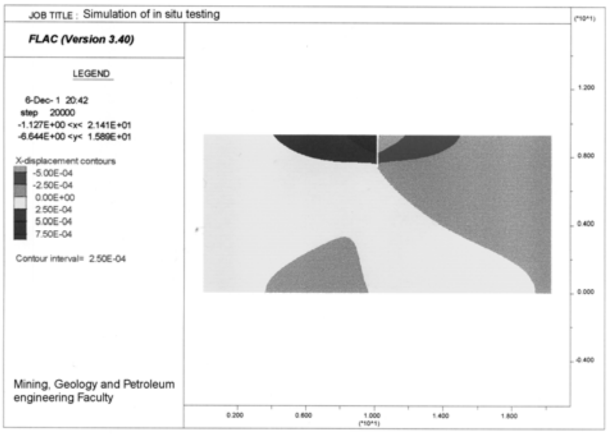

Figure 5. Solution for horizontal displacement of points on the cuts of the model 2

Slika 5. Rješenje za horizontalne pomake točaka na rezovima modela 2

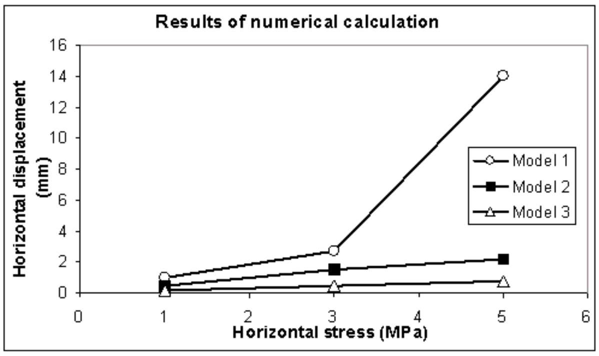

Figure 6. Graph presentation of the results of numerical calculations

Slika 6. Dijagramski prikaz rezultata numeričkih proračuna

The results of the calculation point to the appearance of plasticity and large displacements for the area of stress higher than 3 MPa in the model 1, whereas plasticity was not observed in other models. The solutions for the model 2, whose values were obtained by application of adjustment in the amount of 0.3 and horizontal stresses of 2 MPa, most probably show the real situation in the quarry, taking into consideration the values of displacements and stresses.

Numerical analyses of stress state of rock mass in the quarry of Zečevo

In order to perform exploitation in the quarry with as less losses as possible until completion of the second phase, analyses of stress state in rock mass of the quarry were carried out. By the previous mentioned in-situ testing and its numerical analyses the horizontal initial stress in rock mass of approximately 2 MPa was obtained on the working level i.e. current exploitation. These analyses showed that such a situation required, besides stresses caused by the weight of the massif itself, the activity of additional horizontal stresses too. For this level of horizontal stresses the calculation model must have an activity of additional horizontal stresses of 1.5 MPa. The solution of the condition of horizontal stresses for a characteristic profile, which is placed approximately in direction of a larger main stress, is presented in the Fig. 7.

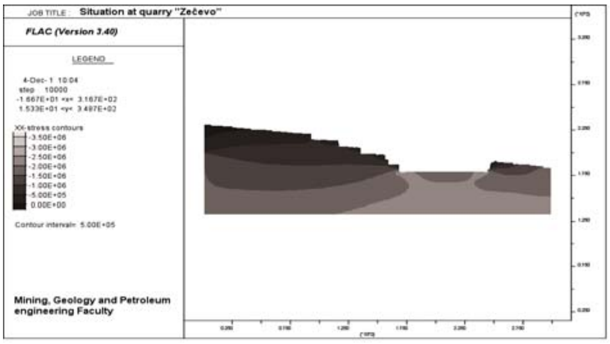

Figure 7. State of horizontal stresses in the quarry

Slika 7. Stanje horizontalnih naprezanja na kamenolomu

In order to adequately unload rock mass there was a plan to make excavation channels and unloading cuts vertical to the direction of activity of a larger main stress, in the approximate direction north-south. Considering the requirement to unload rock mass and the exploitation technology, numerical analyses have showed that optimum values of channels depth amount to approximately 12 m with their spans of approximately 12 m too. The solution of the analyses is presented in Fig. 8.

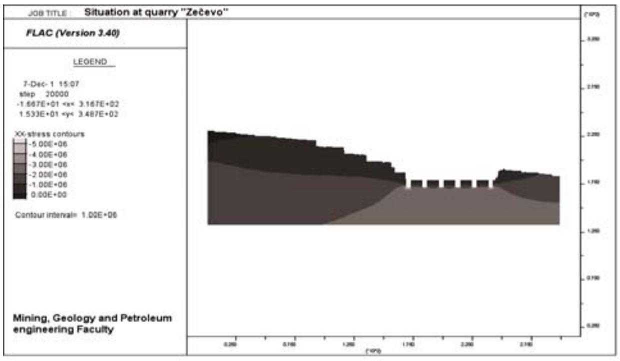

Figure 8. Solution for horizontal stresses after formation of unloading cuts

Slika 8. Rješenje za horizontalna naprezanja nakon izrade napadnih rezova

Numerical analyses of stress state of a rock mass in the channels for unburdening of rock mass and bed opening

These analyses were carried out in order to adequately design channels for unburdening rock mass and bed opening. The calculations were made for the so-called 'blind cut' of channels in the spans of 6, 9 and 15 m from the face of the channels with channel depths of 6 and 12 m. Primarily observed was the concentration of stresses on the very bottom of the cut and on the bottom of the face of the channel. This can cause stacking of a diamond wire upon cutting or development of cracks. Considering the state of stresses it has been concluded that the optimum spans of blind cuts were approximately between 9 and 12 m from the face of the channel for the channel depths of 6 to 12 m. Upon formation of channels or unloading cuts the way of sowing should be such that the cut "is pulled along" from the face towards the rock mass in order to "pull" the stress concentration into the rock mass as much as possible. One should also take into account that sowing is performed as symmetrically as possible i.e. that for example both cuts of the channel are made at the same time. Besides, it is important that sowing is performed continuously without stopping because there is a great possibility of squeezing in the cut. Upon formation of a blind cut sowing should be performed from the top (surface) downwards. Here it is also necessary to sow continuously (without stopping) because there is also a possibility of squeezing of the mass, especially on the bottom of the cut.

Conclusion

Numerical analyses have been adequately applied in the excavation of natural stone in the quarry of Zečevo too. The reason is greater efficiency of solving complicated engineering task by these methods, which is actually the result of development of numerical methods and increased understanding of behaviour of the rock materials. It has been proved that such understanding plays the most important role in selection of the appropriate calculation model, i.e. constitutional relations and evaluation of the values of input data. The technology of block extraction upon excavations of natural stone made possible the determination of in-situ bending strength. These measurements present a great help in solution of correction of the values achieved in laboratories. Since the sown blocks were separated by breaking of base plane by means of water (stain) compression pillows, the impact of force was on the console principle, so the force value could easily be calculated. Stress and bending strength were calculated from the calculated value of the maximum force necessary for the fracture of a specific block. Considering the ratio of these values and the values of laboratory testings of bending strength achieved was the so-called "reduction co-efficient", which reduced the other input sizes used in the numerical analysis.

However, regarding the number of in-situ testings making a final conclusion would be too early. In order to finally determine the direction of excavations and to plan the corresponding exploitation method as well as to finally determine the reduction coefficient it is necessary to perform more in-situ measurements of material strength and in-situ testings of material deformability, whereby the position and direction of the tested in-situ "samples" would be changed (second phase of testings).

After completion of more in-situ testings (bending strength and material deformability) with various positions and directions of in-situ samples the real condition of stresses and the characteristics of rock mass will be completely known, which will make it possible to find the adequately solution of pit development and the way of exploitation. For such solution it is very important to carefully observe the conditions during exploitation i.e. to register all the appearances during sowing for specifically determined directions and sowing types.

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