Underground natural stone excavation technics in Slovenia

Tehnike podzemnega pridobivanja naravnega kamna v Sloveniji

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Abstract: In recent years in addition to the economic reasons environmental concerns are the ones, which lead to the consideration of production of natural stone blocks by underground methods. Such development is on the way in most developed European Union countries, particularly in Italy as leading natural stone producing country.

Underground excavation of natural stone in Slovenia started in 1993, when company Marmor Hotavlje was affronted with a higher and higher overburden of this coloured and mechanically very favourable natural stone in Hotavlje I. quarry, which treatened to stop the production, because of increasing costs of excavation. In the year 2001 a test project of new natural stone production technology started also in Lipica II. quarry in company Marmor Sežana.

The paper describes situation of the natural stone quarries, shows basic technical data about underground excavations of natural stone and gives a brief description possibilities of revitalization for a number of abandonned surface natural stone quarries.

Povzetek: V zadnjih nekaj letih se predvsem zaradi ekonomsko-ekoloških razlogov vedno pogosteje razmišlja o uvajanju podzemnega načina pridobivanja blokov naravnega kamna. Tak razvoj je mogoče opaziti v večini razvitih držav Evropske unije, še posebej pa v Italiji kot vodilni državi na področju pridobivanja in predelave naravnega kamna.

Podzemno pridobivanje naravnega kamna se je v Sloveniji pričelo poskusno uvajati leta 1993 v podjetju Marmor Hotavlje, kjer so zaradi naraščajočih stroškov pri odstranjevanju vedno večjih količin odkrivke nad barvno pisanim in mehansko zelo iskanim naravnim kamnom v kamnolomu Hotavlje I. celo razmišljali o prenehanju pridobivanja. Leta 2001 so s poskusnim projektom pričeli uvajati novo tehnologijo pridobivanja tudi v kamnolomu Lipica II. podjetja Marmor Sežana.

V članku je pregledno predstavljeno predhodno stanje v obeh kamnolomih naravnega kamna, osnovni tehnični podatki podzemnega pridobivanja naravnega kamna in kratek opis možnosti oživljanja številnih, danes zapuščenih površinskih kamnolomov naravnega kamna.

Key Words: dimension stone, Hotavlje I. quarry, Lipica II. quarry, natural stone, room and pillar mining method, underground mining

Ključne besede: rezani kamen, kamnolom Hotavlje I., kamnolom Lipica II., naravni kamen, komorno-stebrna odkopna metoda, podzemno pridobivanje

INTRODUCTION

Natural stone is a common name for all rock masses of natural origin that are suitable for cutting, grinding and polishing as well as for construction in regard to composition, properties and appearance. The term "natural" denotes that this is exclusively a natural material which is used in this natural form. Its working merely emphasises its structure, but does not change it – the basic properties, the distribution of minerals and grains as well as the appearance remain unchanged in this process. Terms such as decorative or ornamental (dimensional) stone, natural decorative stone, architectural

and construction stone, paving stone, building stone, sculptural stone etc. are also used. When naming stone, the adjective usually describes the mode of stone's use[11]. For natural stone to be suitable for mining and working, it must have sufficiently good physical and mechanical properties, such as strength, compactness, wear resistance, water absorption, freezing resistance etc. Along with appropriate physical and mechanical properties of the rock, it is its colour that most commonly affects the choice of the stone and often has a decisive influence on its use. The source of the rock mass (igneous, metamorphic or sediment rock), its chemical composition (carbonate or silicate) and other geological conditions at the rock mining site (tectonics) are the decisive factors that affect the selection of the mining method.

Underground mining of natural stone is not an idea conceived by the modern information society – it originates from the times of the ancient Romans. There is evidence that Romans were probably the first to undertake underground mining of stone, for example in the now already abandoned quarry in the Eastern British town of Beer in the province of Devon, which has been changed to a museum[7].

In Europe, underground mining of natural stone is nowadays performed in various quarries in Italy (Carrara, Apuan Alps, Bolzano, etc.), Great Britain (Avon, Somerset, Dorset[7], etc.), Greece (Dionysos – Athens[8]), Portugal (Solubema-Lisbon) and elsewhere.

In Slovenia, underground mining of natural stone began to be introduced in 1993 at the Hotavlje I. coloured limestone quarry, and since 2001 also at the Lipica II. limestone quarry.

Marmor Hotavlje, one of Slovenia's leading stonecutting companies, began with organised mining of natural stone

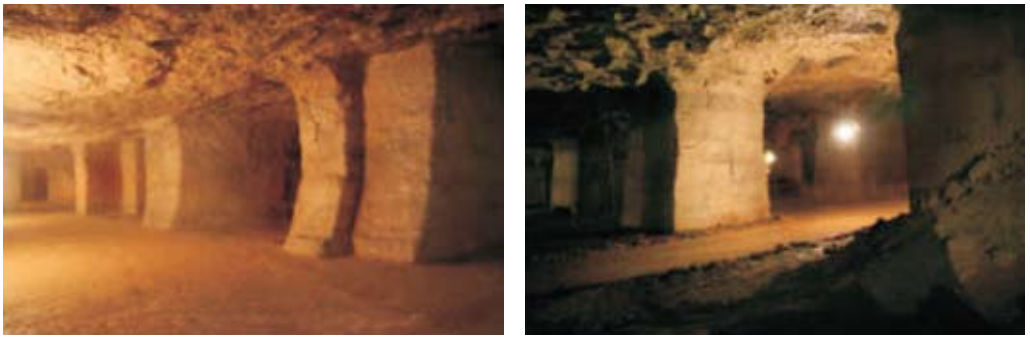

Figure 1. Underground mining of natural stone at the Beer quarry[7]

at the Hotavlje I. quarry in the year 1948[9]. The beginnings of mechanical breaking of natural stone at the quarry's current site date back to the seventeenth century. At the Hotavlje I. quarry, the so-called Hotavlje natural stone is mined, a limestone which comes in various colours (red, grey, pink, and sometimes almost black, with white calcite veins, coral remnants and limestone algae). The management of Marmor Hotavlje decided to implement underground mining due to the geological structure of the site and the quarry's condition resulting from an increasing demand for this raw material.

Figure 2. Lipica II. quarry[10]

Marmor Sežana, which has been the main company performing the stonecutting activities in the Karst region for over five decades, began mining natural stone at the Lipica II. quarry in 1986. Karst stonecutters named the natural stone mined at the Lipica II. quarry Lipica-Unito and Lipica-Fiorito[6]. In terms of size, the Lipica II. quarry belongs among the largest Slovene natural stone quarries. For similar reasons as for the Hotavlje I. quarry, the management of Marmor Sežana also decided in 2001 to begin with trial underground mining of natural stone blocks in Lipica II. quarry.

Before the beginning of underground mining, numerical modeling and stability calculation of underground spaces foreseen were performed by finite difference method (FLAC^{2D}), for the evaluation of global stability of the openings foreseen and to derive a sensitivity analysis of input parameters, such as shape and dimensions of galleries, primary stress field and mechanics characteristic of the rock mass. Another block analysis (Unwedge) was also made, which was concentrated on block stability underground structures. Monitoring of stability was followed indirectly by monitoring relative deformations of the discontinuities. Results given by calculations were finally the basis for the design of underground spaces for a long term underground extraction of natural stone blocks[1].

Work at both quarries used to be partially seasonal. During the winter, interruptions of the mining process lasted between one and three months in case

of poor weather conditions (snow or rain).

The following factors have a crucial role in the selection of the mining method:

- Geological factors: overburden thickness, site compactness - wall masses, waste rock, shape of the rock body,
- Ecological factors: lesser surface damage to the environment, smaller rock waste deposits and significantly lower noise burden on the surroundings (because works are performed underground),
- Technical and technological factors: development of the technology and the mining methods enables efficient, simple and safe mining,
- Economic factors: expensive overburden works are unnecessary; mining can be done throughout the year and even in poor weather conditions (winter, rain); the costs of mining are initially higher due to quarry opening works and additional research costs, but they decrease rapidly with the development of open underground spaces called galleries,
- Regulatory factors: in the majority of countries, there are no stipulations in the legislation on this mining method, therefore regulations on the performance of underground work are reasonably applied.

Excavation technics for mining of natural stone

Natural stone quarries are much smaller than technical stone quarries. Their annual production rarely exceeds 1500 m^3 of natural stone blocks. A low utilitization value of natural stone blocks, which ranges between 8 % and 25 %, results in the fact that natural stone quarries always have sufficient waste, which can be used for final quarry site rehabilitation.

Excavation technics for mining natural stone are as follows[4]:

- performatic drilling,
- drilling and cutting with helicoid wire and flintstone sand,
- drilling and cutting with a diamond wire saw,
- cutting with a chain cutting machine (belt saw),
- combined cutting method.

The performatic drilling method consists of drilling into the rock with the use of pneumatic drilling hammers or drilling machines. Drilling is done in the horizontal and vertical directions, at several places. The bore diameter (usually ϕ 34 mm) and the distance between the bores (usually 100 mm) depends primarily on the splitting capacity of the rock mass[2]. Separation of a block from the rock mass is done using rock splitting wedges, which are ham-

mered into the bores in alternation until a block is separated off the rock, or by using black blasting powder for mining or detonation string. This mining method is being gradually abandoned due to the formation of microcracks within the rock at the mining site (rock damage), large energy consumption, difficult and heavy work, and excessive noise burden on the surrounding areas.

Figure 3. Diamond wire

The drilling and cutting method involving the use of helicoid wire and flintstone sand is based on cutting of the rock using flintstone sand, which is harder than rock, as the abrasive. Helicoid wire (with diameters up to 5.8 mm) is a woven steel wire rope made from three strands, which serves as a means of transporting flintstone sand into the cut. In this method, flintstone sand represents the cutting tool, and the added water acts as a coolant. The cutting speed amounts to between 0.3 m^2/h and 0.9 m^2/h and depends primarily on hardness of the rock mass. At cutting sites, ϕ 240 mm vertical and horizontal bores are first drilled; stands with wire guiding wheels are then installed and a helicoid wire is fed over them. The helicoid wire is joined at the ends to form an endless wire with a length of up to 1500 m. The wire is then led into the cut, over the driving wheel and the guiding wheels. A mixture of flintstone sand and water is added at the point of contact between the helicoid wire and the rock. This method was very widely used in the past for the mining of compact limestones and marbles, but nowadays is has been completely replaced by the method of diamond wire cutting.

The stone cutting method with the use of diamond wire saw is based on cutting of the rock with a diamond wire. A diamond wire with a diameter of 5 mm is a woven wire rope with diamond rings (the diamonds are sintered or inserted/bonded galvanically), springs and spacer rings arranged along it in alternation.

Figure 4. Drilling of vertical bores using a drilling machine

The mining of stone blocks according to this method is performed in several phases:

- Drilling of a vertical bore with a diameter of 240 mm and two horizontal bores with a diameter of 90 mm in such manner that all the three of them converge at the same point;
- Sawing of both vertical cuts; the diamond wire is drawn through the vertical and horizontal bores, and then its ends are connected together to form an endless wire rope using special joints. The wire is placed on the driving wheel ring of an electric aggregate and the wheel is placed on guides with a cogged rail that enables uniform movement of the diamond wire during sawing;
- Sawing of horizontal cuts; the diamond wire is drawn through the horizontal bores; its ends are then joined together to form an endless wire rope and mounted on the driving wheel of the electric aggregate.

The cutting speed using a diamond wire saw amounts to 5 m^2/h to 10 m^2/h and is by far the highest compared to other cutting methods.

The cutting method involving the use of a chain cutting machine is based on cutting of rock using "widia" or diamond plates that are mounted on the cutting machine's chain blade. Chain cutting machines can cut rock in a horizontal or vertical direction. The cutting machine's blade moves along the cogged rail and guiding rails. For work in underground spaces, cutting machines with hydraulic guides for blade movement in the horizontal and vertical directions are used, with hydraulic pillars that enable machine stabilization during operation. This method is simple and safe. The chain cutting machine is placed directly in front of the stope face and attached rigidly. Horizontal cuts are first made from below upwards and finally on the side. Technical water is used for cooling the saw chain and washing the stone slurry out of the cut. The cutting speed is between 2 m^2/h and 4 m^2/h, the cut thickness is 4 cm and the cut depth 2.40 m or more. The speed of blade movement is up to 7 cm/min and the chain speed up to 0.7 m/s.

Figure 5. Cutting of the lower horizontal cut using a chain cutting machine

The combined cutting method unites the methods of chain cutting machine and diamond wire saw cutting. It is primarily suitable for opening and prepa-

ration of upper underground mining levels (galleries, cross-cuts, niches), which later enable increasing of the depth by creating chambers with the use of the more cost-efficient diamond wire saw cutting method.

UNDERGROUND MINING OF NATURAL STONE BLOCKS

Underground method of mining natural stone blocks has many advantages over surface mining. In the Hotavlje I. and Lipica II. quarries, it is suitable primarily due to terrain configuration, shape of the quarry and the large amount of the overburden. In addition to a considerable reduction in the amount of overburden, which certainly improves the cost-efficiency of natural stone mining, the underground mining method also enables selective exploitation of the high-quality portions of the site, much more so than surface mining. This increases the utilization value of natural stone blocks, which can result in lower costs of mining per unit product and ultimately in a higher cost-efficiency of mining, which is certainly the greatest advantage of underground mining of natural stone. However, when planning the technological equipment to be used in underground mining, it is necessary to observe the applicable regulations for mines with underground exploitation of mineral raw materials, and this could make mining slightly more expensive.

In addition to the research that is necessary for planning the galleries, underground mining of blocks also requires extensive systematic geological and geotechnical observation and measurements during the performance of works. Only in this way is it possible to prove that the planned mining system ensures safe work and that it will increase utilization value of high-quality stone blocks. To a certain extent, the underground mining method also enables selective mining which results in the achievement of a higher average quality of mined natural stone that can be sold on the market at a higher price.

In both quarries, Hotavlje I. and Lipica II., the room and pillar mining method with irregular distribution of pillars will be used in future, along with the combined cutting method. The combined method of natural stone cutting is primarily suitable for opening and preparing underground open spaces (galleries, cross-cuts, niches and chambers). This method has so far been proved to be the most successful for underground mining of natural stone. The horizontal and then vertical cuts are first made using the chain cutting machine. If necessary, depending on the required block size and load-carrying capacity of the transport machine equipment, several

intermediate horizontal and vertical cuts are then made. In order to cut the rear surface of the natural stone blocks, a channel is first made with a width of between 0.5 m and 0.8 m. Blocks in the channel are obtained using hydraulic bags. The rear surface of other blocks is cut using a diamond wire saw. The depth of one stage depends on the blade length of the chain cutting machine and amounts to between 2.40 m and 2.80 m or even more. The minimum stope face width is 5.80 m. The heights of individual mining levels depend on the technological and geological conditions and range between 4 m and 6 m (usually 4.50 m). Water is used for cooling the cutting tool, washing of slurry from the cut and reducing dust formation.

Figure 6. Stope face with underground mining of natural stone

In the future, surface and underground mining of natural stone blocks will be done concurrently using the diamond wire saw cutting method or the combined cutting method, and the lower lying mining levels will be opened from up downwards.

Conclusions

The development of new technologies and mining methods for underground mining of natural stone enables more cost-efficient mining, better raw material and labour utilisation, smaller damage to the environment and safer work, but it also requires a significantly higher level of professional training from employees. The introduction of underground mining of natural stone means an immediate possibility of renewed operation for many already abandoned natural stone quarries, while for active ones it should be considered as a significant alternative from the viewpoints of ecology, cost-efficiency, selective mining and possibilities for further development and mine expansion, better raw material and labour utilisation, reduced influence of weather and seasonal changes, as well as from other viewpoints.

In the future, experience acquired in the two Slovene natural stone quarries will serve for the introduction of underground mining also in other Slovene and foreign natural stone quarries which are suitable for this mining method.

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