



TUYỂN TẬP BÁO CÁO HỘI NGHỊ KHOA HỌC QUỐC GIA

PHÁT TRIỂN BỀN VỮNG

KHOA HỌC CÔNG NGHỆ MỎ VÀ MÔI TRƯỜNG

Sustainable Development of Mining Science, Technology and Environment



NHÀ XUẤT BẢN ĐẠI HỌC KINH TẾ QUỐC DÂN



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COMPUTER-AIDED DESIGN AND PLANNING METHODOLOGY FOR OPEN-PIT AND UNDERGROUND DIMENSION STONE MINES: EUROPEAN EXPERIENCES AND APPLICABILITY IN VIETNAM

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ABSTRACT

The paper discusses the Computer-Aided Design and Planning Methodology (CAD-PUMA) for underground marble mining and analyzes its relevance to the dimension stone industry in Vietnam. The methodology supports both existing underground operations and open-pit quarries, with consideration given to a transition to underground mining. The objective is to optimize quarry layout and extraction planning to maximize block recovery while also ensuring safety and cost efficiency. It integrates pilot-scale excavations with detailed rock mass characterization, including deposit geometry modeling, discontinuity analysis, and geomechanical calibration based on field monitoring data. These inputs are used in advanced numerical simulations to generate reliable models of recoverable blocks, which are structured into a rock block database. This database underpins computer-based decision support systems that assess alternative layouts, extraction sequences, and production scenarios, enabling improvements in mine design, product quality, and operational performance. Safety is evaluated through calibrated geomechanical models and numerical analysis. The study highlights the relevance of this methodology for Vietnam, where open-pit quarrying predominates. Using underground mining beneath pit floors or highwalls while evaluating reserves and planning for long-term goals can enhance the recovery of high-value blocks and contribute to the sustainable use of resources.

Keywords: *Computer-Aided Design and Planning Methodology (CAD-PUMA); discontinuities; block model; modelling; dimension stone; open-pit marble quarrying; underground marble quarrying*

1. Introduction

Stone, especially, limestone is a key non-metallic mineral resource vital to mining, construction, and many industrial applications. While often associated with iconic buildings and monuments, stone is also crucial in everyday life for infrastructure, housing, transportation, and industrial products (Nguyễn Anh Tuấn, 2016, 2021). The scope, therefore, includes both rock fill and armourstone, in addition to dimension stone. Although end uses vary, selection and performance rely on petrogenesis, physical and mechanical properties, and rock mass discontinuities, such as fracturing and jointing. Large volumes of rock serve as civil engineering fill, particularly for dams, highways, and railway embankments, where geomechanical behavior and modern compaction techniques determine construction outcomes. Armourstone for coastal protection and harbor works is evaluated and prepared in a similar manner (Smith, M.R., 1999).

The Computer-Aided Design and Planning Methodology (CAD-PUMA) was created for underground marble quarries that already exist and operators that are planning to move to underground exploitation. The purpose is to offer advanced and optimized design and production planning methods for underground quarrying. These techniques enable the prediction and selecting of quarry layouts that are both cost-effective and safe, while also making it possible to recover size stone blocks that meet market requirements in terms of size and quality.

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The depletion of near-surface marble reserves and increasingly strict environmental regulations are driving the industry toward underground exploitation. Although underground quarrying of dimension stone has been widely adopted in Europe, standardized methods for designing room-and-pillar layouts remain underdeveloped (Thoraval, 2001). In practice, the design of pillars and room spans still relies largely on empirical experience. To ensure sustainable development under these more complex conditions, the dimension stone industry must address the technical and operational challenges associated with underground mining. These include reduced recovery rates, limited working space, and stability issues related to pillars and roofs, all of which may increase production costs. While many companies recognize the necessity of transitioning underground, they often delay implementation due to high risks and insufficient technological support. Therefore, a comprehensive scientific and technological framework is urgently needed to guide safe, efficient, and economically viable underground marble quarrying.

Several European projects aim to improve underground marble quarrying by optimizing extraction processes, support systems, and production planning (Thoraval, 2001). Efficient extraction tailored to rock discontinuities and quality distribution can maximize recovery while ensuring safe operation. Optimization of reinforcement systems reduces costs by minimizing failures and unnecessary support measures. Integrated decision-support tools, combining geomechanical, geological, and deposit data, enable the design of safer, more productive, and cost-effective underground layouts. Accurate prediction and optimization of block recovery in terms of size, quality, and quantity are essential for both new and existing quarries. Advanced planning methods also help the European marble industry meet strict environmental regulations, maintain quality standards, and remain competitive in the global market.

In the broader context, future demand for building stone is expected to focus mainly on granite and marble, alongside other mineral materials such as limestone, sandstone, and clay.

1.1. Current status of quarries in Europe

To sustain efficient operations in complex underground conditions, the industry must address key challenges such as reduced recovery, limited working space, and stability issues of pillars and roofs, which can increase production costs (Asof, 1991; Thoraval, 2001). While many companies recognize the need to transition underground, implementation is often delayed due to high risks and insufficient technological support. Therefore, a comprehensive scientific and technological approach is urgently required to enable safe, efficient, and economically viable underground marble quarrying.

Experimental mining sites:

The main activities at the four experimental mining sites are illustrated through the case of Dionyssomarble Co. (DMCO). Following the withdrawal of the Portuguese partner SOLUBEMA, DMCO was responsible for preparing and operating two test sites, namely “Site A” and “Site B”. The activities carried out by the other industrial partners, Lasa Marmo (LASA) and Cooperativa Condomini Lavoratori dei Beni Sociali di Levigliani (CCLL), are essentially similar to those implemented by DMCO. Any peculiarities of the work at these sites, however, will be emphasized (Merrien-Soukatchoff, V., Korini, T. & Thoraval, A., 2012).

Before the start of the exploitation and in order to minimize the risk of unsatisfactory site selection, exploration drilling was carried out. The rock mass characteristics at the extent of the experimental site were investigated, and core samples were collected for preliminary testing. The appropriate number of the boreholes was decided according to the specific characteristics of the experimental site and companies experience. Thus, at “SITE A” of DMCO, three horizontal core sampling boreholes were drilled, two in the same location but perpendicular to each other and one in another location. The boreholes were drilled until the contact between marble and the overlaying schist was reached and thus the existence of the marble deposit required for the excavation of the experimental rooms and pillar was assured. In addition, from the collected core samples, which were carefully “reassembled” and “oriented” based on the “known” orientation of the marble bedding plane, measurements of the discontinuity characteristics were carried out (dip, dip direction, and apparent spacing).

Preliminary investigation of the rock mass structural characteristics was carried out, and the data collected were used for the setup of the fracture network models and of the numerical geomechanical

models. More specifically, during a student training course, DMCO, in collaboration with INERIS, carried out a detailed survey of the discontinuities present in “SITE B”. The collected data were used to develop models for simulating fracture networks and building a rock block database. At CCLL, detailed fracture studies were conducted at both the quarry and experimental site, including a student training program in collaboration with POLITO. The data supported the development of stochastic fracture models, followed by the collection of additional data for deterministic modeling, which were provided to POLITO and INERIS. These included comprehensive graphical and photographic documentation of the excavation walls. Data collection is ongoing throughout the exploitation process.

In the initial phase, the three industrial partners developed underground experimental quarries, typically consisting of a 9 m wide room surrounding a square pillar of up to 15 m. Instrumentation was installed to collect data for modeling, with plans to expand room width to 15 m. DMCO prepared detailed construction drawings, including excavation stages and geological contacts, which are continuously updated. CNR designed monitoring systems, while DMCO supplied marble samples and schist blocks for laboratory testing.

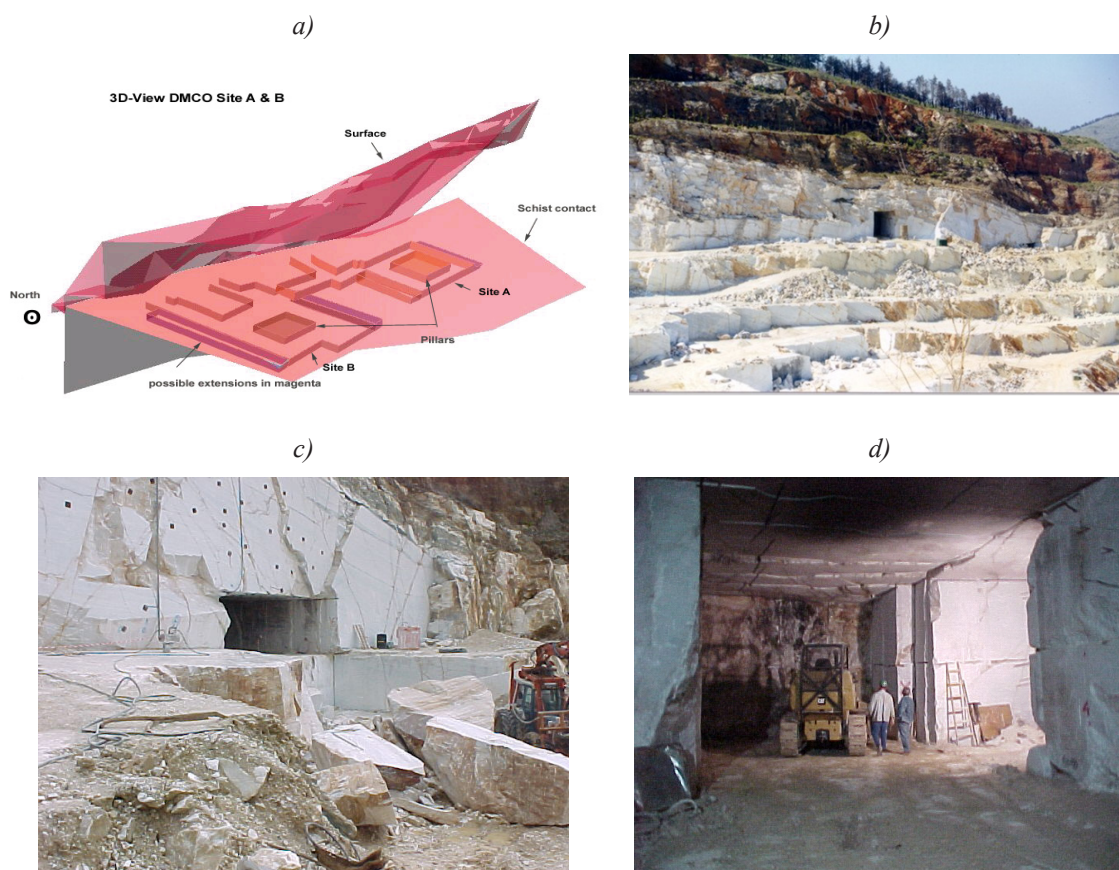


Figure 1. The main activities at the four experimental mining sites of Dionyssomarmble Co., Athens, Greece (DMCO). a) 3D-View of DMCO SITE A & B (possible extensions of the underground quarry layout); b) Entrance portal of “SITE A”; c) Entrance portal of “SITE B”; d) Inside view of “SITE A”.

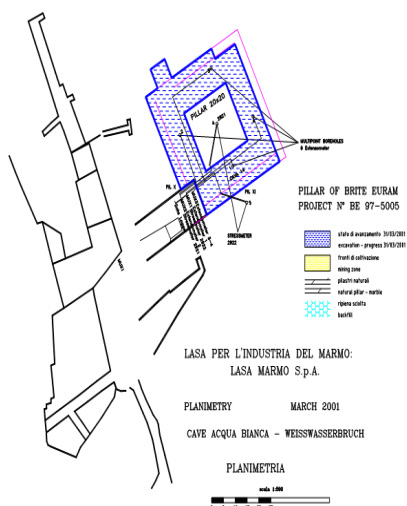


Figure 2. LASAMARMO Site in Lasa with test pillar excavation, Italy

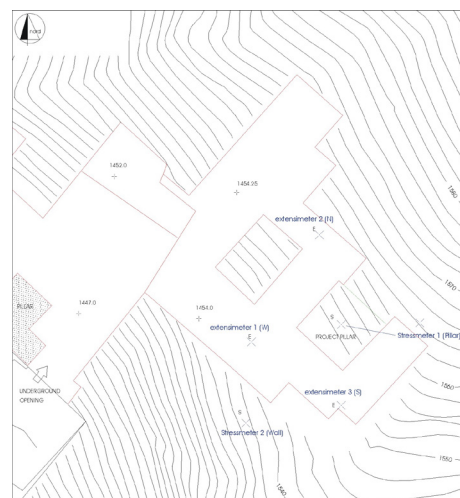


Figure 3. CCLL Site in Levigliani with test pillar excavation, Italy

1.2. Current status of quarries in Vietnam

In addition to coal, Vietnam hosts over 410 quarries (for Construction Material - CM quarries) extraction sites with an annual output exceeding 30 million m³. While most quarries are concentrated in the North, production is predominantly sourced from the South (approximately 20 million m³). Dimensional stone potential in Vietnam is enormously diverse in types of rocks, such as granite group, quartz group, marble group, calcite group, slate groups, and other group with enough colours: red, yellow, white, pink, blue, and black (Ministry of Agriculture and Environment, 2024). The different qualities of them change from granite group to slate group with the aim of fully supplying to social demands for constructing various facilities, leading to replacing imported high-class dimensional stones for paving and tiling modern-architecture building. Dimensional stones have been widely used for houses, fence walls and city pavements. The stone is broadly distributed in the Northern Midland and Mountainous area and Northern Middle and Middle coast areas.

Construction stone has a wide range of applications: dimension stone, cement raw material, road base, concrete aggregate, and backfilling; in metallurgy and chemical industries (lime, soda, alumina, fertilizers); in agriculture (soil conditioning, animal feed additives); and in other industries (ground calcium carbonate, ultrafine powders for paper, paint, plastics, rubber, and pharmaceuticals). Geological differences between the two regions dictate distinct mining practices: limestone is the dominant resource in the North, while magmatic and sedimentary rocks prevail in the South, often requiring additional dewatering and overburden stripping operations.

The table 1 shows the number and reserve of stone groups: granite, marble, limestone, and shale. The total number of dimension stone quarry are 410 mines, with total proven resources are about 37.590 mil m³ (mining reserves are 300 mil m³; probability resources are about 37.298 mil m³) (Nguyen Anh Tuan, 2016, 2012), (Decision No. 47/2008/QĐ-BCT).

Table 1. The number and reserve of stone group in Vietnam.

No	Regions	Number	Reserve, m ³
1	Northern Midland and Mountainous area	90	5.188.860
2	Red river delta area	12	59.330
3	Northern Middle and Middle coast areas	205	25.213.393
4	Central Highland area	55	580.680
5	Southeast area	40	1.319.976
6	Mekong river delta	8	5.228.000
7	Total	410	37.590.239

In terms of technology and equipment, large-scale coal and CM quarries apply continuous bench mining systems with full-bench stripping, using rotary drills with diameters of 200-250 mm, hydraulic excavators with bucket capacities of 1.5-12 m³, off-highway dump trucks of 12–96 tone, and bulldozers rated 180–300hp. Conversely, many small-scale CM quarries still rely on semi-mechanized or manual methods with outdated equipment, such as handheld drills, small excavators (0.5-1 m³), and trucks of 5-10 t capacity, resulting in low efficiency and high resource losses. An overview of the research problem, the existing issues that have not yet been resolved, a summary of the main tasks carried out in the study, and the principal results achieved.

2. Experience in prototyping a decision support system for dimension stone mining method selection

2.1. Basic methodology

Decision Support Systems (DSS) are software tools designed to assist decision-making by integrating analytical methods with expert knowledge. By incorporating expert systems, DSS provide a structured platform where data, models, and domain expertise are combined, enabling users to make informed and consistent decisions.

Within the CAD-PUMA framework, the DSS integrates decision rules, numerical models, and a comprehensive database with expert knowledge to support the design and planning of underground marble quarrying. Its primary objective is to optimize quarry layout and production strategies in order to maximize the recovery of marketable blocks while ensuring safety and economic efficiency (Thoraval, 2001; Nguyễn Anh Tuấn, 2021). The effectiveness of such optimization depends on three key factors: geological conditions, technical extraction capabilities, and economic constraints. Accordingly, the DSS knowledge base is structured in a modular form, allowing systematic integration of geological and mining information.

The main modules include: Geological and environmental conditions (GEO); Marble mass properties (MMP); Quarry layout and extraction techniques (UQL); Mineral economics (MEC).

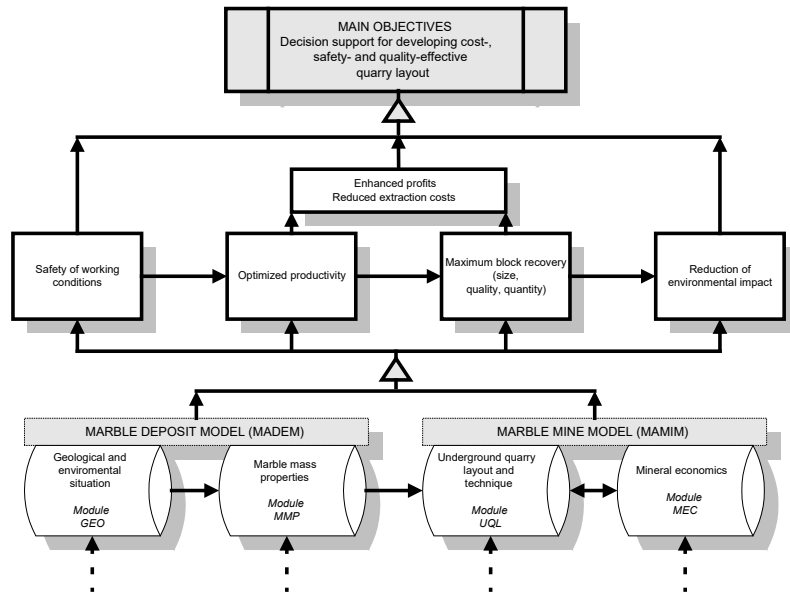


Figure 5. Modules of the knowledge base

2.2. Influence diagrams

The CAD-PUMA project analyzed the geosystem governing both open-pit and underground marble quarrying. Through expert interviews and collaboration with project partners, this complex system was decomposed into key practical components. These components and their relationships were qualitatively analyzed using influence diagrams, forming a network of interactions and decision rules for underground quarrying. Central to this framework are the Marble Deposit Model (MADEM) and the Marble Mine Model (MAMIM). To support the development of these diagrams, the cognitive mapping tool BANXIA Decision Explorer was used to structure and analyze geological, geostructural, and geomechanical information relevant to underground marble mining (Thoraval, 2001).



Figure 6. Simplified and condensed qualitative influence diagram

2.3. Extraction of rock from quarries

Extraction, focuses on the methodologies and technical considerations involved in removing rock material from a mine or quarry. Figures 7 and 8 provide detailed flowcharts illustrating the recommended selection of extraction techniques, which depend primarily on the desired end-product specifications and the geomechanical properties of the rock mass. It is assumed that prior exploration and evaluation activities have identified sufficient potential reserves in terms of rock volume or tonnage, and that the mineralogical and petrographic characteristics of the rock mass are generally favorable for extraction (Smith.M.R, 1999).

Accurate recording of discontinuity characteristics is essential when assessing deposits for armourstone or dimension stone, as joint and bedding plane features control block size and shape. For reliable evaluation, 150–350 discontinuities should be measured at 5–15 locations, generating 1,000–2,000 data points. This ensures dependable block size estimation and quarry planning. Key parameters include: orientation, spacing, and persistence of discontinuities; number of joint sets; block size; surface roughness; wall strength affected by weathering; aperture width; infilling material; and seepage conditions. Collecting sufficient data on these factors provides a robust basis for engineering design, slope stability assessment, and the economic viability of quarry operations.

It should be noted that scan-line or window sampling techniques may provide data limited to specific joint sets, and even comprehensive face mapping may fail to distinguish differences in continuity between joint systems, such as continuous set A versus discontinuous set B (ISRM 1978b; Priest 1993). The paper provides detailed technical descriptions of the extraction processes for dimension stone, with specific consideration of operational efficiency, resource recovery, and product quality depend on number of joint sets or network of fractures.

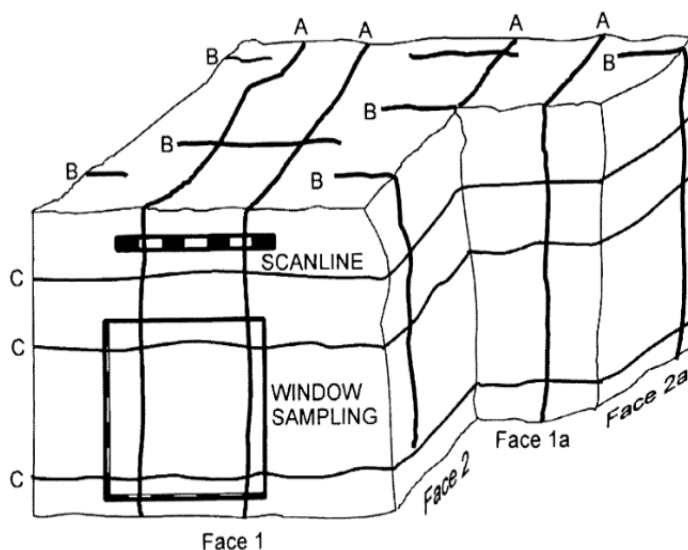


Figure 7. Discontinuity surveys must capture all joint sets, as limited sampling may miss continuity differences between sets (Smith, 1999)

Dimension stone is defined as natural rock quarried, cut, and shaped to specific sizes for construction and civil engineering applications. Initially regarded as a local building material, dimension stone has developed into a globally traded resource, primarily valued for decorative and structural purposes. Dimension stone must be free from fractures, tough, and chemically stable, ensuring long-term performance. Surface treatments such as honing, polishing, or flame texturing enhance both functional and aesthetic properties. Overall, the chapter provides guidance on material selection, processing, and application of dimension stone to meet diverse architectural and engineering demands.

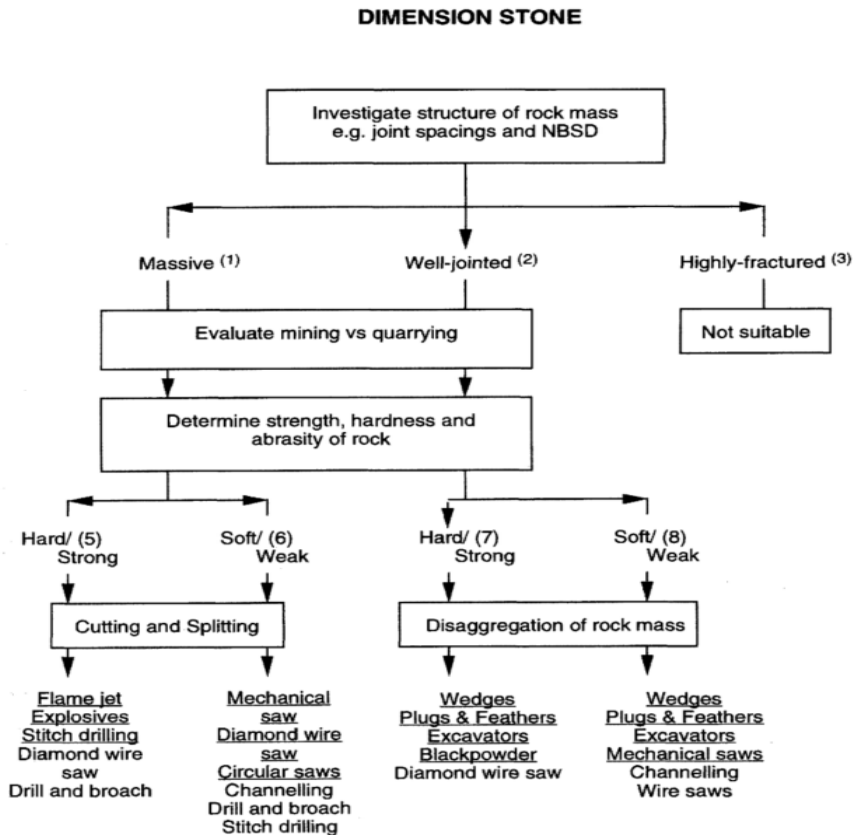


Figure 8. Dimention stone flowsheet for selection of extracrion method: (1) widely spaced joints, the Natural Block Size Distribution (NBSD); (2) Joints spacing and NBSD; (3) Joints spacing and NBSD; (5) as typified bay many granites, (6) as typified by many marbles, (7) as typified by many sandstones and slates and (8) as typified by many limestones (Smith, 1999)

The flowchart outlines the decision-making process for selecting quarrying methods for dimension stone based on rock mass characteristics. First, the structure of the rock mass is assessed, considering joint spacing and NBSD. Massive and well-jointed rocks are suitable, while highly fractured rocks are not. Mining versus quarrying is then evaluated, followed by the determination of rock strength, hardness, and abrasivity. For hard and strong rocks, cutting and splitting methods are applied, including flame jet, explosives, stitch drilling, diamond wire saws, and circular saws. For soft or weak rocks, mechanical cutting with wire saws, drills, and wedges is preferred. In cases requiring disaggregation, plugs and feathers, black powder, excavators, and channeling are employed depending on rock strength and condition.

3. Rock mass modelling for underground quarry

The optimization of gallery orientation with respect to discontinuities considers two cases: new and existing underground quarries. For new designs, orientation and pillar dimensions are based on statistical fracture data, while existing quarries additionally use deterministic measurements from nearby galleries. Rock mass behavior is modeled using deterministic joint networks generated by the RESOBLOK code. The process includes geometry definition, assignment of mechanical properties and in-situ stresses, numerical simulation of excavation stages, and calibration with field data.

Key outputs include pillar stress, displacement, and overall stability. Numerical tools such as 3DEC and LMGC90 are applied to evaluate stability and support decisions on quarry expansion. This approach has been implemented at four experimental sites.

a) LASA Quarry

The rock mass model, including the slope geometry and excavation sequence, is shown in Figure 9a,b. The model dimensions are $110 \times 50 \times 110$ m, comprising 4,328 blocks and 41,968 contacts.

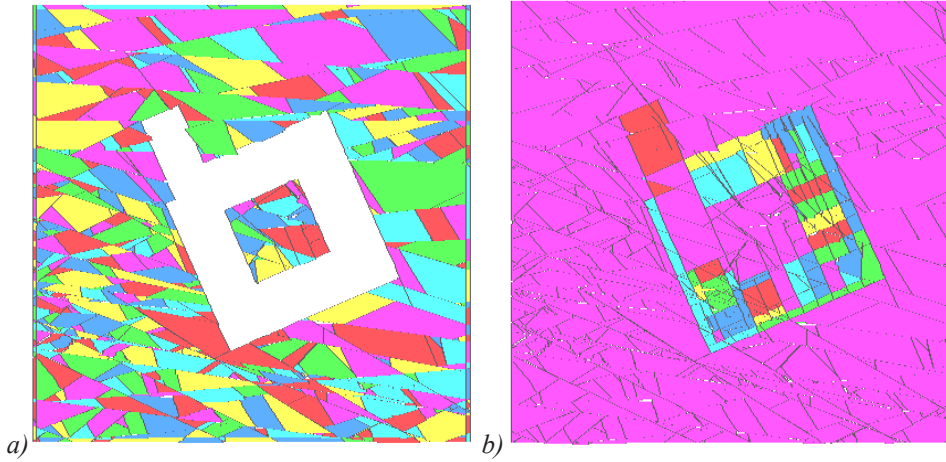


Figure 9. Rock mass model with excavation void (a) and excavation sequence (b) at the LASA quarry.

b) LEVIGLIANI quarry

The rock mass model with the slope configuration and excavation sequence is presented in Figure 10a,b. The model dimensions are $150 \times 50 \times 150$ m, including 3,252 blocks and 3,762 contacts.

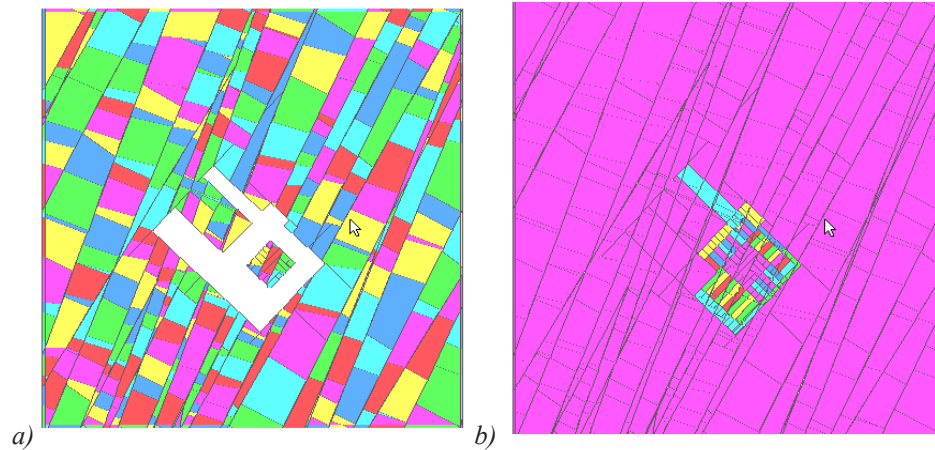


Figure 10. Rock mass model with excavation void (a) and excavation sequence (b) at the Levigliani quarry

c) DMCO quarry site A

The rock mass model, including the slope geometry and excavation sequence, is illustrated in Figure 11a,b. The model dimensions are $120 \times 60 \times 120$ m, comprising 1,658 blocks and 16,290 contacts.

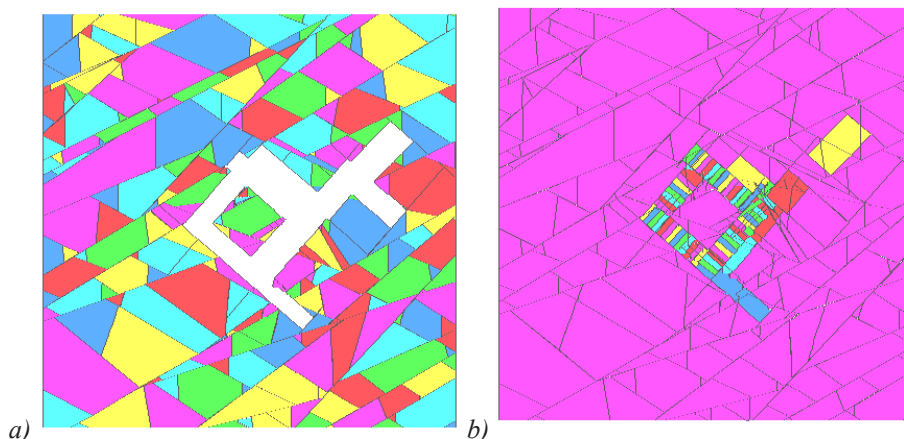


Figure 11. DMCO Rock mass modelled with the excavation void (a); Excavation step sequences (b)

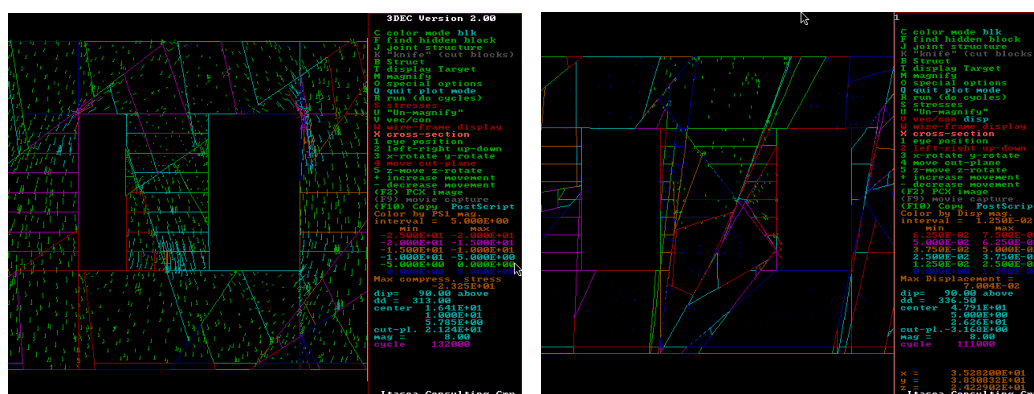


Figure 12. Computed displacements and stress around an underground marble quarry

Simulations at two quarry sites, assuming a 21 m high pillar, indicate generally stable excavations with only minor local block instabilities (Figure 12). In contrast, modelling of another site reveals poor stability, requiring roof support and pillar reinforcement.

RESOBLOK-generated block sizes from fracture sets are computed and filtered (e.g., blocks larger than 100 m^3 , equivalent to the theoretical average block size of $6 \times 4 \times 4 \text{ m}$) using Elements Expert, and then visualized in Surpac 2000. Figure 13 illustrates an example showing the distribution of blocks exceeding 100 m^3 in the statistical model.

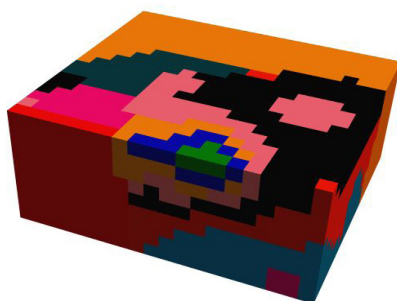


Figure 13. DMCO SITE A. Statistical distribution for blocks greater 100 m^3 . Heading north light Grey: $130\text{--}140 \text{ m}^3$, Dark Grey: $150\text{--}160 \text{ m}^3$, Medium Grey $160\text{--}190 \text{ m}^3$. VRML view of the block distribution. The model shows different areas of density according to the fracture spacing

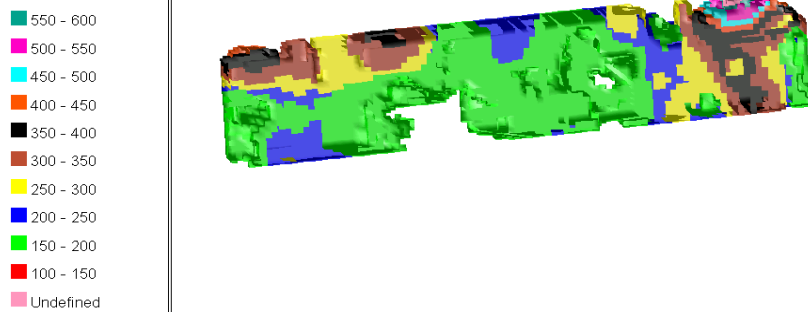


Figure 14. Lasa: Statistical distribution of blocks $> 150\text{m}^3$. Right = North.
Different areas of fracture density are displayed in Surpac2000

Based on the expert system's rule set and quarry data (e.g., fracture networks, lithology, and morphology), optimal orientation and development directions for underground marble mining can be determined. To visualize the 3D configuration of the pilot sites, TU Berlin developed models in Surpac 2000. Figures 25 and 26 present the 3D layouts of DMCO Sites A and B, along with the proposed lateral extensions.

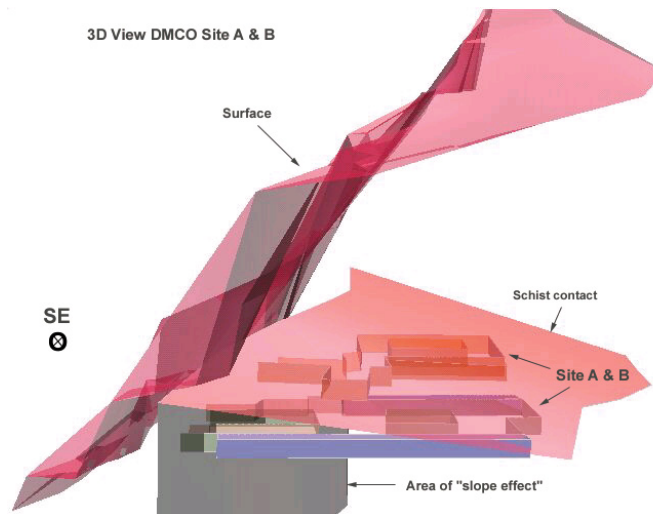


Figure 15. 3D-View of DMCO SITE A & B.
Possible extensions of the underground quarry layout are displayed

3D view of DMCO Sites A and B showing the excavated areas, pillars, potential extension zones, surface topography, and zones affected by slope effects, including surface-parallel extensional fractures and highly mobile marble masses with predominantly open discontinuities.

4. Further activities

The experimental sites in Vietnam are still being excavated. Continued mining, guided by numerical simulations, will enable validation of the proposed methodology. The calibration of rock block models and expert system predictions will be supported by monitoring block production in terms of size, volume, and quality. As the sites expand, additional geomechanical instrumentation, monitoring, and data evaluation will be required under the supervision of the Vietnam Department of Geology and Minerals. Increasing dimension stone recovery, particularly near final pit slopes, has been achieved globally by integrating open-pit and underground mining methods while maintaining the stability and safety of both excavations and surrounding rock masses.

These practices indicate that the integration of mining methods is essential. Analysis and visualization of RESOBLOK results at the studied sites should take place in the expert system with the help of 3D deposit modeling tools developed by TU Berlin. The optimization of quarry geometry, location, and orientation allows for maximum recovery and stability. The DSS knowledge base should incorporate geomechanical simulation and monitoring results (POLITO and CNR), and project partners should work together to continuously update and validate it. Vietnam's construction and mining industries rely heavily on resources, with applications that extend beyond traditional building stone. The demand for granite, marble, limestone, dolomite, and other industrial minerals continues to grow ahead, reinforcing stone's strategic role in infrastructure development. Economic value, environmental balance, and long-term contribution to national development will be ensured by exploitation. Research should focus on advanced testing methods, digital technologies, and climate adaptation strategies to improve resource efficiency. Developing comprehensive guidelines for sustainable stone utilization will require interdisciplinary studies linking geology, engineering, and environmental sciences. Improving mining efficiency and optimizing the recovery of dimension stone resources can be achieved by implementing this approach, which shows significant potential.



Figure 16. Tran Yen Quarry in Yen Bai province, Vietnam



Figure 17. Binh Dinh Quarry in Binh Dinh province, Vietnam

The model focuses on analyzing the block sizes, with the discontinuity aspect being statistically evaluated based on the geometrical modeling of the individual fractured rock mass. The authors propose conducting additional research and conducting pilot implementation in high-value and representative dimension stone quarrying areas in Vietnam, based on the analytical results and practical experiences mentioned earlier. These include the black stone quarries in the Thừa Thiên Huế region; the white stone deposits in Yên Bái and Quỳnh Hợp; as well as dimension stone quarries located in Phú Yên and Bình Định.

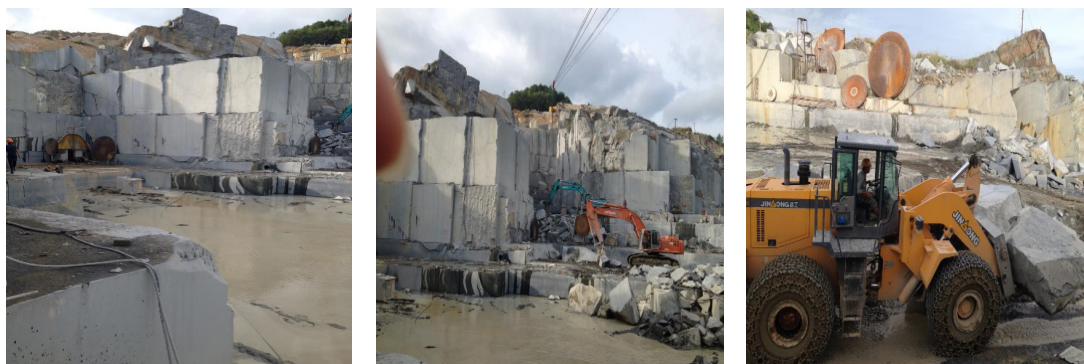


Figure 18. Haa An Quarry in Phu Yen province, Vietnam

5. Conclusions

International experience suggests that integrating open-pit and underground mining methods in dimension stone quarries is a practical and technically effective approach. By combining this strategy, resource recovery is enhanced, especially when surface extraction is constrained by final pit slopes or geological conditions, while also enhancing the stability and safety of quarry slopes, underground openings, and surrounding rock masses. From a technical and operational perspective, this approach offers significant potential for optimizing resource exploitation and promoting sustainable mining. To assess its feasibility and economic performance under specific geological conditions, additional research and pilot applications are needed.

The outcome of this project indicates that a multidisciplinary approach is necessary to develop an effective planning methodology for underground marble quarrying. The integration of geological data, discontinuity and block distribution, geomechanical conditions (stress and displacement), and economic factors is essential for generating reliable decisions. Advanced numerical modeling of rock mass behavior and block distribution, along with excavation performance and monitoring data from experimental sites, is used to support such a framework. The integration of these components enables the development of decision support systems to optimize quarry design in terms of safety, cost, and product quality.

This paper presents the mining operation, the size of the blocks, and the direction of mining that affects the recovery ratio in some dimension stone quarrying areas in Eroupe. It also proposes a new approach to dimension stone quarrying in Vietnam. According to the analysis, the rock mass model can give a good indication of the distribution, number, and volume of blocks, which is useful for designing dimension stone quarries in Vietnam.

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