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COMBINED METHODS FOR DIMENSION STONE DEPOSITS' JOINTS AND FRACTURES DETECTION, DIGITALISATION AND VISUALISATION

Gelu MADEAR[1], Camelia MADEAR[2]*

[1]ECO-ROCCA Engineering SRL, Petrosani, Romania, gelu.madear@eco-rocca.ro
[2]University of Petrosani, Petrosani, Romania, cameliamadear@upet.ro

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Abstract: *Characterising joint and fracture systems is crucial for dimension stone deposit evaluation and optimisation. This paper reviews and analyses combined methodologies for detecting, digitalising, and visualising joints and fractures in dimension stone deposits. Integrating traditional field measurements with modern technologies like terrestrial laser scanning, photogrammetry, and specialised software enables comprehensive fracture system analysis. These combined methods provide advantages, including large dataset collection, access to inaccessible areas, and detailed 3D visualisation capabilities. The study examines how these techniques contribute to accurate block size estimation, quarry planning, and waste reduction. Special attention is given to computer-aided modelling systems that evaluate fracture orientation and density to determine potential block volumes and shapes. The research demonstrates that integrated approaches offer superior results for sustainable quarry management and economic viability assessment.*
Keywords: *dimension stone, discontinuity, LiDAR, Structure-from-Motion, point clouds, DFN*

1. Introduction

Dimension stone deposits are characterised by their unique geological features, including joints and fractures, which significantly impact the quality and extractability of the stone. The accurate detection, digitalisation, and visualisation of these structural elements are crucial for efficient quarry planning and operation. Traditional fracture characterisation methods have accuracy, coverage, and efficiency limitations.

This paper presents a comprehensive approach that combines advanced technologies and traditional techniques to enhance the understanding and representation of joint and fracture systems in dimension stone deposits. It is based on the work carried out within the research project "Artificial Intelligence and Combined Survey Techniques for Stone Quarries Optimization" - (AI-COSTSQO) and combines the fieldwork carried out in Romania, Italy and Turkyie dimension stones' test quarries with office processing of data and reporting, demonstrating the state-of-the-art workflow used in this project. [1, 2]

2. Traditional Methods

2.1. Field Mapping and Manual Measurements

Field mapping and manual measurements have long been the primary methods for characterising fractures in rock masses. Geologists typically use compasses, measuring tapes, and clinometers to record discontinuities' orientation, spacing, and persistence. While these methods provide direct observations, they are time-consuming, labour-intensive, and limited in their coverage of inaccessible areas. Classical geological mapping of fissure systems, joints and discontinuities was carried out according to the International Society of Rock Mechanics' recommendations in the locations where GPR tests were performed to calibrate and integrate these measurements.

The Scanline / window sampling method was used, employing specific equipment: geological compass / electronic device (digital compass) with CLINO software (iPhone), rollers of various lengths, different coloured sprays for demarcation of dimensions/ windows, ruler, geological hammer, Schmidt hammer, digital cameras, digital tablet for processing primary information.

* Corresponding author: Gelu Madear, Eng. Ph.D., ECO-ROCCA Engineering S.RL., Petrosani, Romania, 3 Mihai Viteazu Street, 0746082288, www.eco-rocca.ro, gelu.madear@eco-rocca.ro

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Fig.1. Defining the window sampling at marble and travertine quarries, Romania

Aspects from in-situ joint measurements using the window sampling method are presented in Fig. 1 and Fig. 2.

Fig.2. Azimuth and inclination measurement of a vertical crack at the Botticino quarry, Italy

2.2. Borehole Camera Surveys

Borehole camera technology offers a quick, effective, and relatively low-cost method for geological surveys of fractured rock masses. This technique provides valuable information on fracture orientation, aperture, infill, and cross-cut relations. However, it is limited to the vicinity of the borehole and may not fully represent the overall fracture network of the deposit. [3]

Fig.3. Equipment used for the camera in the borehole and the horizontal hole logging - Ruschita, Romania

Fig. 3 shows the moment the camera was introduced along the borehole at Rușchița quarry. In contrast, Fig. 4 represents the superimposition of the calibration mesh and the interpolating sinusoid for the same borehole.

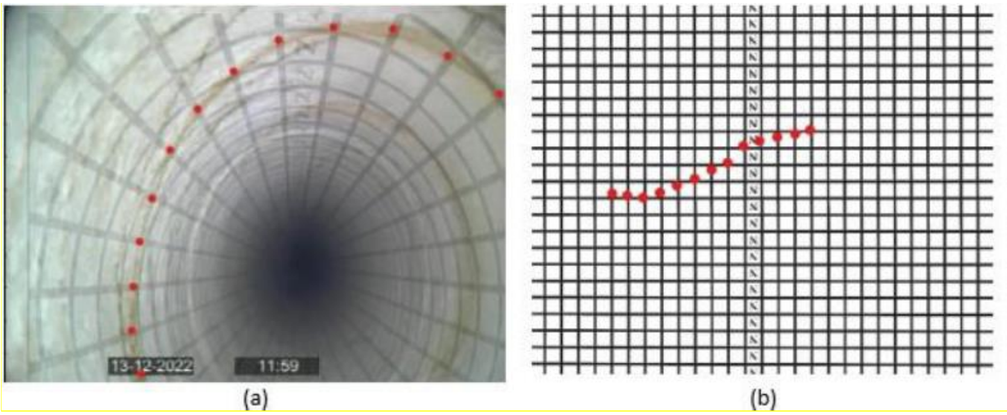

Fig.4. (a) Hole 1 horizontally - depth of 4.8 m (fracture and calibration mesh) and (b) the interpolating sinusoid

2.3. Limitations of Traditional Approaches

Traditional methods often struggle to capture the full complexity of fracture systems, especially in large deposits or areas with limited accessibility. They also face challenges in accurately representing the three-dimensional nature of fracture networks and may be subject to sampling bias.

3. Advanced Detection Methods

3.1. Terrestrial laser scanning (TLS)

Terrestrial laser scanning has become a powerful tool for acquiring accurate 3D point cloud data of rock masses. TLS provides high-resolution spatial information, enabling the creation of detailed 3D models of complex rock structures.

This technology is particularly useful for preserving geometric information and can be more cost-effective than traditional methods for large-scale surveys. [4]

Fig. 5 shows the layout and the position of the Terrestrial Laser Scanner (TLS) from the face at the Onur marble quarry, whereas Fig. 6 presents the mounting on the backpack of the mobile LiDAR scanner.

Fig.5. LiDAR scanning using TLS at Onur marble quarry, Turkey

3.2. Photogrammetry and Drone Surveys

Close-range photogrammetry and Structure from Motion (SfM) techniques have improved significantly, allowing for the creation of 3D models from multiple overlapping photographs.

Unmanned Aerial Vehicles (UAVs) equipped with high-resolution cameras can capture imagery of large areas and inaccessible locations, providing a comprehensive view of the deposit. These methods are particularly useful for preserving colour information and can be more cost-effective than laser scanning. [5]

Fig.6. LiDAR scanning using Mobile LiDAR at Onur marble quarry, Turkey

Aspects from drone surveying at Carpinis quarry (travertine) to generate point clouds from Structure-from-Motion are presented in Fig. 7.

Fig.7. Drone surveying for SfM at travertine quarry - Carpinis, Romania

3.3. Ground-penetrating Radar (GPR)

Ground-penetrating radar can provide valuable insights into the subsurface structure of dimension stone deposits. GPR can detect hidden fractures, voids, and other discontinuities that may not be visible on the surface, offering a more complete understanding of the deposit's internal structure. [6]

Ground Penetrating Radar measurements were carried out in all the projects' quarries and complements the previous investigations. Fig. 8 shows how GPR measurements were carried out at Botticino, whereas Fig. 9 presents measurement locations and radargrams from Carpinis.

Fig.8. Drone surveying for SfM at travertine quarry - Carpins, Romania

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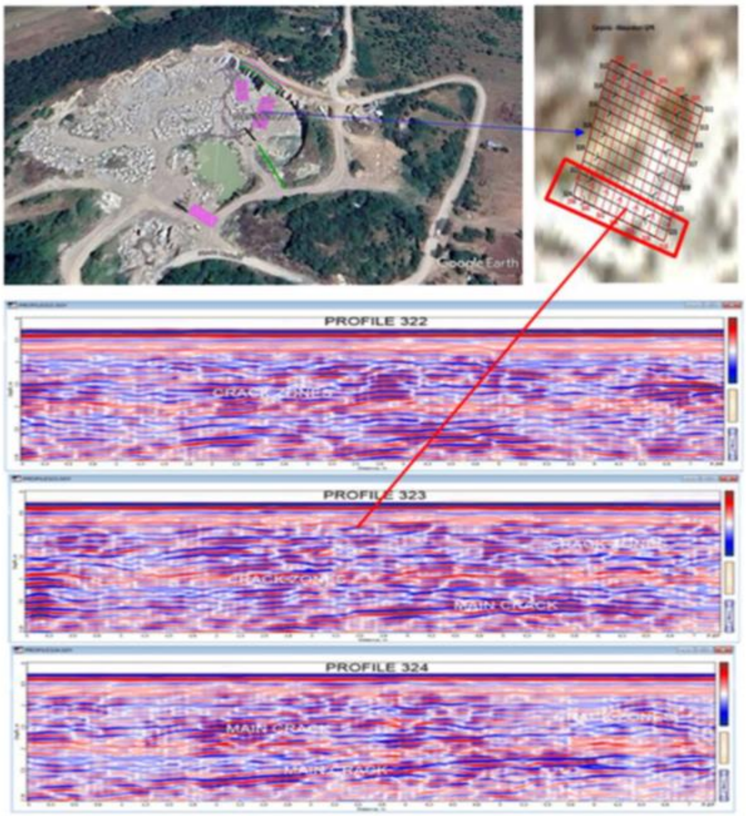

Fig.9. Carpinis Quarry and location of GPR measurement profiles and radargrams

4. Digital Analysis and Processing

4.1. Image processing techniques

Advanced image processing algorithms can be applied to extract fracture information from digital imagery. These techniques can automatically detect and measure fracture properties such as orientation, spacing, and persistence. [7, 8]

Machine learning approaches, including convolutional neural networks, have shown promise in automating fracture detection and classification.

Before the extraction algorithms are applied, the point cloud has to be classified (only the point cloud representing the terrain is retained, and other features, such as vegetation, are removed). [9, 10]

This is further processed by calculating the normals / poles of the planes that are formed by joining the points. An ultra-efficient algorithm is Hough Normals, which uses Machine Learning techniques, namely CNN - Convolutional Neural Networks (Fig. 10).

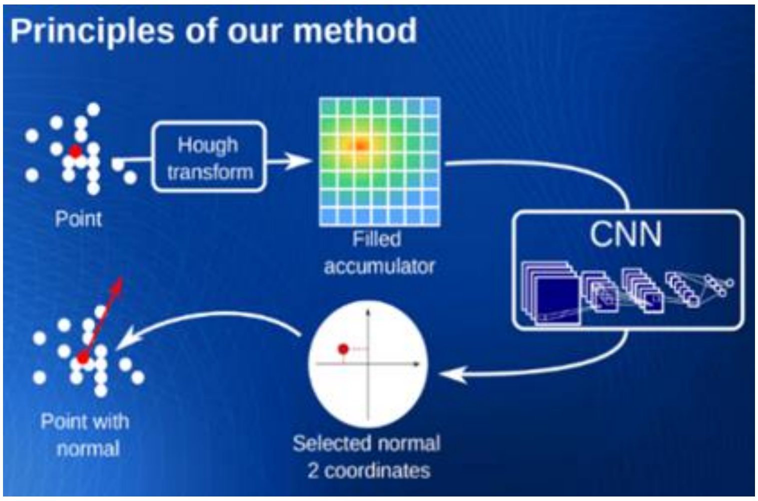

Fig.10. Cloud processing to extract discontinuities by computing Normals using CNN

4.2. Machine Learning and Deep Learning Approaches

Machine learning algorithms, particularly deep learning models, have demonstrated significant potential in automating the process of fracture detection and characterisation.

These approaches can analyse large datasets of images or point clouds to identify patterns and features that may be difficult for human observers to detect consistently. [11, 12, 13]

a) Discontinuity Extraction Methodology using CloudCompare

The first method utilises the open-source program CloudCompare, employing two techniques: K-D Tree and Fast Marching. The results are shown in Fig. 11 - 12.

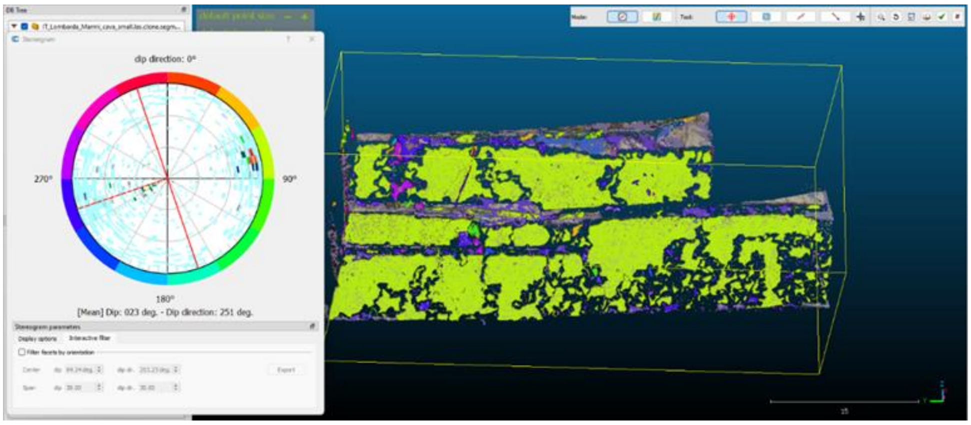

Fig.11. Classification of face discontinuities by azimuth/ inclination - Fast Marching

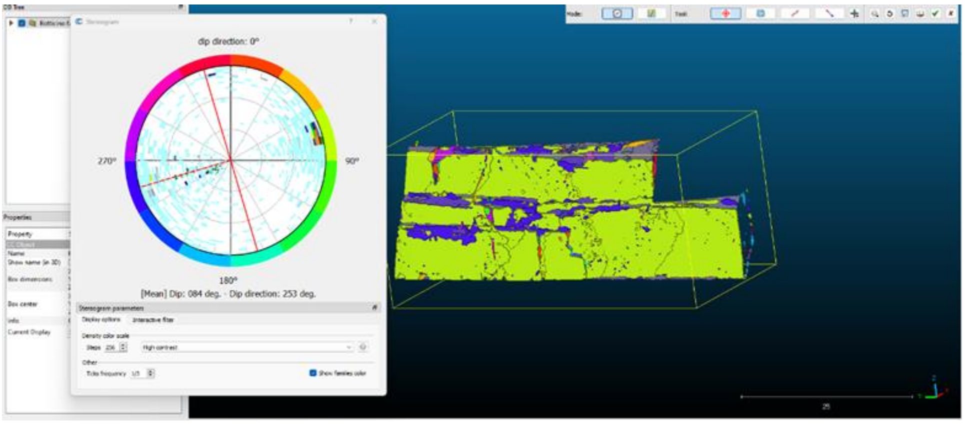

Fig.12. Classification of face discontinuities by azimuth/ inclination - K-D Tree

b) Discontinuity extraction methodology using Discontinuity Set Extractor

This method identifies and defines the algebraic equations of the different planes of the rock mass surface, using the coplanarity test, with the determination of the main orientations - Kernel Density Estimation (KDE) and the identification of crack families with the DBSCAN algorithm - Density-Based Scan Algorithm with Noise. The results are shown in Fig. 13 - 14. [14, 15]

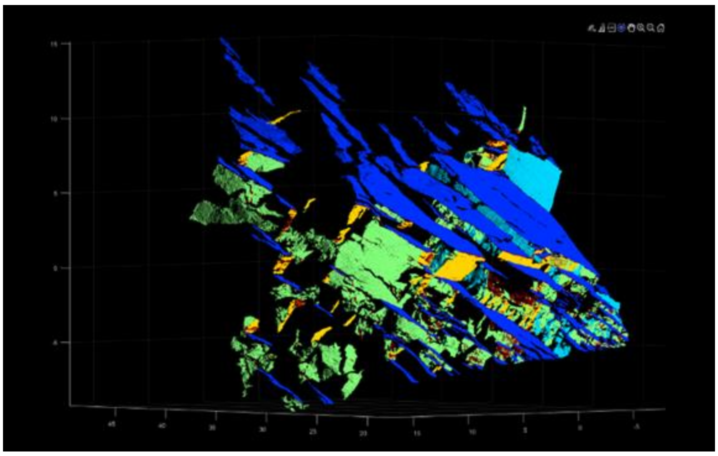

Fig.13. Discontinuity set assignments – families J1, J2, J3, J4 and J5

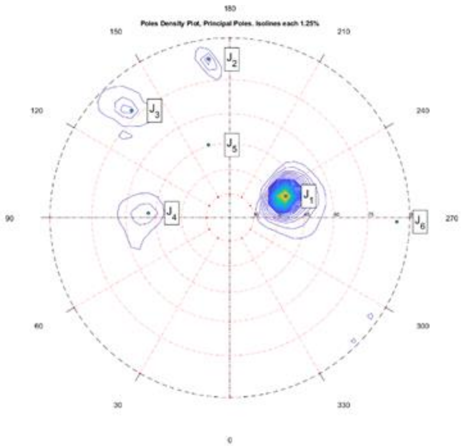

Fig.14. Stereographic projection of main poles

c) 3D Modelling and Visualisation

Three-dimensional modelling and visualisation techniques allow for the creation of comprehensive representations of fracture networks within dimension stone deposits. These models can integrate data from multiple sources, including TLS, photogrammetry, and borehole surveys, to create a holistic view of the deposit's structure.

Advanced visualisation tools, such as virtual reality and augmented reality, can enhance the interpretation and communication of complex fracture systems. Project AI-COSTSQO developed a SaaS with a very powerful 3D visualisation of the blocks and generating DFNs, accordingly. [5, 16, 17]

Fig. 15 shows the first version of the software visualising discontinuities (and their intersections), and the corresponding DFN and Fig. 16 presents a DFN generated in Version 2. [18, 19]

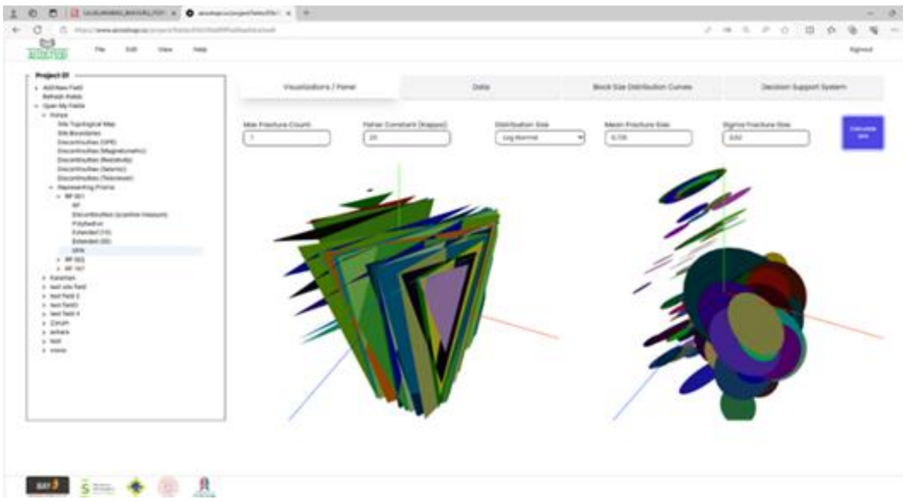

Fig.15. Representation of a DFN system in the SaaS web portal – Version 1

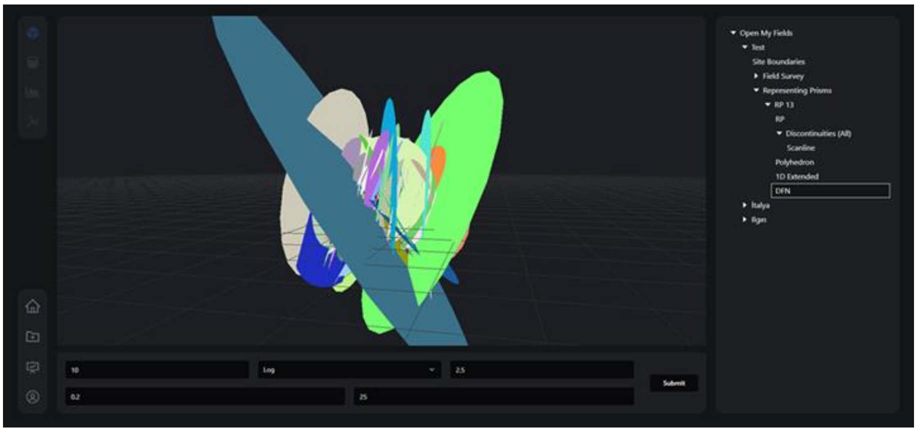

Fig.16. AI-COSTSQO SaaS program interface and DFN representation – Version 2

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5. Integrated Approach

5.1. Combining Multiple Data Sources

An integrated approach that combines data from traditional field surveys, advanced remote sensing techniques, and subsurface investigations provides the most comprehensive characterisation of fracture systems in dimension stone deposits. [20]

This multi-method approach allows for the cross-validation of observations and helps overcome individual techniques' limitations.

5.2. Workflow for Comprehensive Fracture Characterization

A systematic workflow for fracture characterisation in dimension stone deposits should include the following steps:

- Initial site assessment and geological mapping;
- Remote sensing data acquisition (TLS, UAV photogrammetry);
- Subsurface investigation (borehole surveys, GPR);
- Data processing and integration;
- 3D model creation and visualisation;
- Fracture network analysis and interpretation;
- Validation through field observations and sampling.

5.3. Case Studies Demonstrating Effectiveness

Several case studies have demonstrated the effectiveness of integrated approaches in characterising fracture systems in dimension stone deposits.

The authors and AI-COSTSQO team members have used the above workflow for the following quarries:

- Romania:
  - Ruschita – marble;
  - Carpinis – travertine;
  - Pietroasa – andesite.
- Italy:
  - Botticino – marble.
- Turkyie:
  - Onur – marble.

6. Implications for the Dimension Stone Industry

6.1. Improved Deposit Evaluation and Block Size Estimation

The integrated approach to fracture characterisation enables a more accurate evaluation of dimension stone deposits. By providing a comprehensive understanding of the fracture network, quarry operators can better estimate the size and quality of extractable blocks, leading to more efficient resource utilisation and reduced waste.

Generation of Block Size Distribution Curves and delineation of the commercial limits are performed in AI-COSTSQO SaaS.

6.2. Optimised Quarry Planning and Extraction

Detailed 3D models of fracture systems allow for optimised quarry planning and extraction strategies. Quarry operators can use this information to design cutting plans that maximise the yield of high-quality blocks while minimising waste and operational costs.

Again, algorithms are used in AI-COSTSQO software for optimisation, such as SlabCutOpt.

6.3. Reduction of Waste and Environmental Impact

By improving the accuracy of deposit evaluation and extraction planning, the integrated approach to fracture characterisation can significantly reduce waste in dimension stone production.

This not only improves the economic efficiency of quarry operations but also reduces the environmental impact of extraction activities. This action aligns with EU ECO-LABEL standards – which were also integrated into AI-COSTSQO SaaS.

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7. Conclusion and Future Directions

Integrating advanced detection methods, digital analysis techniques, and traditional geological surveys represents a significant advancement in characterising joints and fractures in dimension stone deposits. This comprehensive approach provides a more accurate, efficient, and detailed understanding of fracture systems, enabling improved quarry planning and operation decision-making.

Future research should focus on further automating the process of fracture detection and characterisation, developing more sophisticated machine-learning models, and improving data integration from multiple sources. Additionally, developing real-time monitoring systems for fracture evolution during quarrying operations could further enhance the safety and efficiency of dimension stone extraction.

As technology continues to advance, the dimension stone industry stands to benefit significantly from these integrated approaches to fracture characterisation.

By embracing these methods, quarry operators can improve their operational efficiency, reduce waste, and minimise environmental impact, ensuring the sustainable exploitation of dimension stone resources for years to come.

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