OSnet

Dimension Stone quarrying in Europe and stability of quarrying operations

OSnet
Ornamental Stones network

EUROPEAN COMMISSION
Competitive and Sustainable Growth Programme

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OSNET Editions
Volume 2

Edited by: N. Terezopoulos, I. Paspaliaris

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Part A: Review of Dimension Stone quarrying in Europe

Part B: Control and Monitoring of stability conditions in Dimension Stone exploitation: methods and instruments

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Forward

Quarrying is one of the most important stages in the production of ornamental and dimension stones as many critical parameters concerning the cost and the quality of the final stone product and defined at this stage. Moreover, due to the huge quantities extracted material and the big amounts of the waste material produced it is necessary to exploit the store reserves in a reasonable way in order to avoid the various environmental problems that may be encountered. On the other hand quarrying is a very difficult task including a lot of uncertain factors and in this respect stability and thus safe operation of the quarries is of at most importance.

This work is part of a wider attempt aiming to address key issues concerning the qurrying operations and also improve performance and competitiveness of the European ornamental and dimension stone sector.

I am sure that this study has been carried out in the framework of the Ornamental and Dimensional Stones Network (OSNET), funded by the European Commission, under the Growth Programme will considerably contribute in this direction.

Prof. I. Paspaliaris

OSNET Coordinator

Preface

OSNET is a Targeted Thematic Network on Ornamental Stones in Europe which primarily aims to provide the forum to share problems and experience and to facilitate the transfer and incorporation of technology to the market.

The Quarrying industrial sector is very important in European Union (EU). The production and consumption of ornamental and dimensional stone has been continuously increasing over the past twenty years at an annual rate of 7%. A large portion of the produced raw materials is exported to third countries after appropriate processing.

The problems faced by the industry are the “low recovery of raw material” and the “generation of wasted raw material” and “poor safety conditions”. Methods of quarrying have also to be improved because they heavily depend on manual work. From the whole production of a dimension stone quarry only 10-15% results a good quality final product. The rest results as wasted raw material. The average waste production in quarries in the EU is estimated to be about 40-50 million tones. This huge quantity of wastes produced represents a serious environmental threat and the ornamental stones industrial sector seeks appropriate modifications in quarrying and processing technology in order to minimise wastes. The cost of production is also high and not competitive. For many years poor safety conditions during mining (mainly underground) led to serious accidents for the workers and the facilities in general. Nowadays although working conditions have improved, unpredictable accidents still occur.

The Quarrying Sector of OSNET is expected to focus on the quarrying methods and technologies, traditional and modern, investigate the possibility of improving the existing problems, and familiarize the industry with the new improvements.

As the Sector Leader of the Quarrying Sector, I believe that through this edition entitled “Dimension Stone quarrying in Europe and stability of quarrying operations” an essential contribution was made towards the above mentioned targets. The completion of the edition was a result of hard work by people with many years in the stone industry and great experience and expertise. As a consequence of this work is a comprehensive, easy to study and complete report which summarizes all aspects of the Quarrying Sector industry, which can be used as a reference especially by SME’s.

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PART B

Summary

In Europe, more than any other part of the world, ornamental stone has been throughout in history and is at present time, an important construction material. Worldwide use and production of stone is steadily increasing, and during the last 30 years, the technological development within the sector has been tremendous. Europe counts for approximately 35-40 percent of world production and consumption of stone. The European stone quarrying industry shows great variations in size of operation and thus the level of industrialisation and application of new technology. Nevertheless, the ornamental and dimensional stone quarrying industry in Europe will be facing great challenges in the years to come; the import of stone from low cost countries is increasing and the quarrying sector faces more and more regulations and environmental restrictions.

The quarrying of ornamental and dimensional stone is generally not covered by mining laws in Europe, and there are no European directives on quarrying, mineral right claims and exploration. The practises and legal framework on mining vary significantly throughout Europe, including the way stone is treated compared to other mineral commodities. The commencement of ornamental and dimensional stones exploitation activities, as well as, the production development of operating quarries, is today dependent on strict environmental regulations. The most important environmental issues for the ornamental and dimensional stone quarrying are waste handling (rock fillings and dust), direct impact (noise, visual impacts, dust) and land use (competing interests). The EU Policy regarding waste focuses on two aspects – handling and prevention. A directive for handling mining waste is in progress, and Eco-labelling criteria for hard floor coverings, including stone, have recently been established. The document has raised discussions within parts of the stone industry. Regarding land use, the NATURA 2 000 areas in particular can cause operational problems to any quarrying activity. Rehabilitation, during and after quarrying has become a determined requirement and obligation.

Regional and quarry scale geological exploration defines the rock type, the structure, the volume and quality characteristics of the economic target. Reserve estimation and feasibility studies aim to optimise the quarrying operations to be undertaken. Rational exploitation plans aim to increase the recovery rate and minimize the waste production. Economic evaluation of ornamental and dimensional stone deposits can be complicated, and require very detailed knowledge of the sector. At present, the education and training of geologists/mining engineers on ornamental and dimensional stone is very limited throughout Europe, and (compared with other mineral commodities) the number of professionals working in the sector is small.

The future of the ornamental and dimensional stone industry in Europe depends on a proper management of the resources. At the present time, the extractive industry is subject to a strong pressure from other needs of the society, ranging from urbanisation of traditional quarry areas to the formation of an increasing number of natural habitats, national parks and recreation

areas. There are many examples of quarries that have been forced to close down, or concentrate their activity to smaller and less productive areas. Of importance for a better and less fragmented management of the stone deposits in Europe would be a catalogue easily available with useful information about the most important deposits.

In recent decades, there has been a tremendous development of new technology for dimension-stone quarrying, especially regarding sawing techniques, drilling and handling. Generally, sawing is substituting other methods for a variety of rock types, and is getting more and more usable also for the hard ones. However, there are still large differences in extraction methods, and there is probably a large potential both in the development of new, innovative technology (especially for hard rocks), further improvements of established technology and in the exchange of knowledge between different regions. A special challenge exists in the application of quarrying technology – optimising available methods to specific quarries, and selecting the most efficient, productive and environmentally methods.

Finding efficient and high–productive quarrying operations is of great importance. In this context, underground quarrying has great advantages, and is becoming more and more common for "soft" rock types. Interesting new technology and methods are preparing grounds for underground quarrying of also hard rocks.

One of the great challenges for the ornamental and dimensional stone industries is the utilization of quarry waste. There are several interesting examples of developing commercial by-products from waste, increasing the overall exploitation efficiency of the stone deposits. Turning waste into resources is one of the most important issues for the industry in the future, as is the proper handling and disposal of non-useable waste, and local/regional planning for alternative uses of waste and closed-down quarries.

Part A entitled “Review of Dimension Stone quarrying in Europe” is an attempt to summarise some characteristics of the ornamental and dimensional stone quarrying industry throughout Europe and underline the challenges that this sector is facing. Furthermore, it seeks to highlight some of the most important innovative technologies and methods contributing to improve the viability and sustainability of ornamental and dimensional stone quarrying. In addition to quarrying itself, the edition also deals with other important aspects directly relevant to quarrying – such as exploration, some environmental issues, management of deposits and handling and use of waste rock.

A very important aspect concerning stone exploitation, both underground and open pit, is the stability condition of the excavation. The last fifty years an evolution has been observed from an occasional qualitative observation of the physical phenomena involved in stone quarrying such as convergence, settlement, collapse, rock burst, swelling and drainage, to the establishment of a scientific methodology that theoretical and interpretative supports the increasing number of observations acquired through methodical measurements and experimental controls. The stability of the excavation, the excavation methods used, the duration and the recovery of the quarry are all fundamental objectives that have to be accomplished when planning a quarrying activity, despite the many difficulties involved.

The target of this new approach is the minimisation of the geological risk, which in engineering terms is the achievement of the best safety conditions in the working area at the lowest cost, and the improvements in the safety conditions of excavations. The basic characteristic of modern design approaches for stone exploitations is a geognostical - geotechnical investigation carried out before, during and after the execution of the excavation. Investigations are performed before the excavation to collect the project data, during the excavation to verify the plan hypotheses, and after the excavation to check the effectiveness of the employed excavations methods over time. It will then be possible to formulate a comprehensive description of the possible relationships between the planned excavations and the pre-existing natural state of stress, and afterwards to evaluate the environmental impact of the underground exploitations.

Part B entitled “Control and Monitoring of stability conditions in Dimension Stone exploitation: methods and instruments” is an attempt to summarise the available methodology and instrumentation, in terms of minimising the geological risk and improving safety factors. It describes the most common methods and devices utilised to measure the state of stress (natural and induced by the excavation), the groundwater pressure and the displaced around the excavation, both during the design phase and during the excavation and the most promising developments in the field of monitoring.

Ornamental and dimensional stone quarrying in Europe is characterised by a great variation in traditions, extraction methods and, not at least, rock types. To give a complete picture of everything happening within the sector would demand far more pages and time than available. However, the edition has been “coloured” with examples and case studies from several countries like Greece, Italy, Portugal, Sweden, Finland and Norway having a more general validity.

The terms "ornamental” and “dimensional” stone used in this edition include all types of building stone, such as slate, marble, granite, soapstone etc.

Part A

"Review of Dimension Stone quarrying in Europe"

1

Introduction

TOM HELDAL , NIKOLAOS ARVANITIDES

The exploitation and use of ornamental stone in Europe dates back to Antiquity. In Europe, more than any other part of the world, stone has been an important construction material throughout history, and stone is the primary material of which our rich cultural heritage is made.

It is difficult, probably impossible, to estimate the exact number of stone quarries throughout Europe. However, within the EU/EFTA countries, the number of unique stone types approaches 2500 (Figure 1). While not all of these are operating quarries, most of them are at present time in production. A considerable amount can be characterised as "classic European stones", meaning that they have been produced for more than a century and have contributed to the architectural heritage of Europe.

Some ornamental and dimensional stone quarries are large-scale, comparable in size with large mining operations. Others are smaller, involving regular or periodic extraction of small volumes of stone. Others again, involve combined extraction of ornamental and dimensional stone and other mineral products, such as rock aggregate or industrial minerals. Thus, the European stone quarrying industry show great variations in size of operation and thus the level of industrialisation and application of new technology.

The economically most significant part of the European stone industry is located in Mediterranean Europe – Italy, Spain, France, Portugal and Greece; these countries account for 90% of EU production[1]. This is partly due to the geology (large marble and granite resources), but also because of strong traditions for producing and using stone. In several Central and Northern European countries, urbanisation and a general decline in the stone industry in the Early to Mid 20th century led to closure of a large amount of quarries. However, at the present

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[1] Production quantities (European Minerals Yearbook 1996/1997)

time, the ornamental and dimensional stone industry is more vital than ever. Worldwide use and production of stone is steadily increasing, and during the last 30 years, the technological development within the sector has been tremendous. The European stone industry counts approximately 35-40 percent of the world production (ca. 20 mill. tons)[2]. Europe's share of the world consumption is almost equal (37 percent).

Nevertheless, the ornamental and dimensional stone quarrying industry in Europe will be facing great challenges in the years to come; the import of stone from low cost countries is increasing and the quarrying sector faces more and more regulations and environmental restrictions. Although the stone sector has deep roots in European history, these are important challenges that must be solved in order for the industry to be as successful in the future as it has been in the past.

This dual pressure on the industry from both increasing competition and environmental demands is expressed by an EU Commission Communication[3]:

"The objective of this Communication is to set the broad policy lines for promoting sustainable development in the EU non-energy extractive industry by reconciling the need for more secure and less polluting extractive activities while maintaining the competitiveness of the industry."

On the competitiveness, the Communication says:

"The most important factors for the competitiveness of all sub-sectors of the industry include human resources, land access, a stable and predictable legal framework generating legislation proportionate to the objectives sought, research and technological development, availability of infrastructure, including transport, low freight costs and energy supply."

This edition – State of the art of European ornamental and dimensional stone quarrying – focuses on some of the most important aspects of the quarrying sector: the legal framework, environmental aspects, geological investigations, quarrying technology and waste[4] handling. It addresses, furthermore, some key problems that could benefit from cooperation between industry and the R&D sector on a European level, either with respect to research, networks or technology transfer. In the quarrying sector, the main questions raised concern the quality upgrading of the exploitable resources, the increase of the recovery rate and the minimization of the quarry-waste production.

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[2] See http://www.immcarrara.com/stat/index.html and http://www.marbleandmore.com/econ/econ.asp

[3] Communication from the Commission: Promoting sustainable development in the EU non-energy extractive industry. COM (2000) 265

[4] "waste" is here defined as left-over stone in ornamental stone production, possibly usable for other purposes, not to be confused with hazardous materials.

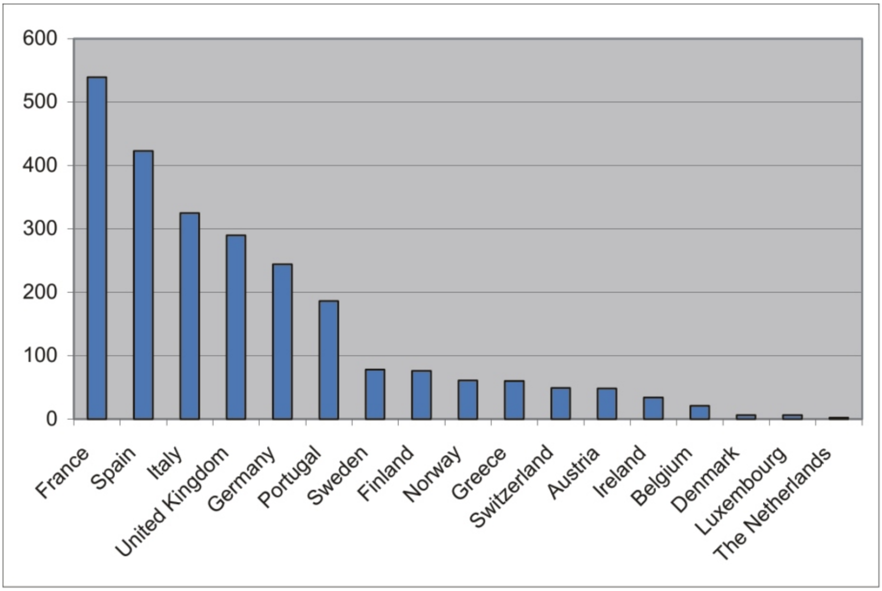

Figure 1. Number of ornamental and dimensional stone types produced by country[5]

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[5] CEN EN12440:2000, annex

2

Stone and legislations

TOM HELDAL , NIKOLAOS ARVANITIDES

2.1. Variations through Europe

The quarrying of ornamental and dimensional stone is generally not covered by mining laws in Europe[6] and there are no European directives on quarrying, mineral right claims and exploration. The practises and legal framework on mining vary significantly throughout Europe, including the way ornamental and dimensional stone is treated compared to other mineral commodities.

In most cases, the mining laws in European countries deal with metallic ore alone, or include a selection of industrial minerals commodities. The exploration and mining of ornamental and dimensional stone (as well as aggregate, gravel and sand) is usually excluded from the national mining laws, and there are no national licensing systems for exploring or extracting such. Stone deposits belong, therefore, to the landowner and not to the "government's right". However, all mineral development and, in some cases, exploration usually requires planning permission from a mineral planning authority.

The procedure in most countries concerning exploration and extraction of ornamental and dimensional stone can be summarised as follows:

- Initial investigations – agreement with landowner.
- Exploration/pilot quarrying – exploration permission (local/regional authorities, mineral planning authority).

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[6] Some exceptions exist. In Finland, marble and soapstone are treated within the mining law, whereas granite is not. The reason for this different treatment is probably that the mining of marble and soapstone building stone often are closely related to extraction of industrial minerals from the same sources.

- Planning of extraction – environmental assessment/planning.
- Quarrying.

On a European level, the greatest attention is paid, at present, to the environmental side of quarrying (see below). Some countries have on their own initiative, changed their legislation framework (or are in a process of doing so) in order to increase the industrial activity in the mining and ornamental and dimensional stone sector. Rationalisation of the mining legislation in Finland and Sweden in the early 90's resulted in a substantial increase in metallic ore and industrial mineral exploration activities.[7] However, this legislation only partly involves stone. A more detailed investigation and benchmarking of common practises/legislation on ornamental and dimensional stone in European countries could help develop "best practice" solutions for the future, and perhaps improve the overall competitiveness of the industry. Such questions could be raised within the OSNET framework.

Regulations for small stone quarries?

There are many small-scale ornamental stone quarries in Europe, either producing for restoration purposes or just keeping alive old traditions. However, the legislations in most countries do not differentiate between such activity and large scale quarrying. Therefore, the extraction of two restoration blocks a year for the restoration of a medieval church is subject to the same procedure of environmental risk assessment, backfilling, etc. as a 1 million ton aggregate quarry. Surely, it is not of the interest of the European Community to loose neither the historical stones nor the traditional skills necessary for working them. Thus, regulations must be changed to fit this kind of "artisan quarrying". Steps have been taken in Belgium, to prepare own regulations for historical quarries.

Source: Jean Feraud, BRGM, France.

2.2. Important environmental issues

The Extraction and use of **mineral resources in general** raises several concerns regarding the environment:

1. Use of non-renewable resources may cause limited availability for future generations.
2. Direct impacts on the local or global environment, such as dust, noise, visual impact, disturbance of natural habitats, eco-toxicological pollution and effects on ground water levels.
3. Indirect impacts on the environment e.g. use of energy in the production process and life-cycle patterns of the materials.
4. Risk of disasters during extraction and distribution.

These concerns vary significantly depending on the type of mineral resource and characteristics of the production site. **Regarding ornamental and dimensional stone**, the first and third points are almost irrelevant: although stone is a non-renewable resource, there is no risk of a future lack of such resources. Furthermore, the indirect impacts are considered to be much lower than many other construction materials. The consumption of energy for production and transportation of stone is low, even for the most sophisticated ornamental stone products. The material itself is durable and long lasting, and the recycling ratio is high.

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[7] Promoting sustainable developments in the EU non-energy extractive industry. Communication from the Commission, COM (2000) 265 final.

As the eco-toxicological pollution from ornamental and dimensional stone production is small or absent, the main direct impacts relate to noise, dust, visual impact (Figure 2) and effect on landscape and natural habitats.

The recovery rate for ornamental and dimensional stone quarrying varies from 5 to 50 percent. This is a high rate compared to the recovery of metallic ore, but lower than aggregate and some industrial minerals. In addition to the actual use of land for quarrying, the handling of waste rock is considered to be the stone sector's largest environmental issue. Although the waste rock has the same composition as the surrounding bedrock, and does not contain any toxic additives, the huge waste dumps seen in many quarry areas cause a significant visual impact on the environment. The quarrying technology is improving, contributing to increase the recovery. However, the strong international competition as well as demand for better quality raw material in the processing industry has driven recoveries in the opposite direction. As a consequence, the recovery of ornamental and dimensional stone resources has not improved significantly during the last decades.

The utilisation of waste rock for other products, such as aggregate or industrial minerals, is increasing, and this issue is perhaps one of the most important future developments towards a more sustainable and eco-efficient stone production. The handling and utilisation of waste will be treated separately in chapter 7.

The most important environmental issues for the ornamental and dimensional stone quarrying can be summarized as follows:

- Waste handling (rock fillings and dust)
- Direct impact (noise, visual impacts, dust)
- Land use (competing interests)

2.3. European directives and policy

The activities of the stone industry are governed by EU Directives on waste/landfill, water, air quality, nature conservation, birds, habitats and Natura 2000. The Directive on environmental impact assessment covers quarries where the surface of the site exceeds 25 hectares.

In this report, only some of the **key factors** involving exploration and quarrying will be discussed.

The EU Policy regarding **mining waste** focuses on two aspects – **handling** and **prevention** of waste. Regarding handling of waste (at present covered by the Landfill Directive), a new directive on *"Management of waste resulting from prospecting, extraction, treatment, and storage of mineral resources"*[8] is in progress (second draft in circulation). Comments on the draft proposal from several institutions and organisations reflect some controversy regarding the view on waste from aggregate and stone quarrying. Such "waste" has the same composition as the soil and bedrock of a specific quarry site, no toxic constituents are added (the waste is inert) and it could be viewed as "leftover stone" with possible future use rather than "waste". Such arguments are also reflected in various practises throughout Europe on the handling of waste from ornamental and dimensional stone quarries. For example, in Sweden, waste rock from quarries has to be disposed of in a way that secures a future utilisation of the material. In other words, the "waste" is viewed upon as a possible future resource. On the other side of the scale, Portugal has a different practise, considering the leftover stone

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[8] http://europa.eu.int/comm/environment/waste/mining.htm

material which is not immediately used in the quarrying process, to be waste and nothing else, and to be buried and covered with soil once and for all.

Waste or by-product?
What is called "waste" by some is called "by-product" by others. According to Commission Decision 2000/532/EC, waste rock from ornamental and dimensional stone quarries belongs to the category called *"waste from mineral non-metalliferous excavation"*. A recent decision by the Court of Justice of the European Communities made clear the legal meaning of such leftover stone. The judgement (18 April 2002, case C-9/00) was based on a case from Finland, regarding a dispute between a company (Palin Granit) and the local authorities:

"Palin Granit and the joint board brought an appeal before the Korkein hallinto-oikeus challenging the classification of the leftover stone as waste. Palin Granit submitted that the leftover stone, whose mineral composition was identical to that of the basic rock from which it was quarried, was stored for short periods for subsequent use without the need for any recovery measures and did not pose any risk to human health or the environment."

However, this view did not reach through to the court, which concluded:
"The holder of leftover stone resulting from stone quarrying which is stored for an indefinite length of time to await possible use discards or intends to discard that leftover stone, which is accordingly to be classified as waste within the meaning of Council Directive 75/442/EEC of 15 July 1975 on waste."

Furthermore,
"The place of storage of leftover stone, its composition and the fact, even if proven, that the stone does not pose any real risk to human health or the environment are not relevant criteria for determining whether the stone is to be regarded as waste."

Although the legal side is made clear, it is obvious that considering the quarry waste as a potential resource and stimulate for uses, is the best practise from an environmental point of view.

Other reactions to the draft directive include the proposed procedures for documentation and monitoring waste; it could be questioned if a small enterprise disposing small volumes of inert waste each year should need to do the same amount of documentation and monitoring as a sulphide mine. Problems related to handling and utilisation of waste will be further treated in the last chapter of this report.

Regarding waste prevention, some important goals can be read from the documents preparing the 6th Environmental Framework Programme[9]:

- Identify and encourage substitution of the hazardous substances that present the biggest problem in different waste streams.
- Integrating waste prevention objectives and priorities into the Community’s Integrated Product Policy.
- Encouraging the use of economic instruments, for example, eco-taxes on resource- and waste-intensive products and processes.

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[9] On the sixth environment action programme of the European Community: ”Environment 2010: our future, our choice”. Proposal from the Commission to the European Parliament and of the Council. COM (2001) 31 final.

- Influencing consumer demand in favour of products and processes that give rise to less waste e.g. via green procurement policies, eco-labels, information campaigns, and other tools.

The first point is not very relevant for ornamental and dimensional stone, since the waste in no cases can be defined as hazardous. Of great importance to the stone industry, however, are the guidelines for *"Eco-labelling of hard floor coverings"*[10]. This has been voted upon in the Regulatory Committee (of the Eco-label Unit of the European Commission) meeting of 5 December 2001. The Decision will be translated into the 11 official European languages, adopted by the Commission and published in the Official Journal. Eco-labelling is voluntary, and is meant as a tool for stimulating *"ecological behaviour"* among producers and consumers. It differentiates between *"Natural products"* (ornamental and dimensional stone) and *"Processed products"* – hardened (agglomerated stones, concrete paving units and terrazzo tiles) and fired products (ceramic and clay tiles). For natural products, the criteria are largely concentrated on the raw material extraction operations, e.g. quarrying. The criteria for the processed products are, on the other hand, more focused on the processing stage of the production.

Among the most important criteria for ornamental and dimensional stone production are the following:

- Recovery of commercial blocks (marble 20%, granite 30%, other stone 10%[11]).
- Natural resource appreciation or total recovery of the deposit, including uses of leftover stone as aggregate, industrial minerals etc. (marble and granite 35%, other stone 25%).
- Water recycling ratio >80%.
- Rehabilitation simultaneity degree.
- Air and water quality.
- Noise (<60 db along border of quarry area).
- Visual impacts.
- Working conditions of operating equipment.

The document has raised discussions within parts of the stone industry, especially regarding the block recovery criteria, which possibly will exclude a significant part of the European stone industry. The critics emphasize that the criteria "discriminate" natural products, and that they are not well adapted to the real situation in ornamental and dimensional stone quarrying. In several countries, there are now ongoing studies on life-cycle analyses for ornamental and dimensional stone. Such studies will perhaps bring new aspects into the discussion, and contribute to improve the eco-labelling criteria for the next revision in a few years.

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[10] http://www.europa.eu.int/comm/environment/ecolabel/producers/pg_hardfloor.htm

[11] Exclusion hurdle

Life cycle studies

Ongoing project in Finland : *"Development of an environmental database management system for natural stone industry and the life cycle of natural stone production"*. This cross-scientific project aims to find out about the actual environmental impacts of Finnish natural stone production by measuring the environmental loadings of natural stone production during its life cycle (impacts on ground water, noise, tremor, radiation, production release and production residue impacts). The project will build an environmental GIS- and Internet-related database management system for the small-scale Finnish natural stone industries. Using the gathered information, a life cycle analysis/assessment (LCA) concerning natural stone production will be made.

Source: http://kiviteollisuusliitto.gsf.fi/environmental.html

Like all extractive industries, ornamental and dimensional stone quarrying is dependent on **access to land**. The mineral industry is often one of a number of competing land uses, and has in an increasing amount of cases, lost the "battle" on land access. During the last decades, restrictions have been put to any industrial use of an increasing part of the areas in Europe, either through national legislations (national parks, nature conservation areas) or through EU directives[12].

The Directive (92/43/EEC) **on the conservation of natural habitats and of wild fauna and flora** addresses the establishment of a network of sites for the conservation of natural habitats. These sites are known as **NATURA 2000** areas. The directive sets out the framework for site conservation and protection, and includes proactive, preventive and procedural requirements. A Community list of such areas is established, and member states shall act in a way to ensure that the aims of the directive is not jeopardised. Furthermore, Member States are advised to abstain from any activity that can cause deterioration of a site on any national list, or a site that, on the basis of the criteria, ought to be on a list. NATURA 2000 areas also include sites under protection according to Directive (79/409/EEC) **on the conservation of the wild birds**. Extractive industry within NATURA 2000 sites is not excluded, but the sites are under strong protection[13].

However, although the number of protected areas in Europe is increasing rapidly, there is still, in many places, a lack of any integrated land-planning framework seeking to balance competing interests between national and local levels and between mining and conservation. In this context, the industry could work together with planning authorities and governments and find *"better practises that can help achieve a better relationship between protected areas and other land uses, such as how to incorporate areas of known mineral potential into decision-making about new protected areas"*[14]

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[12] EU documents on nature protection are found at http://europa.eu.int/comm/environment/nature/home.htm

[13] Assessment of Plans and Projects Significantly Affecting Natura 2000 Sites: Methodological Guidance on the provisions of Article 6(3) and 6(4) of the 'Habitats' Directive 92/43/EEC. http://europa.eu.int/comm/environment/nature/natura.htm

[14] Breaking new ground: the report of the mining, minerals and sustainable development project, May 2002. http://www.iied.org/mmsd/

Figure 2. Visual impact? Quarry and scenery.

Protected areas

Protected areas now cover approximately 10% of the earth's land area. Governments are responsible for the management of their own protected areas, but have international obligations, e.g. through EU. Some important protected areas are recognised under other international agreements, such as the World Heritage Convention. The World Conservation Union (IUCN) has made criteria for categorizing natural, protected areas:

- Strict nature reserve or wilderness area (for scientific purposes or wilderness protection).
- National parks (for ecosystem protection and recreation).
- Natural monuments (for conservation of specific natural features).
- Habitat or species management areas (for conservation through management intervention).
- Protected landscapes or seascapes (for landscape protection and recreation).
- Managed resource protection areas (for the sustainable use of natural ecosystems).

Source: Breaking new ground: the report of the mining, minerals and sustainable development project, May 2002. http://www.iied.org/mmsd/

3

Exploration and Prospecting – Economic target selection

TOM HELDAL, NIKOLAOS ARVANITIDES

3.1. Ornamental stone – the aesthetic mineral resource

Ornamental and dimensional stone differs from other mineral resources in several ways. First of all, stone quarrying is the art of collecting whole, massive pieces of rock, without the need for crushing, grinding and separation of individual minerals. Furthermore, stone processing does not include removal of "unwanted" components from the rock; it simply deals with a more or less advanced way of shaping pieces of rock into finished products. Stone products of excellent quality may readily be produced using simple tools and manpower, although the extraction and processing may equally involve the use of highly sophisticated machines. Applications vary from crudely shaped blocks for local housing to polished slabs cladding skyscrapers in the cities around the world.

The market for stone products depends highly on the consumer's personal taste and on fashion trends. Thus, the aesthetic properties of the rocks are often more important than physical and chemical properties. Predominantly, rare colour s such as blue, yellow, pure white and deep black are highly priced, whilst rocks of more 'ordinary' colours obtain lower prices. For rough blocks, the most exclusive rocks may be 20 times more expensive than the cheapest.

Building stones are often classified according to their technical quality and usability. A standardised, international classification scheme does not exist, but it is common to differentiate between massive stone (extracted in large blocks) and slabby stone, extracted as slabs which are cleaved along a planar structure, such as sedimentary layering or metamorphic foliation – e.g. slates. Massive stone is further divided into 'soft' varieties such as carbonates and serpentinite, and 'hard', essentially quartzo-feldspathic rocks.

3.2. Important aspects in the evaluation of ornamental and dimensional stone deposits

The evaluation of ornamental and dimensional stone deposits differs significantly from other types of mineral resources, especially since the quality of the deposits rarely can be established only by objective measurements. The market value depends on the colour and texture of the stone and minor variations in the deposits can have great impact on how profitable the production is. Furthermore, since stone quarrying depends on extracting large blocks without cracks and fissures, the distribution and spacing of fractures in the rock is of vital importance, but can in many cases be difficult to predict.

Generally the evaluation differs between general, geological and industrial features when investigating ornamental and dimensional stone deposits. The general features include:

- Ownership (landowners, mining rights)
- History of operation
- General environmental issues, land use
- Size of quarry/concession area

The geological features can be summarized as follows:

- Regional setting and occurrence
- Geometry and structure (stratigraphy, structural geometry, contact relations)
- Size (realistic depth and area of workable part of the deposit)
- Petrographic characterization (minerals, texture and fabric)
- presence of imperfections (segregations, pyritization etc)
- Quality (durability aspects, physical properties)
- Fractures and faults (spacing, distribution, relations to block yield)

The industrial features include the following:

- Commercial value, market (colour, market concept)
- Access and logistics (roads and infrastructure)
- Use (experiences, references to architectural applications)
- Workability (cutting directions, production properties)
- Working facilities (topography, climate, other activity in the area)
- Area for present and future movement of machinery, explosive magazines, statutory safety zones and basic amenities
- Area for disposal (far from deposit/near to workings)
- Availability of semi skilled and skilled personnel in the region

An investigation program of ornamental and dimensional stone begins with regional investigations and selection of economic targets, based on introductory geological evaluation and market studies. A more detailed study of one or several targets follows, applying geological mapping, core drilling or other specialized methods and sampling. The last step is pilot quarrying.

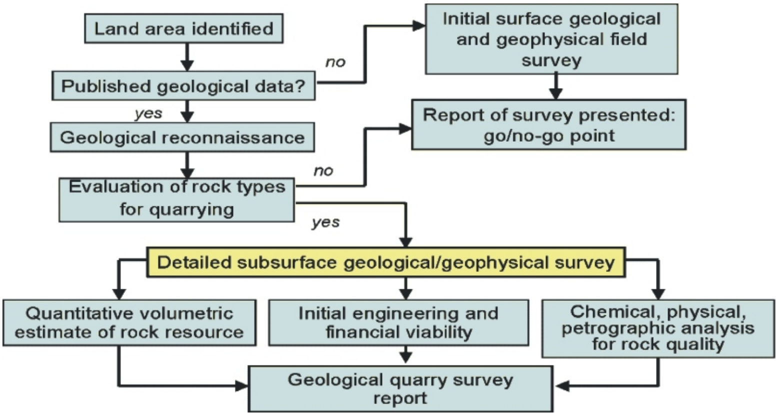

Figure 3. Example of evaluation scheme for ornamental stone deposits. Source: Institute of Geology and Mineral Exploration, Greece.

3.3. Regional scale exploration and surveys

A regional ornamental and dimensional stone survey is often focused on locating potential economic deposits within a geological province – e.g. a granite pluton or a sedimentary limestone basin. A good geological model of the province can be extremely helpful, especially for predicting where the most valuable rock types can be found, and for developing an **exploration model**. The modelling methods vary, depending on the rock types in question. Field reconnaissance is important, following pre-selected targets, such as valuable formations or granite bodies. In some cases, geophysical techniques (generally airborne geophysics in regional surveys) can be valuable; magnetic anomaly maps can, for example, be of use when exploring certain igneous rocks and soapstone. Aerial photographs and/or satellite images may give valuable information for separating fractured from non-fractured rocks.

3.4. Exploration methods

In detailed surveys of ornamental and dimensional stone deposits, there are two aspects of specific importance; the uniformity of the rock (homogeneity of appearance and quality through the workable part of the deposit) and fracturing (size of blocks limited by natural fractures).

Surface investigations include geological mapping of outcrops, sampling and interpretations of fracture systems, deposits geometry, weathering aspects, etc., resulting in a 3D interpretation. Since the evaluation of stone deposits differ significantly from other mineral commodities, geologists with basic knowledge of market aspects and production techniques should carry out surface investigations.

One important challenge in the interpretation of ornamental and dimensional stone deposits is that the commodity includes a wide range of rock types, and there will be differences in how to approach them; investigations of igneous rocks are different from mapping marbles.

Exploration models

A good geological model can be useful for regional ornamental and dimensional stone surveys. The Orivesi granite in Central Finland can serve as an example (Figure 4); the granite is divided in two parts by a fault, and geological investigations by Selonen (1998) concludes that the most interesting stone potential is in the western fault block. The eastern one exposes a higher level of the granite body, which has a less homogenous appearance, containing more dykes, veins and fine-grained granites.

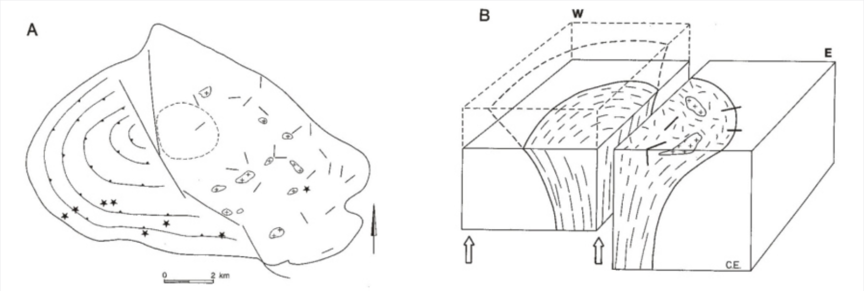

Figure 4. Map and perspective model of the Orivesi granite, Finland. Left: map image. Right: 3D interpretation. Stars (left image) show positions of ornamental stone quarries and potential deposits.

Source: Selonen, O. 1998: Exploration for dimension-stone deposits – geological aspects. PhD thesis, Ebo Akademi Universit y, 64 pp.

For *subsurface investigations* there are different methods, which can be applied. *Core drilling* is still one of the most important techniques for getting underground information. It is, however, expensive, and holes must be well planned and targeted from a good exploration model. Small and light weighted core drilling machines, specially designed for short-hole drilling in stone deposits, are now available.

A cheaper alternative to core drilling is to photograph drill holes made by ordinary quarry drilling machines or well-drilling equipment. An *optical televiewer* is an example; a digital, high-resolution image of the drill hole can give valuable information on both rock types and fractures, and it is also possible to obtain the exact orientation of any planar structure (Figure 7). The experiences so far are fairly good. The costs lay between 30 and 50 percent of regular core drilling.

In recent years, there have been many attempts of using different geophysical methods for predicting subsurface quality, especially regarding fractures. *Ground Penetrating Radar (GPR)* is perhaps the most popular. The penetration depth increases with the wavelength, but so does also the detectable size of discontinuities. In other words, small features can be detected only in a small depth below the surface. For large fractures, however, especially when their orientation approach parallel to the measuring surface, the GPR can be highly effective. Other applications of the GPR include measuring thickness of soil cover, waste dumps etc. above the rock surface.

Airborne surveys

Magnetic anomaly maps have proven to be of great value for the mapping of larvikite resources in Southeast Norway (Figure 5). The larvikites contain magnetite and ilmentite, and the internal relationship between these two minerals decides the magnetic properties of the rock. The deposits are composed of several ring-shaped bodies, and this pattern is reflected clearly on the magnetic anomaly map. The most important larvikite resources (Blue Pearl, Emerald Pearl and Sea Pearl) are found in intermediate anomaly levels. The geophysical survey also revealed the existence of two large faults, which have divided the larvikite complex into three fault blocks with different quality assortments. Combined with field mapping, the geophysical survey contributed significantly to making an interpretation map of the distribution of different commercial larvikite types.

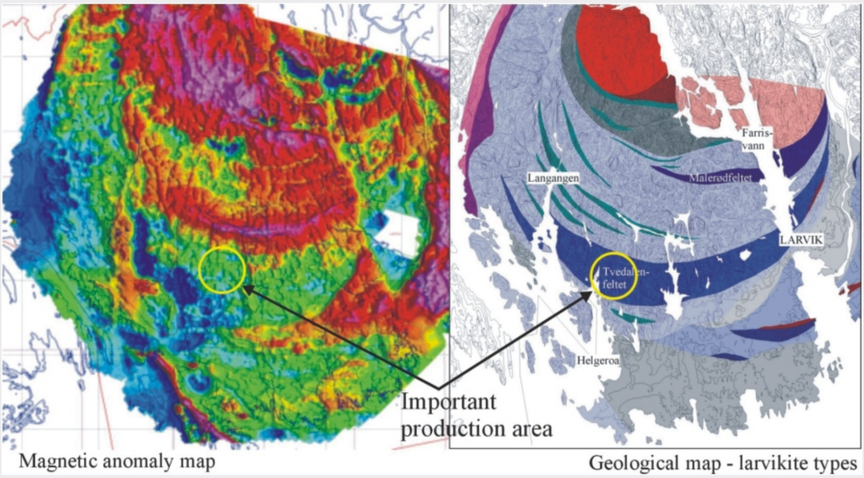

Figure 5. Magnetic anomaly map (left) and geological map of larvikite resources, Southeast Norway. The main quarry area ("Blue Pearl" larvikite) is marked with circles.

Source: Geological Survey of Norway (NGU)

Structural analysis of marble quarries in Greece

An example of the value of detailed structural analysis of a marble quarry area comes from the MK1 and DR1 quarries of Marmara Kavalas S.A. in Northern Greece. Here detailed structural mapping performed on a scale of 1:250 have enabled the construction of 3D models of the target areas, in which all open and brittle fractures are shown. In the main production site MK1 80% of all fractures are open, and have an average spacing of 2.5 m, and the detailed map means that the production of marble can proceed in a more cost effective way, extracting only good material, and at the same time reducing significantly the amount of waste produced in the quarry. Previously 40% of blocks extracted were rejected due to high fracture content. A computer model based on the structural data has been made to guide exploitation. Exploitation at a new quarry (DR1) has also been helped by a detailed structural analysis of open fractures, and the main cutting direction of N300 determined on the basis of this structural study. This approach has been extended to cover 7 operating quarries in the region, and will lead to major cost savings, as well as waste reduction.

Source: Cronquist T, & Sahlin T. (1997) Structures in marble and their relationships to the regional tectonic evolution, NE Greece. Earth Sci Centre, Goteborg University ISSN1400-3821 53pp.

GPR

The Ground Penetrating Radar (GPR) is much applied for predicting low angle fractures (“sheeting”) in granite deposits in Finland (Figure 6). The topography has essentially a low relief, and terrain-parallel fractures tend to be nearly horizontal. For such specific applications, the GPR is an efficient tool for predicting the thickness of granite benches.

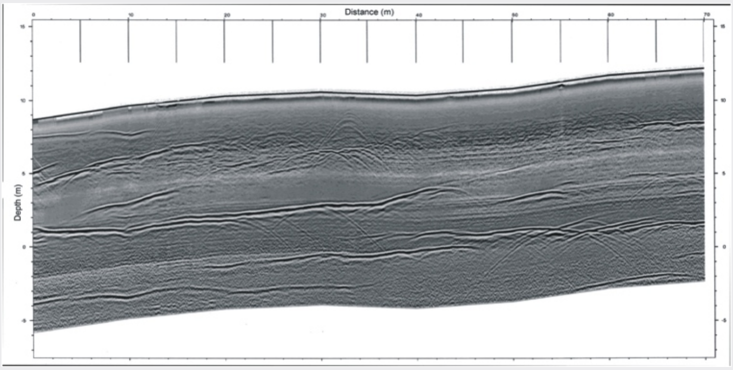

Figure 6. GPR section from a Finnish granite quarry, showing clearly the horizontal fractures.

Source: Luodes, H. & Selonen, O. 2000: Use of geo-radar in dimension stone investigations. Roc Maquina (37), 36-38.

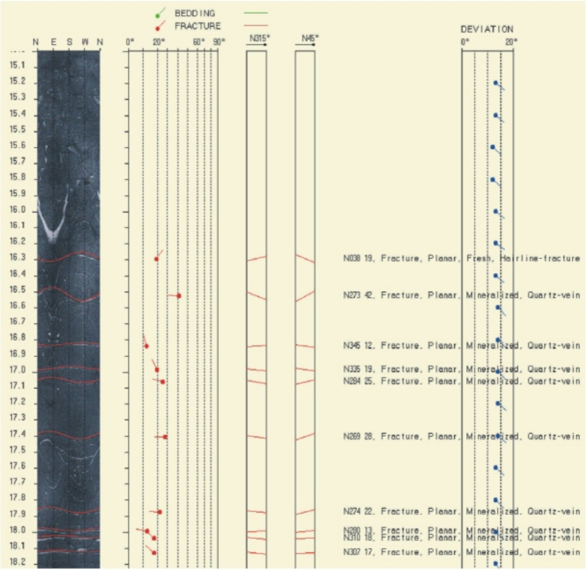

Figure 7. Optical televiewer drillhole log. Left - image of drill-hole (80 mm in diameter) projected to a flat surface. Interpretation of joint surfaces (directions, groupings and spacing) and layering is done semi-automatically. Source: Geological Survey of Norway (NGU).

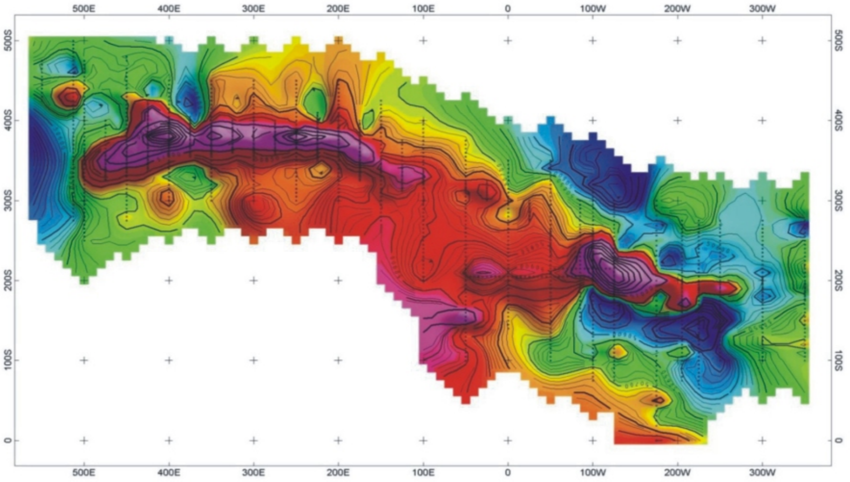

Figure 8. Ground magnetic survey for tracing the extension of a soapstone deposit beneath soil cover. Violet colour marks the soapstone formation. Grid in metres.

Fracture modelling

Fracturing is the quarrier's "enemy number one" in stone production. Several methods can be used for interpreting the directional frequency of fractures and predict block yield from such models. The example below (Figure 9) is from a Swedish slate quarry, showing a dataset from measured fractures along a 30 metres long section (top – 1) to modelling/extrapolation and finally estimated block sizes (lower – 4).

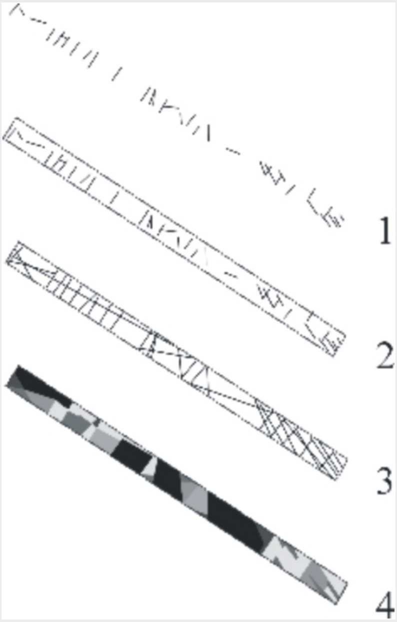

Figure 9. Dataset from measured fractures along a 30 metres long section (top 1) to modelling/extrapolation and finally estimated block sizes (lower 4)

Source: Loorents, K. J. 2000: Sedimentary characteristics, brittle structures and prospecting methods of the Flammet quartzite. PhD thesis, Getebord University.

There are several other geophysical methods that can work for ornamental and dimensional stone exploration. Such specialized methods are not applicable for stone exploration in general, but for solving specific problems related to some rock types. Below are the most important:

- *Seismic refraction* is a commonly used technique to determine the thickness of the overburden, which has to be removed before quarrying can begin, and which is often a limiting factor on the viability of an operation. The technique is also used in combination with conductivity measurements specifically for granite rocks to determine the thickness of any weathered material above fresh rock, which would also have to be removed.
- *Ground-magnetic surveys* can pinpoint the orientation and width of any rock dykes which might occur in granites. The method has also proved to be viable also for some other rocks, such as soapstone.

- In carbonate rocks, *ground-magnetic* or *terrain-conductivity surveys* can detect anomalous thicknesses of overburden in sinkholes and enlarged joints. More sophisticated *seismic reflection, seismic tomography*, or *resistivity surveys* can detect cavernous areas. *Acoustic emission studies* can accurately pinpoint caves carrying groundwater, which might flood a quarry. Once located, these conduits can be economically grouted.
- In sandstone deposits, *Resistivity, terrain conductivity* or *spontaneous-potential surveys* can delineate low quality, pyrite-rich areas of bedrock so that they can be avoided during mining.

SQS system – stone quality and sound

Sonic methods can be used for evaluation of block quality prior to cutting, thereby reducing waste and energy costs. The basic idea of sonic methods is the analysis of the mechanical energy propagation (elastic wave – pressure – sound) across the materials (Figure 10). If different materials (shape, compositions, and physical conditions) are mechanically simulated, also the energy propagation inside those materials will be different.

The specific application of the sonic test is simple and profitable. Sonic tests can furthermore be executed along three different directions. In this way, it is possible to detect a plane fracture that, although invisible to a sonic control executed along a section which is planar to the defect, can be detected from different sides of the block.

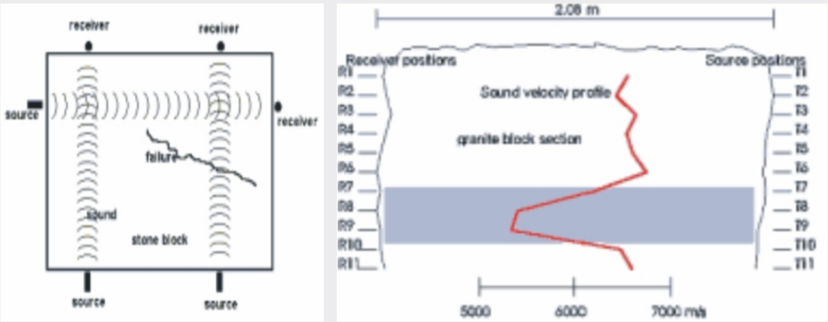

Figure 10. The figure shows the results of a real sonic test on a granite block, along a detailed vertical profile. After block cutting, the central slabs showed the presence of an important fracture in their lower part.

Source: Guiseppe Lenzi and Stefano Limonta, 1999: SQS system – stone quality and sound. Lithos, January 1999.

One of the most difficult tasks in the investigation of stone deposits is to predict the block yield. Any geological features that limit the block size, or reduce the value the final product (such as veins, inclusions and segregations) influence the block yield. Most of all, this applies to natural fractures in the rocks. In geology, there are standardised methods to determinate distribution of fracture systems (orientations), and there are methods which use geostatistics to model volume of non-fractured rock based on observations in small type areas. However, such methods are only applicable if they can be related to a realistic quarry situation, where aspects such as orientation of cutting planes and primary block sizes are taken into consideration.

3.5. Feasibility studies/market

In ornamental and dimensional stone exploration, two important issues are market price and recovery rate[15]. In European granite and marble quarries, the recovery rate varies between 2 and 50 percent, probably averaging 10-20 percent. For exploiting a deposit where the recovery is estimated to be very low, the block price must be significant. Vice versa, the recovery in a quarry producing low priced stone materials need to be high. When both price and recovery are low, the annual extraction costs per. m^3 easily get too high for a profitable production.

Regarding rough blocks, the price can vary substantially depending on the colour and structure of the material – from 250 to 6000 euro/m^3. In addition, large blocks are generally 50% more expensive than small ones. Thus, it is important that estimates of market value and recovery rate are made as early as possible in the exploration process.

The situation for slate, flagstone, sandstone and some limestone products is somewhat different, but also in such cases, the relationship between market aspects and recovery rate is crucial.

Another issue that is getting more and more important is the environmental costs. In most European countries, funds for environmental rehabilitation must be provided by the quarrying company either as a deposit before opening a quarry or on a more regular basis.

Market and recovery

In Sweden, an average recovery rate for granite production is rarely more than 10% - due to the nature of the bedrock. Taking labour costs, taxes and other fixed costs into consideration, the FOB market price for large blocks should be minimum 600 euro/m^3 (somewhat higher in more remote parts of the country) for a profitable quarry operation.

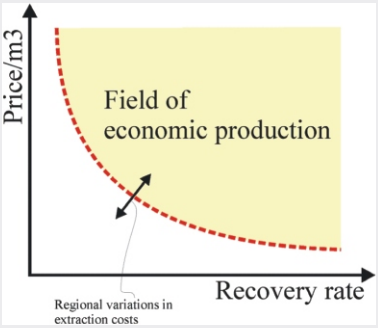

Figure 11. Principal relations between recovery rate and price for rough blocks, and regional variations in fixed costs.

Source: Kurt Johansson, Swedish Stone industry Federation

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[15] In the meaning of portion of the extracted stone that can be sold or used as ornamental stone products.

3.6. The problem of predicting stone quality

Although more or less standardized geological methods can be applied to ornamental and dimensional stone deposits with success, it is a fact that **stone production is extremely sensitive to minor variations in appearance and quality.** Such features can be difficult to predict. Even the most sophisticated geophysical methods tend to loose the small-scaled discontinuities, and often, costly investigations give little added value. However, several of the exploration methods can work well if used correctly. It is of great importance to select the right techniques for the specific situation, and to balance the exploration costs to the potential benefit.

Even though the number of geologists and mining engineers working with ornamental and dimensional stone is increasing, it is still a long way to go before "stone geology" is as common as "ore-geology". The amount of professional literature (books, publications) on ornamental and dimensional stone is small, especially in English. In addition, there are few stone companies that have their own geology section, and few universities with courses on the subject.

4

Management of stone deposits

TOM HELDAL , NIKOLAOS ARVANITIDES

4.1. Access to land

One of the key competitive factors for the ornamental and dimensional stone industry is access to land – for present and future quarrying. In this context, there is need for a balanced approach to assigning areas of land for future extractive operations[16]. Documentation of deposit areas is thus important for influencing on the future land use in many areas.

Decision-aiding land management systems, integrating data on land us bio-diversity, cultural heritage, geology and water resources are developed throughout Europe. Already, spatial databases (GIS) on many environmental aspects, designed for land use planning, are now available in several European countries. Concerning mineral deposits, spatial databases on important areas for future extraction are not (or only to a very limited extent) available.

4.2. Stone databases

The existing information on ornamental and dimensional stone deposits in Europe is found in a variety of sources. Several countries (including Portugal and Spain) have **catalogues** (published by governmental institutions) displaying photographs of stone types, location of

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[16] "Member States are (…) invited to share experiences and information, for example, on balanced approaches to assigning areas of land for future extractive operations and on how comprehensive decision-aiding systems, integrating data on land use, bio-diversity, cultural heritage, geology and water resources, can be effectively developed and applied."

deposits, petrographic descriptions and physical properties. Similar catalogues are published by the national stone industry federations in several other countries. The most extensive catalogue in Europe is, however, probably the German *Internationale Natursteinkartei*, covering approximately 4000 samples of ornamental stone from all over the world – including the most important European quarries. The original sample collection is at display at the Wunsiedel Tecnische Fachschule for Steinbearbeitung. Some of the catalogues are available on the internet, some not (including INSK).

Most of the geological surveys in Europe have some sort of *mineral resource databases*, where ornamental and dimensional stone is presented. Only few of these are available for the general public on the internet, but this will probably change within short a time.

In several European countries, the development and use of integrated, spatial datasets are increasing. In the near future, it will be possible to interactively combine geographic data from several sources – e.g. topographic and other thematic maps, natural habitats, cultural heritage, demographic data and mineral resources. Possibly, this development will revolutionize the use of GIS in land use planning. Concerning mineral resources, most national databases in Europe seem to present deposits as point locations. This is, however, not very practical in GIS based land use planning, and there are great challenges for bringing spatial data on mineral deposits up to a level which can be practically used by planners.

4.3. Important European deposits

The number of European stone quarries is huge, and range from large scaled, highly sophisticated operations to small “family” based quarries with sporadic production. Some deposits have been exploited more or less continuously for thousands of years, other are recent. A challenge in the future management of this enormous amount of small and large deposits is to find a way to differentiate between important and less important deposits, based on which of them have a future potential of importance to the local, regional, national or European society.

In some countries[17] (Figure 13), the geological surveys, research institutes or other institutions have contributed in making lists of deposits of special value, as an attempt to ensure a better management of these by the authorities. The criteria used for making such priorities can vary, including the following:

- Industrial importance: exploitation of the deposits contributes significantly to the economy of an area.
- Potential industrial importance: new deposits or the extension of quarry areas that have great potential for being an important quarry area in the future.
- Historical/traditional importance: quarries, which have a strong historical significance, e.g. have been used in historical sites, local traditional architecture, etc.
- “Uniqueness”: quarries in rare stone materials.

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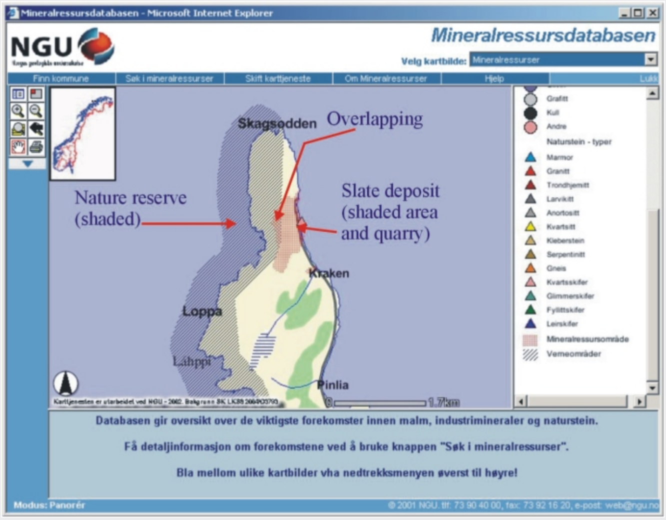
[17] Sweden, Norway

Spatial databases on the web

GIS databases from different sources can interactively be combined and displayed through the internet. Such databases should also contain information about the spatial distribution of ornamental and dimensional stone deposits, in order to improve the management of such resources in land use planning. The example below (Figure 12) shows a case with a possible "conflict" area between a slate deposit and a nature conserve, Norway.



Databasen gir oversikt over de viktigste forekomster innen malm, industrimineraler og naturstein.

Få detaljinformasjon om forekomstene ved å bruke knappen "Søk i mineralressurser".

Bla mellom ulike kartbilder vha nedtrekksmenyen øverst til høyre!

Figure 12. Interactive map showing ornamental stone deposits overlapping a natural habitat area.

Source: Geological Survey of Norway (NGU). http://www.ngu.no/

The historical importance is unique to ornamental stone; since stone has been an important building material since before antiquity in Europe, the stone types have contributed in shaping the European cultural identity. In the restoration of historical buildings and rehabilitation of cities and towns, authentic stones are preferably used. Although many of such "historical stones" have been lost, several hundred quarries in Europe are regularly supplying material to the restoration of our cultural heritage. Even if such deposits are small and industrially marginal, it is important to secure the possibility for extracting stone also in the future.

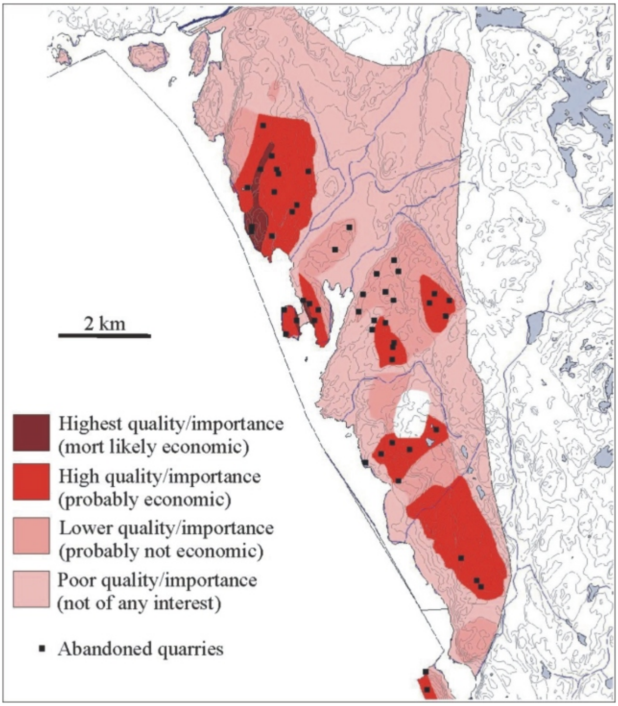


Figure 13. Survey of a granite deposit area, SE Norway, showing the different qualities (importance).

5

Quarrying methods / techniques

TOM HELDAL , NIKOLAOS ARVANITIDES

5.1. General aspects – quarrying dimension-stone

The first step in the quarrying process is to extract **the primary block** from the solid rock. In most marble and granite quarries, the primary blocks are cubic or rectangular, and measure from a few hundreds to 4000 cubic metres. In sandstone, slate, soapstone and some limestone quarries, the primary block tend to be much smaller, and in some cases it approaches the size of commercial blocks.

To loosen the block from the rock face, one can use various methods of making **primary cuts**. Continuous channels are made by sawing (most common), line (slot) drilling, jet burner or water jet (less common). Otherwise, cuts can be made by dynamic splitting (blasting), where explosives are detonated in a row of parallel drill holes. In some quarries, especially marble, all cuts can be made by sawing, whilst a combination of methods are used in others. In most granite quarries, at least one cut (preferably the horizontal) is made with the use of explosives. Where present, natural fractures either vertical or horizontal, can be used as natural limitations for the primary block. In rare cases, wedging is used for primary cuts, especially when the primary blocks are small sized (e.g. sheeted granites).

After the extraction, the primary block is divided into **slices** (Figure 14), which in turn are tipped and subdivided to **commercial blocks**. In granite and marble quarries, such blocks are essentially larger than 3 cubic metres and have a rectangular shape. In slate quarries, such blocks are rarely thicker than 50 centimetres[18]. The squaring is done by sawing, blasting or wedging, depending on the properties of the rock and the formation.

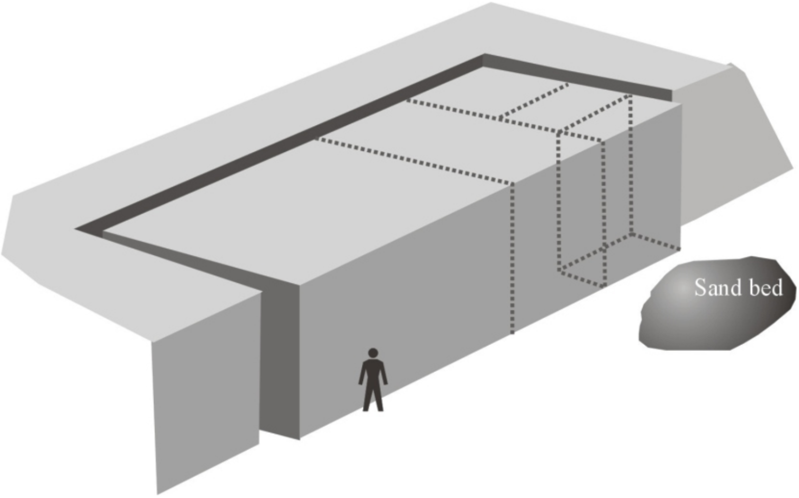


Figure 14. Principle of block extraction – from primary blocks to smaller sized slices, which will be further divided to commercial blocks.

The key issue of all stone quarrying is to extract whole pieces of rock with as little damage as possible, and it is important to minimize the use of explosives. Furthermore, extensive knowledge of rock properties, such as grain orientations, natural cleavage directions, local stress conditions etc. is of vital importance for any quarrying operation. Even though the overall principle of extraction (from primary block to commercial block) is quite similar in most quarries, there can be large differences from place to place, depending on the rocks, local traditions and size of operation.

In the following text, some of the most important extraction techniques are described. For a more detailed, up-to-date description, the Marmomacchine Directory 2002 is highly recommended[19].

5.2. Sawing techniques

The use of saws for the extraction of stone blocks was applied as early as during the Roman Empire, and the use of wire saws gained significant importance in the industrialization of marble quarrying in the late 19th century. In recent years, sawing techniques have improved significantly, and at the present time, sawing is applied in the majority of European ornamental and dimensional stone quarries.

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[18] Slate blocks are usually aplied as raw material for further processing (cleaving to thin slabs) in a nearby factory, and are not "shaped for shipping" in the same way as marble and granite.

[19] Primavori, P. 2002: Technological developments and the state-of-the-art in machinery and installations for extracting and processing stone materials. Marmomacchine directory 2002, 41-196

Figure 15. A primary block has just been loosened by blasting, and moved approximately 10 cm. Serizzo quarry, Italy.

There are many different saws for different purposes, and it would be far beyond the scope of this report to supply detailed technical information about them. However, a short description of the main technologies and recent development is given below. **Wire sawing** is the most widespread technique (Figure 17). Traditionally (and in a minor amount of modern quarries), a simple steel wire was used, and the cutting was facilitated by adding abrasives to the cooling water (**helicoid wire sawing**). In modern use, diamond coated beads on the wire do the cutting. The principle is simple – a wire is thread through meeting drill-holes, forming a loop around the rock mass, and by gradually moving the sawing machine on a rail backwards from the rock face, large vertical, inclined or horizontal cuts can be made. Such **diamond wire saws** have improved significantly in recent years, and from being a method most applied to marble and other soft stones, even granite (Figure 18) can now be cut with great success.

Figure 16. Slicing a loose primary block. "Labrador Antique" quarry, SW Norway.

For even harder rocks, such as quartzites, diamond wire sawing is still considered to be difficult (less profitable), but it is probably only a matter of time until the technology can be capable of handling such rocks. There is a great variation of saws and wires for different applications within quarry operations, and several research activities aim at improving the performance of the machines and beads.

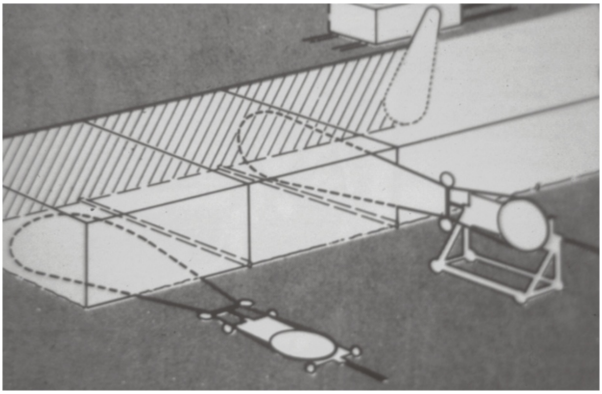

Figure 17. Principle of diamond wire sawing and chain sawing (top).

Figure 18. Diamond wire sawing in a granite quarry, Spain

Diamond wire sawing is best suited for massive (non-fractured) rocks. In quarries where the rocks are highly fractured, wire sawing can be difficult and slow, and in rare cases actually generate a lower block yield than other extraction methods. In some areas (especially in mountainous regions) the remnant (“stored”) stress in the rocks can be high, causing movements in the rock mass when cutting. The wire can easily get trapped in such situations. Furthermore, wire sawing is dependent on running water, so that in areas were the winter is long and cold, the method may not be very practical. In Finland, the cold climate and high remnant stress are important reasons for that wire sawing is only used to a little extent.

Chain saws have become important in soft stone quarrying in recent years. It looks like a larger version of a power saw for trees, with a mobile arm ("sword") carrying a toothed chain – containing abrasives of tungsten carbide or diamond beads. It can work both with cooling water and dry. Cutting depth can reach as high as 6 metres. Chain saws are especially suitable for making "blind cuts", e.g. for opening underground quarries.

Chain saws are yet not applicable for quarrying of granite and other hard rocks. It is considered to work best in rocks with few fractures and homogenous structure. In open cast quarrying, it is specially suited for quarries with a regular layout and low-step architecture. A modified chain saw is the **diamond belt saw**, carrying a belt around the "sword" rather than a chain. It works in similar way as the chain saw, but uses no grease or lubricants (more friendly to the environment). It is considered to be highly efficient in underground quarry operations, but cannot be used for hard rocks.

Disc saws are not frequently used for primary rock extraction, but some examples do exist. Disc saws can run on rails, or be mounted on an excavator. Their size and performance vary considerably. They are used predominantly for vertical cuts, but there are also smaller types cutting two directions (vertical and horizontal) simultaneously; such *tuff-cutters* are designed for direct extraction of ashlars. Disc saws are only applied for the extraction of softer rock types.

Figure 19. Curved surface after wire sawing in serizzo (gneiss)-quarry, Northern Italy. The curving is due to stress.

5.3. Drilling

Drilling in ornamental and dimensional stone quarries is predominantly used as an independent method, in combination with splitting techniques, or for continuous channelling (line drilling). It is also used as an auxiliary method for making holes for diamond wire cutting. Drilling equipment is either **pneumatic** (compressed air) or **hydraulic** (Figure 20). The latter is gaining increasing interest, since it is faster, more powerful and consumes less energy. There are numerous varieties of specialized drilling equipment designed for any kind of quarry operation, from the extraction of primary blocks to the squaring of commercial blocks. In ornamental and dimensional stone quarries, accurate drilling is of fundamental importance, since even small deviations cause lower recovery and consume time and labour.

Line drilling for continuous channelling (primary cuts) is generally considered to be an expensive method, and is essentially applied where other cutting techniques work badly.

5.4. Blasting

Although blasting in stone quarrying has been declined due to the improvement of sawing technology, there are areas and rock types were this is still considered to be the most efficient method of extraction. Especially, this is the case when either climatic conditions or rock quality makes sawing difficult or too expensive. In addition, drilling and splitting is frequently used in combination with sawing – both for one or more primary cuts and squaring.

The use of explosives in the extraction of ornamental and dimensional stone is a difficult art, and there are many different practises, depending on rock type, local traditions and experiences. Furthermore, rocks are not isotropic materials, so that their ability to split along a drill hole line can have strong, directional variations. “Fast” explosives, such as dynamite, will generally crush the rocks so that they are not usable as dimension-stone. In traditional quarrying, especially for granite, “slow” explosive (black powder) in small quantities worked well, combined with a detailed knowledge of the natural splitting directions (“rift” and “grain”) in the rocks. A spoonful of black powder in each of three central placed drill-holes can be sufficient to split a ten metres long and two metres tall quarry face. Black powder is still used in some modern quarries, essentially in granite production, but most common are detonating fuse (12 g/m, 20 g/m or 40 g/m) and tube charges with "reduced strength".

Figure 20. Multi-hammer, hydraulic driller for squaring of blocks.

However, the traditional explosives (black powder, gel ammonite) are cheaper, and for that reason still in use in some small-scaled quarries or in quarries where the extraction costs must be kept to a minimum.

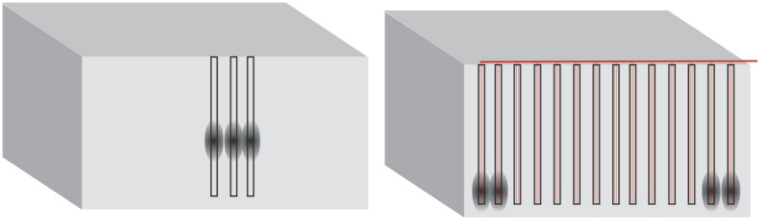

Figure 21. Two examples of granite splitting with the use of explosives. Left: black powder (dark spots) in three central holes placed along the primary cleavage plane of the granite. Right: detonating fuse (red line). In this example, combined with black powder only in the marginal holes

Up to three cuts (two vertical and one horizontal) can be made by blasting, but most common is one (horizontal) or two; the third (and fourth) are cut by channelling. A successful blast will move the primary block five to fifty centimetres away from the rock face without damaging it significantly.

Finland: blasting only

In Finland, the use of explosives in dimension-stone quarrying is still the most common way of extracting granite. This is explained by the long and cold winters, which make sawing with cooling water difficult, and to the high amount of remnant stress in the granites. Due to stress, the rock mass moves during cutting, closing the cut and trapping the wire. Pipe charges (20 – 150 g/m^3) are essentially used. The spacing of drill holes along the drilling line varies according to rock type and cleavage properties. Two or three cuts are made by blasting, whilst the other(s) are made with slot drills. It is important that all angles between cutting planes are larger than 90 degrees, to avoid that the primary block gets trapped and crushed during blasting. The "Finnish method" (Figure 22) of granite quarrying is based on extensive development work by the stone companies in the 1970's to 80's, and is accompanied by the development of advanced quarrying technology specially designed for extraction of ornamental stone, such as the Tamrock drilling machines.

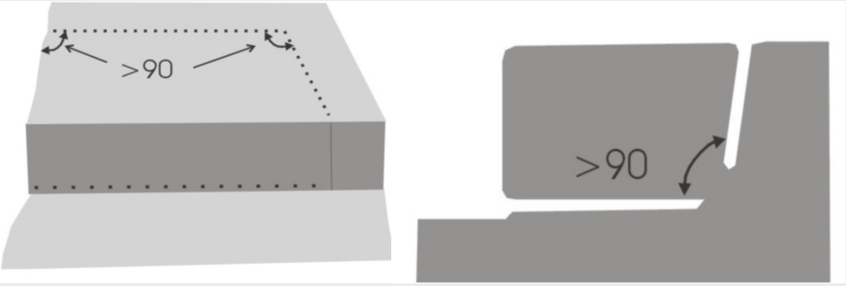

Figure 22. Illustration of the "Finnish method" in granite quarrying. Front view (left) and cross section through a primary block (right).

Blasting is also frequently used for the subdivision of the primary block. A traditional method in granites was to charge one drill hole in the centre of the block; when blasting, the rock would "find its way" – the cut would follow the primary cleavage direction in the rock. Nowadays, this method is most common in boulder quarries outside Europe, although there are still examples also in European countries. Another way of splitting commercial blocks is the use of detonating fuse in water-filled, closely spaced drill holes.

As mentioned above, blasting of ornamental and dimensional stone is difficult and far too often one sees unnecessary damage to the rock mass. Blasting will always cause damage to the rock, not only those visible to the naked eye, but it is important to minimize the consequences by finding the right balance between the following important parameters:

- Position, size and spacing of drill holes
- Accuracy in drilling
- Type, amount and distribution of explosives
- Plugging of the holes
- Angle between firing lines (>90)

5.5. Wedging/splitting techniques

Wedging as a method of splitting rocks was introduced in the Antiquity. Wedges, or "plugs and feathers", are placed in drill holes or pits in the stone to split, at regular intervals. By hitting the wedges, stress is created in the rock, and finally it will burst (Figure 23). Hard and brittle rocks, such as granite, are easier to split than softer ones. Furthermore, splitting properties show directional variations – where planar features, such as foliations and layering, are the easiest directions.

Wedging in modern quarries is predominantly restricted to the squaring of blocks – e.g. the subdivision of primary blocks extracted by blasting or sawing. Tools and methods vary considerably depending on rock type, local traditions and skills. "Easy" rocks can be split by the use of small wedges in short drill-holes. "Tough" rocks, however, need closely spaced wedges in long drill-holes and the costs per cubic metre squared blocks turns considerably higher. In many cases, better knowledge of rock properties and natural cleavage directions could improve the wedging process and reduce the number of drill-metres used for shaping blocks.

Although manual wedging is widespread in modern quarries, and probably will be also in the future, there are examples of new technology in this field. Hydraulic wedging – or rock splitters – is in daily use in some large quarries[20] – in the form of "plugs and feathers" placed in pre-made drill-holes (Figure 26).

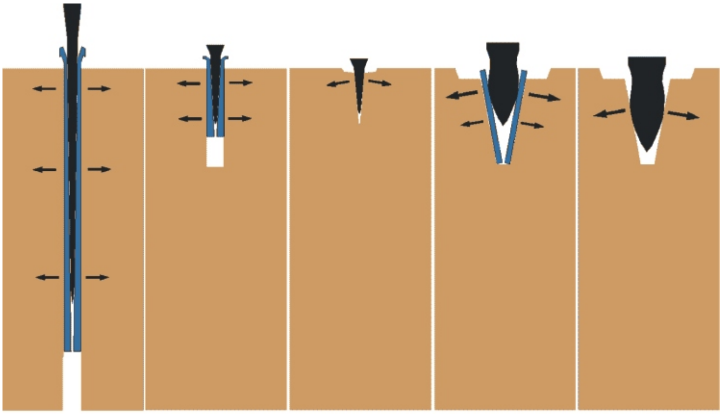

Figure 23. Principles of wedging. From left to right: long "plug and feather" and penetrating drill holes, short "plug and feather" in short drill holes, short plug in chiselled groove, and finally two examples with large wedges.

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[20] especially in Norway and Finland

Figure 24. Worker using short plugs for wedging granite block in Vigo, Spain.

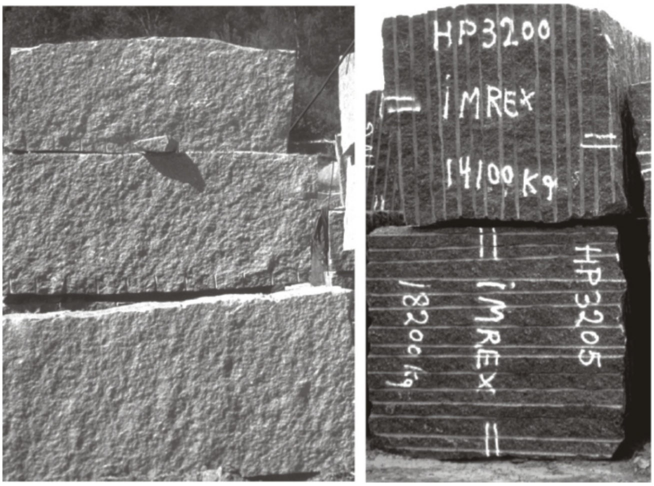

Figure 25. Rough granite blocks squared with short wedges (left) and long "plugs and feathers". The former granite is far more brittle and easier to split than the latter.

5.6. "Slow splitting" techniques

Splitting with **expanding mortar** placed in drill holes is a technique which is most applicable in quarries where the use of explosives is restricted. It works slowly, is expensive and the mortar tends to "escape" into open fractures and cavities in the rock. Recently, a CRAFT research project addressed the use of **shape memory alloys** in ornamental stone quarrying[21].

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[21] Source: Ditta Ripamonti, presentation at http://europa.eu.int/comm/research/growth/gcc/projects/in-action-craft01.html

Shape memory alloys 'remember' the shape in which they are originally formed and will return to it if not constrained in some way.

Hydraulic splitting

In the Larvik area, Southeast Norway, hydraulic wedging is frequently used for the shaping of rough blocks (Figure 26). The larvikite is a feldspathic rock that is difficult to split, and manual wedging is both hard labour and time consuming. The hydraulic wedges are fixed to a tractor, are flexible and work efficiently over a large quarry-area. The principle of splitting is the same as manual wedging with long plugs and feathers, but a lot faster.

Figure 26. Hydraulic wedging in a larvikite quarry, Norway.

The strong forces generated by the SMAs as they return to their original shape can be focused far more than those of soft explosives. So, although some drilling is still required, far fewer holes are necessary than with conventional stitch drilling, saving the quarry both time and money. In addition, the SMA can be re-used, which makes it extremely cost-effective. Several prototypes of the system have been manufactured and tested with small-scale blocks in the laboratory and full-scale blocks in the quarry. These tests were successful and the partners are continuing development of a simple system for use not only with marble, but also with other types of stone. A product should be launched in the stone quarry market in 2002 to 2003.

5.7. Other techniques

In addition to the above mentioned, there are other techniques that, with more or less success, are used in dimension-stone quarrying. **Jet burner** is a high temperature jet flame used for making channels in granite (Figure 27). The high temperature makes quartz-grains expand, with pulverisation of the rock as a result. It only works properly for quartz-rich rocks. The use of this method is declining, especially since it is extremely noisy, dusty and because it is difficult to do other work in the quarry during channelling. More and more, wire sawing is taking over for making cuts in granite quarries.

High pressure (up to 350 MPa) **water jet** has not found any widespread application in the stone sector, but it can be expected interesting developments in the years to come. At present, the method is costly and slow, and it works predominantly on granites. One of the most interesting future potentials is probably for underground granite quarrying – in combination with diamond wire sawing.

Figure 27. Channel from jet-burning in granite quarry and jet-burner (right).

5.8. Application in the quarrying sector

5.8.1. Hardrock ("granite") quarrying

Granite, gneiss and other hard, siliceous rocks are the most difficult to saw, especially the ones with high content of quartz. Diamond wire sawing is used to a much greater extent than for ten years ago, due to the improvement of the technology.
In several large scaled quarry areas, drilling and blasting have been reduced to a minimum. However, there are also many granite quarries where sawing is not applied at all, or just to a small extent. This is generally reasoned either by climatic conditions (cold winters), remnant stress in the rock (the wire gets trapped) or to the fact that sawing sometimes is not profitable in highly fractured rocks. In addition, some granites have generally excellent splitting properties, so that blasting and splitting can be carried out with few drill metres, and thus be a cheap way of extraction. The composition of the rocks are of great importance to the costs of sawing; "true" granites have a high content of quartz, and in most cases sawing can be relatively more costly than for feldspathic rocks, such as syenites and gabbros.

It is probably within granite extraction that we will see the greatest innovative achievements regarding ornamental and dimensional stone quarrying in the years to come. Better sawing techniques, water jet technology, underground quarrying and rock splitting without the use of explosives are all areas with ongoing important developments.

5.8.2. Marble quarrying

In most large marble quarries throughout Europe, wire sawing is the far most important way of extraction – in some quarries even the only way. Not only because marble is a soft rock, easy to cut, but also since marbles are more risky and difficult to blast or split than granites. In addition to wire saws, chain saws and diamond belt saws are increasingly applied in marble quarries, especially for making openings and "blind cuts" in underground operations. For final squaring of commercial blocks, stationary wire saws or disc saws are frequently applied.

5.8.3. Quarrying of limestone and sandstone

Most limestone and sandstone deposits exhibit a distinct, sedimentary layering (bedding). Thick-bedded limestone and travertine (inorganic limestone) are mostly quarried in a similar manner to marbles, with wire sawing as the most widespread method. In thin-bedded deposits, extraction methods can vary significantly. In many cases, beds of good quality stone are intercalated with poorer quality, and selective quarrying of high-grade beds is necessary. Thin beds of limestone or sandstone are often highly fractured, and the contacts between the beds act as planes of weakness. In such deposits, wedging alone may be the most effective quarrying method. In other cases, especially for the softer varieties of sandstone and limestone, chain saws or disc saws are used.

Some examples of marble quarrying
Inclined diamond wire sawing perpendicular to the stratification of the deposit (upper left photograph).
Entrance to underground marble quarry Greece (upper right photograph) and tiltin marble slices with hydraulic "pillows (lower left photograph).

The Jura Limestone
Quarrying of Jura limestone beds, Germany. The workable beds of limestone are first loosened along natural fractures with a jack (top photograph). Afterwards, the blocks are shaped at site by wedging – adding hydraulic pressure on the wedges (lower photograph).

Different granite – different practice

In the Gris Perla quarries, Spain, the cutting is made with diamond wire sawing (upper left photograph). Granites in Finland, of approximately the same composition, are extracted by drilling and blasting only (upper right photograph). The third example (lower left photograph) is from a sheeted granite deposit in Germany. The "sheets" forms low, inclined benches, which are extracted one by one with the means of blasting and wedging.

5.8.4. Slate and flagstone quarrying

Slate and flagstone are layered rocks, and often the quarry faces ("benches") are less than a few metres tall. Single blocks, which are to be cleaved to slabs, are essentially less than 50 cm thick. Traditionally, blasting was the primary method of extraction. In modern **slate quarries**, sawing is becoming more and more common. Wire sawing is used where it is preferable to make deep, primary cuts, whilst chain saws and even disc saws are applied were more shallow cuts are necessary. Some **quartzitic flagstones** (or quartzite schists) are, on the other hand, extremely hard, and attempts to introduce wire sawing have not been successful. Thus, blasting is still the most common way of quarrying. Generally, gel ammonite or black powder is preferred to the more specialized "ornamental stone" explosives.

5.8.5. Soapstone quarrying

Soapstone is an extremely soft rock, composed of talc, chlorite and carbonate. Traditionally, soapstone blocks were carved out with axes or pick hammers. In modern soapstone quarries, sawing is the only method of extraction (Figure 29). Predominantly, this is done with chain saws – wet or dry cutting. Generally, the depth of each level of the quarries rarely exceeds one to two metres.

5.9. The importance of rock properties

Knowledge of rock properties is of crucial importance when choosing the right methods and technology of extraction. Much of this knowledge is empirical, formed during many years of trial and error. However, when introducing new technology and improving the old one, as well as when moving from one type of extractive operation to another, R&D on rock properties become more important. There is probably much to gain in optimising quarrying methods to the behaviour of the rocks.

Figure 28. Low step, quartzitic flagstone quarry in Central Norway (Oppdal). Provided by Oppdal Skifer.

Figure 29. Soapstone quarry in Central Norway.

The sawing properties not only depend on the overall hardness of the rocks (e.g. mineralogy), but also on grain size, grain boundaries, grain distribution, micro fractures, porosity, etc. Thus, the performance of diamond wire can vary significantly even for granites with approximately similar mineral composition.

Regarding wedging and dynamic splitting, there are also large differences between apparently similar rocks, and the directional variations within one single quarry can be large. The principle of "rift and grain" in granites is well known, but could perhaps be practised better. Using optimised parameters for drilling and blasting could contribute both in reducing waste and the amount of drill metres used per cubic metre commercial block.

Rock stress is a problem that is familiar to many stone producers, causing problems with cutting, cracking of blocks and other difficulties in quarrying. Those problems can be reduced if the quarry layout and primary block size and orientation are optimised to the principle local stress directions.

Part B of this edition addresses such problems similar to these. It includes a review of the most used monitoring instruments and systems available to forecast and control the stability conditions of stone excavations. It also describes the back-analysis procedure based on the comparison between the measured parameters (such as induced stress and displacement) and the computed one in order to set up calibrated models able to determine optimum excavation layouts.

In the monitoring of stress and changes of such during quarrying, groundwater level changes and slope stability, new methods in the use of radar satellite images could be interesting. Movements down to 1 mm can actually be measured[22]. For example, the effect on the surrounding rocks of rising water level after construction of a dam in Norway has been measured by such methodology.

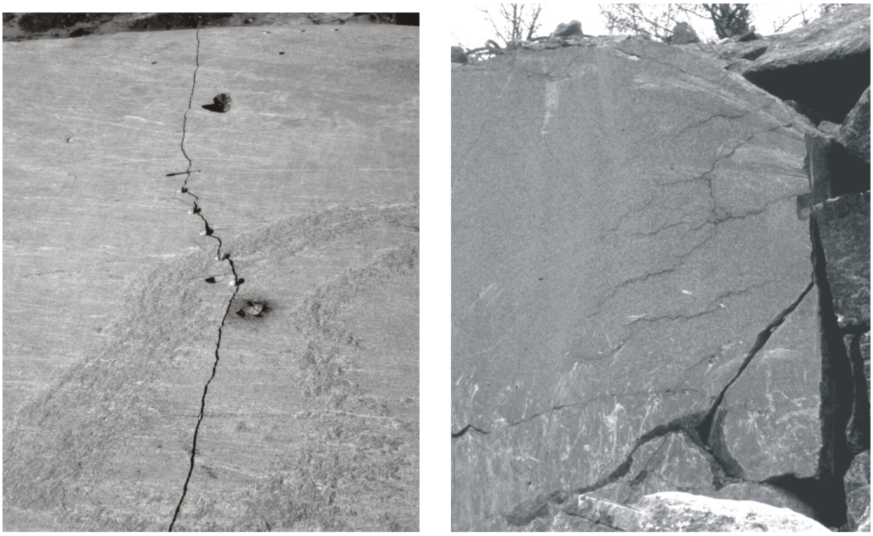

Figure 30. Left: an example where direction of blasting (row of drill holes) did not correspond with the natural, secondary cleavage ("grain") in granite. The cut followed the latter. Right: damages (cracks) from blasting

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[22] See Tele-Rilevamento Europa: http://www.treuropa.com/

Research on rock stress

"In many dimension stone quarries rock stress problems such as closure of boreholes and rock failure have occurred. The orientation of the quarry has been chosen in the worst cases by trial and error (i.e. changing the orientation of the primary block constantly during the development of the quarry) and in the best cases by following the orientation of the major joints. However there is not necessarily a clear correlation between joint orientation and the directions of the principal stresses. Besides, the state of stress (orientation and magnitude) changes as the quarry operations advance.

The estimation of the principal stresses through measurements should be included in the planning phase of a new quarry in order to help in finding out the optimal direction of quarrying. In this research hydraulic fracturing method and measuring set called Minifrac System (Mindata Australia Pty Ltd) was used for rock stress measurements. The chosen method and equipment was found out to be very suitable for the determination of rock stress in granitic rocks. In the future also other methods' usefulness for the stone industry should be tested.

On the basis of rock stresses quarrying should be oriented parallel to the direction of maximum horizontal stress, (H. The direction of quarrying should be optimized between the direction of (H and the geological factors affecting the quarrying and the end-product. The direction of drilled slots should be perpendicular to (H. According to the modelling of rock stresses, the distance between slots should be no more than 3 times the depth. In order to minimize the rock stress concentrations the shape of the quarry should be elliptical and its major axis in the direction of H. (Recently finished R&D project, cooperation between industry and universities in Finland).

Source: Sakari Mononen, Helsinki University of Technology
http://www.hut.fi/~mononen/stressi.htm

6

Quarrying operations

TOM HELDAL , NIKOLAOS ARVANITIDES

Quarry operations should be efficient and high-productive, and at the same time, have a high recovery. There is a number of factors influencing the overall productivity of a quarry.

The **nature of the rocks** is important. Fractures, veins and impurities influence the recovery rate, and layering or other natural directions in the rocks are important to the quarry architecture. The geometry of the deposits and the **morphology** is significant for the general quarry layout. Optimisation of **quarrying techniques, machinery and tools**, and **internal logistics** in the quarry, is of vital importance. So is professional and **good planning** of the extraction.

In many cases, it is difficult to optimise an operation; the concession area is perhaps limited, or it can be difficult to modify an old quarry structure to a modern one. Obviously, the possibility of improving the quarry situation also depends on such things as the size of operation and markets.

Most European ornamental and dimensional stone quarries are open cast operations. Their size and layout vary significantly, but there is a general trend of increasing their output, for instance by combining several small, neighbouring quarries into one large. Underground quarrying is increasing, especially in soft rocks in populated areas. However, it is important to realize that a large part of the European stone industry still consists of small companies, producing stone for local markets and/or niche markets, thus basing their activity on small annual volumes of extracted stone.

6.1. Open cast quarrying

Ideally, an open cast stone quarry looks almost like an amphitheatre, where production can take place simultaneously on several levels (Figure 31). Some of the most well planned quarries in granite and large marble deposits are close to this situation, with a high production output per area and volume of extracted rock. A "good" situation in an efficient quarry could be an output of 1000 – 2000 m^3 commercial blocks per Hectare annually.

Figure 31. "Theatre-shaped", well planned marble quarry, Athens, Greece.

However, in many cases the deposits are narrow, inclined and/or occur beneath layers of non-exploitable rocks. A steeply inclined slate or marble deposit, for instance, causes a trench or "well" shaped quarry layout, which has a lower productivity (Figures 32-34). The productivity is also dependent on the internal structures of the rocks – e.g. cutting angles. Horizontal or vertical cuts are more efficient in quarry operations than inclined.

In general, marble, granite and massive limestone quarries have a high-step architecture, where the primary block is approximately 8 metres tall. Quarries in sandstone, slate and other rocks, where ashlars or small sized blocks are extracted, have low-step architecture.

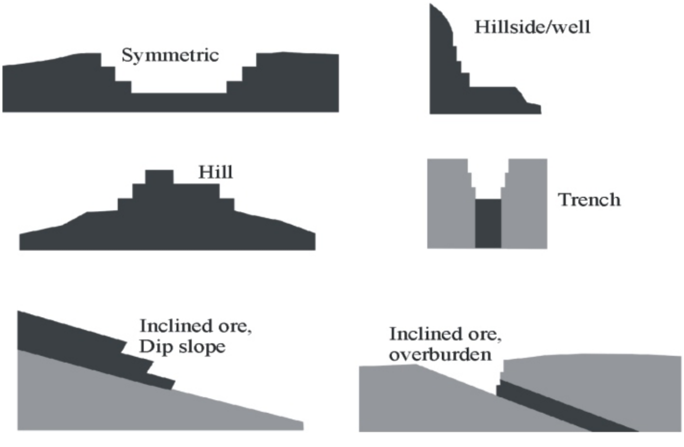


Figure 32. Schematic drawing showing some different open-cast situations. Workable part of deposit shown in black.

Figure 33. Steep hillside quarry, "Serizzo"-gneiss, Northern Italy.

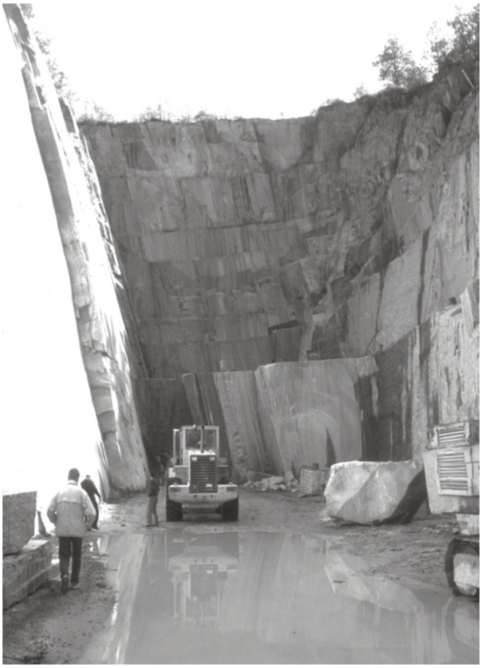


Figure 34. Trench-quarry, "Serizzo"-gneiss, Northern Italy. Note that the layering (foliation) of the rock is almost vertical.

6.2. Underground quarrying

Underground quarrying of ornamental and dimensional stone is not a new invention; in fact it was carried out as far back as more than one thousand years BC in Egypt. However, in recent years, the technological development of quarrying equipment has made large scaled underground operations profitable, especially for soft rocks such as marble (Figure 35). Especially, the improvement of chain saws and diamond belt saws has made this possible.

Underground quarrying has several advantages, of which **less impact on the local environment** perhaps is the most important reason for moving underground. The possibility of **selective quarrying**, leaving the poorest rock quality in pillars, is also important. Furthermore, **local morphological conditions** (steep terrain) and the occurrence of non-exploitable **cap rocks** covering the workable part, also favours underground operations. Generally, underground quarrying causes smaller amounts of waste rock than open cast.

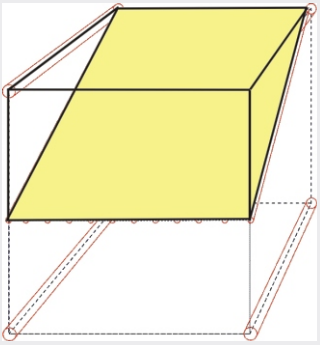
Figure 35. Underground marble quarry, Greece.

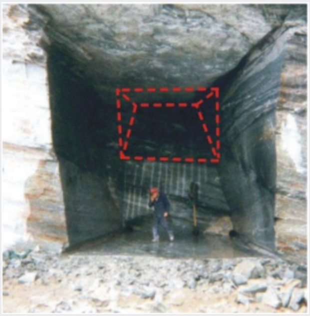
The disadvantages (or rather challenges) mainly relate to that underground operations tend to be **more expensive** than open cast, especially in the early stage of opening. **Good knowledge of the deposits** quality and geometry is crucial. In addition, **rock mechanic studies, stress monitoring** etc. is of great importance for an economic and safe operation.

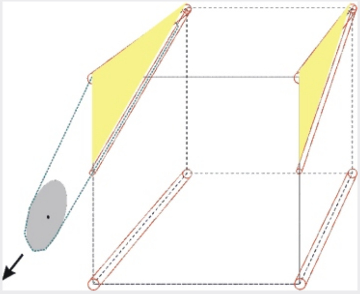
Underground quarrying has so far proven to be economic only for soft rocks – marble, limestone and slate. Approximately 30% of the marble production in the Carrara Basin at present occurs underground. For granite and other hard rocks, the technology still needs improvements. Water jet, in combination with diamond wire sawing, may be, however, of future interest in granite quarrying. At present, only one underground hard-stone quarry has been opened in Europe; a quartzite quarry in NW Italy is mined with the help of diamond wire sawing alone.

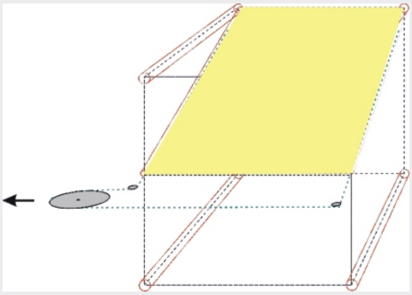
Quartzite underground quarrying

Even for very hard rocks, underground quarrying can be a viable operation. The example below shows the opening phase of an underground operation in the exclusive "Verde Spluga" quartzite, Northern Italy. Top figures: quarry face with four blind cuts made by diamond wire and drill line for dynamic splitting of first wedge (left), principle shown in drawing (right). Middle figures: result after dynamic splitting of wedge (left), and after sawing of second wedge (right). Lower figures: principle for sawing of second wedge.









Source: Cardu, M., Lovera, E. & Zerlia, C. 2002: Optimising Quarrying Techniques and Practices: Underground Quarrying in Hard Stones. Presentation at the 2nd Sectorial Meeting, OSNET quarrying sector, Torino 29-30 April.

Underground modelling

An ongoing, EU supported project addresses new methods and techniques for better planning of underground marble quarries. It seeks to improve the prediction of subsurface quality, for obtaining better safety, cost efficiency and recovery. The work is based on 3D modelling of the rock mass structure coupled with modern surveying techniques and advanced computer simulation (Figure 36). Fracture systems and expected block recovery are modelled, and stress/strain conditions measured and monitored. Hence, the recovery, stress and stability of the rock mass can be simulated, finding the optimal design of the quarry.

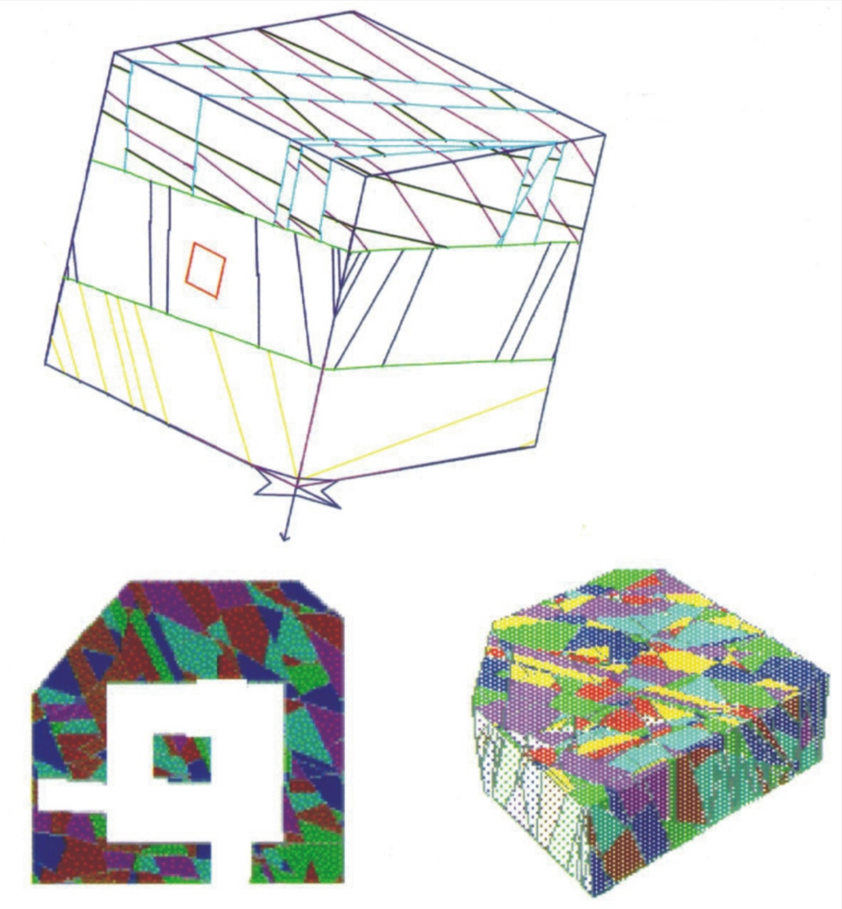


Figure 36. RESOBLOCK model (top) and 3D distinct element simulation of underground room and pillar, Dionysos marble quarry, Greece.

Source: Grassoulis, G. 2001: Development of an integrated Computer Aided Design and planning methodology for underground marble quarries. Georisorse Minerarie, Dec. 2001, 205-211.

7

Waste management

TOM HELDAL , NIKOLAOS ARVANITIDES

7.1. What is waste rock?

"Waste" from ornamental and dimensional stone quarrying is a relative term; some prefer to call it "leftover stone", to avoid confusion with "hazardous waste" and waste from an artificial source. As seen in chapter 2, there are also different attitudes among the European countries on how to treat it. Here, we define "waste" as the leftover stone from stone quarrying – predominantly composed of large and small pieces of rocks (Figure 37). The term "waste" is somewhat misleading, since such material can be regarded as a resource that can be used for a number of applications.

It is accepted that stone quarries generate much such waste rock, and that it is important to minimize it by increasing the recovery and finding alternative uses.

The waste consists predominantly of large and small pieces of rock, either from the deposit or from non-exploitable rocks covering them; such waste does not contain any dangerous substances or additives, and is regarded as **inert waste** – not harmful to the environment. In addition, there are earth and soil, which may cover the rocks, and less amounts of quarry dust, resulting from drilling, sawing or crushing by quarry machinery. The dust is essentially collected and taken care of – sometimes utilised. In the following, we focus on the waste rock.

The amount of quarry waste can vary from 50 to 95 percent of the total volume of extracted rock. Waste is here defined as the leftover stone that is not used directly for the production of ornamental and dimensional stone. Generally, high-priced, exclusive rock types generate more waste than low-priced ones.

The quarry waste may, to various extents, be used for other purposes than ornamental stone. The total utilisation, or recovery of the deposit, can thus reach 100 percent. It is therefore possible that a quarry with low block recovery can have a high total recovery, and vice versa.

Figure 37. Waste handling has been a major aspect in stone quarrying at all times. These waste dumps are more than three thousand years old, and are today "converted" to a protected site of cultural heritage. (Egypt)

7.2. By-products from natural stone quarrying

Technically, there is a wide range of by-products that can be produced from quarry waste, and during the last decades, strong efforts have been made in several countries in finding new ways of using the waste.

Aggregate for road construction, concrete etc. is in volume the most important by-product from stone quarrying. Most ornamental stone types are usable for certain aggregate qualities, and it is more and more common to see crushers in quarries, taking care of the waste (Figure 38). Siliceous rocks are best suited for aggregate production.

Figure 38. Aggregate production from nearby granite quarries, Madrid, Spain.

Crushed rock for **terrazzo tiles** and **agglomerated stone** is another important by-product, especially regarding marble and limestone. Certain feldspathic "granites" are also suitable, but generally not quartz-rich rocks. Limestone and marbles can be suitable for **cement** production (Figure 39).

Dolomite, limestone and marble can be used as **agricultural or environmental lime** – essentially to buffer natural or transported acidity in the soil or water. Certain other rock types (potassium-rich and/or phosphate-rich) can have properties suitable for improvement of agricultural land.

Figure 39. Only the lowermost part of this limestone formation in Germany is usable for ornamental stone. The rest is applied for aggregate and cement.

Application of waste for **industrial mineral** production is highly interesting, but requires rocks with rare and valuable properties. One example is the use of pure limestone and marble around the Mediterranean as filler or slurry for paper production. Soapstone waste is generally used for the production of talc. The feldspars of some granites can be used in ceramics.

Since ornamental and dimensional stone quarrying generate large pieces of waste rock of sound quality, **armour stone** has been evolving as an attractive niche for some producers[23], even to distance markets. Another interesting area is the last years' growing market for **rough stone bricks/rubble** (also called "environmental stone"), used for stone walls, road embankments, traffic dividers, paving, etc[24]. This specially applies for layered rocks, such as sandstone, limestone, slate and gneiss. There are even examples of companies mining old waste dumps for such.

A common by-product from slate is roofing-asphalt. Other, more peculiar uses of waste include additive in chicken food (marble and limestone) and decorative sand and gravel (strongly coloured rocks).

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[23] especially Norway, Finland and Sweden

[24] among other, see Selonen, O., Ramsay, A. & Tolvanen, P. 2001: Use of by-product of dimension stone quarries. Proceedings of Aggregate 2001 – Environment and economy. Helsinki, Finland 6-8 August 2001. Ed. By Pirjo Kuula-Vaisanen & Raimo Uusinoka. Volume 1. Tampere University of Technology, publication no. 50, 231-235.

Although there are many possible uses of quarry waste, there are also **limitations**. Many of the products described above need a strong, local market, since they do not bear a long-distance, overland transport. So, it is relatively easier to get rid of the waste (e.g. finding a market) in a densely populated area than in a peripheral. For instance, long-distance transport of low grade aggregate from a remote quarry is neither economically nor ecologically sustainable.

On the other side, there are probably many examples where quarry waste could substitute other aggregate production: instead of having own quarries for **high-quality** aggregate, there are perhaps neighbouring stone quarries with **sufficient quality**. So, the utilisation of stone quarry waste is not only a question of finding a product and market, but also highly important that "waste resources" are considered in local and regional resource allocation planning.

Armourstone

Waste rock from the larvikite quarries in Norway is used for coastal protection in UK. Armourstone from Larvik ranges in size from 60 kg to 20 tonnes, and since 1990 more than 2 million tonnes have been supplied for use both in marine structures and for coastal protection, including breakwaters, offshore reefs, scour protection, revetments and jetties.

Source: http://www.fjordstein.dk/

7.3. Disposal and handling of quarry waste

For all ornamental and dimensional stone operations, proper disposal facilities for waste rock are important, unless the waste is continuously exploited to commercial products. Waste rock should be deposited in a way that is safe (avoiding direct and indirect danger of landslide) and does not negatively influence water resources.

From the operator's point of view, the facilities should be located as close as possible to the quarry – avoiding unnecessary transport. At the same time, the waste should not be disposed on exploitable stone reserves: moving the waste back and forth is neither good business nor friendly to the environment. From the surrounding society's viewpoint, the quarry waste should be disposed in a way that minimizes the visual impact and any hazards, and environmental authorities prefer that the waste should be hidden (covered) and/or re-deposited into the quarry.

There are several ways, in which the needs of the extractive industry, the society and environmental authorities can meet. The following are some examples.

In large scale quarry areas, where there are several quarries working, a good solution can be **common waste disposal** areas. In the Blue Pearl larvikite quarries in Norway, 10-15 quarries share a few waste dumps. These are located on non-exploitable rocks, and form barriers between the surroundings and the quarry areas, reducing the visual impacts and noise from the quarries.

Continuous backfilling of waste rock into the quarry is frequently mentioned as the best solution[25]. However, there are actually only a very few quarry situations where this is possible. Backfilling requires an operation moving laterally during extraction, exploiting the

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[25] Management of waste resulting from prospecting, extraction, treatment, and storage of mineral resources (second draft) http://europa.eu.int/comm/environment/waste/mining.htm

whole thickness of the deposit. As many quarries move downwards into the rock, any disposal of waste within the deposit, before the quarry is closed, is impractical.

Use of waste for local purposes, such as **landfills**, is a solution, which can be interesting in several areas. Examples are filling swamps or depressions in the terrain for making agricultural land, extension of harbours or industrial areas, etc. In some quarry areas, the ornamental and dimensional stone quarries cooperate with local authorities in planning waste disposals, which are easily accessible for future use as landfill[26]. In such cases, the waste dumps are regarded as future resources that can reduce the need for future quarries for landfilling materials.

7.4. Quarry closure, rehabilitation and after-use

Sooner or later, all quarries are mined out and have to close down. Europe is full of closed stone quarries, some of them caught by urbanisation, others still occurring as dangerous traps in the terrain. In modern ornamental and dimensional stone quarrying, the producers have to prepare plans and secure the financing of quarry rehabilitation, in order to get mining permission.

Safety is a major requirement in the rehabilitation of quarries. Others are to minimize the visual impacts and to (as far as possible) reconstruct the natural terrain. In most cases, waste rocks are used for the rehabilitation, filled back into the quarry. This is covered with soil and vegetated. Recently, a hillside quarry in Spain was, due to its light appearance contrasting with the surroundings, was painted in a greenish colour. However, such rehabilitation will probably not be a very common practise.

An alternative to natural rehabilitation is other uses of abandoned quarries, some which the following examples can illustrate.

Many quarries are located in traditional and historically important quarry areas, and the stone exploitation has contributed in shaping the cultural landscape. In some areas, quarries have been restored and made available to the public, since they bear witness to an important industrial history of the area, and can contribute in increasing the knowledge and understanding of the industry's history and working conditions.

Other common examples of quarry after-use include transforming quarries into farmlands, parks, industrial areas or residential areas. More peculiar examples can also be found, such as the use of abandoned quarries for outdoor theatres! The acoustic in an old granite quarry can be amazing.

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[26] Sweden. Personal comment by Mr. Kurt Johansen, president of the Swedish Stone Industry Federation.

"Afterlife" of an old quarry

An abandoned marble quarry close to Athens, Greece, was rehabilitated recently (Figure 40). Instead of trying to reconstruct the nature, it was decided to transform the quarry into a park area, where the audience also can see how marble was exploited in different periods. The waste rock was used for making footpaths and securing cliffs and slopes in the quarry.

Figure 40. View of the restored marble quarry, Athens, OSNET members on inspection.

Figure 41. Abandoned granite quarry turned into a theatre stage. South Norway.

8

Concluding remarks

TOM HELDAL , NIKOLAOS ARVANITIDES

The ornamental and dimensional stone quarrying industry is facing several important challenges. The international competition is getting stronger, and so are the environmental restrictions: of greatest importance are restrictions on land use, the handling and utilisation of waste and the eco-label criteria. Future work on such legislation should lead to a legislative framework, which should benefit both the industry's development and competitiveness, and the environment. Clearly, it is important that the ornamental and dimensional stone quarrying industry together with R&D institutes supply important background information, such as life-cycle analyses, in order to obtain that. Harmonisation of important issues in national mining laws and legislations for stone exploitation will also be of great importance, and the needs of small-scale "artisan" quarrying, such as restoration quarries, should not be forgotten.

To secure the availability of stone resources for future generations, the exploitation and management of deposits must balance between more efficient and competitive quarrying operations, competing needs of the society and demand for more environmentally sustainable production. Information on ornamental and dimensional stone resources – existing quarry areas and future potential reserves – is scattered, incomplete and not easily accessible. To obtain a better management of such resources for the future implies, among other things, the incorporation of ornamental and dimensional stone in land use planning.

Exploration of ornamental and dimensional stone deposits has, in recent years, shown interesting developments – both regarding new techniques adapted to the sector and concerning the application of methods known for other mineral industry sectors. However, optimising exploration tools and methods, benchmarking and – not at least – create an innovative professional environment on stone exploration, could improve this side significantly.

The technological development of tools and machinery in quarrying has shown a tremendous development during the last decades. This will continue, with better sawing equipment, other tools and the evolution of new, innovative technology such as water jet and slow splitting techniques. The quarry operations turn more efficient, and an increasing number of operations go underground. There are many interesting cases showing creativity in the utilisation of waste rocks, increasing the overall recovery of the deposits. However, this could go much further, and viewing the waste rock as a potential resource – and not just as a problem – could lead to a long lasting improvement in the sector's environmental performance.

There are several areas within ornamental and dimensional stone quarrying that could benefit from more research activities. These include alternative uses of waste rocks, better exploration methods, life-cycles analyses, rock properties related to production techniques, quarrying technology, more efficient quarry operations and resource management systems.

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Part B

Control and Monitoring of stability conditions in Dimension Stone exploitation: methods and instruments

9

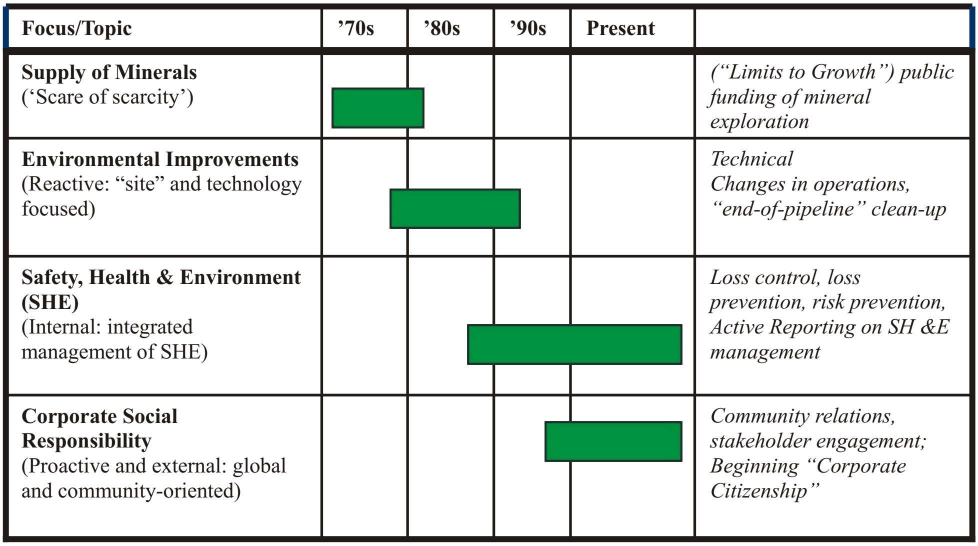
Introduction

ANNA MARIA FERRERO, GIORGIO IABICHINO, NICOLAOS ARVANITIDIS

Risk assessment, safety and working environment issues have through time become an important consideration of the stone industry (Figures 42 and 43). For many years poor safety conditions during mining (mainly underground) led to serious accidents for the workers and the facilities in general. Nowadays although working conditions have improved, unpredictable accidents still occur, and further safety improvements are required. Here and then, workers are reported killed in a number of mines around the world. There is still a lot of research effort to be undertaken, particularly in the field of developing alarming systems, which can predict, assess and minimize the risks during mining. After all, the safety of the workers should take precedence over economic investment and production activities.

Quarrying operations can be as hazardous as underground mining. Stone production deals actually with the extraction of hard rock, and follows also stability rules related to discontinuities and stress – strain conditions. However the open pit nature of most of the exploitation activities means that in addition to human safety issues, specific and strong environmental aspects are also involved.

This edition is an attempt to summarize the available methodology and instrumentation, in terms of minimizing the geological risk and improving safety factors, with respect to quarrying and extraction of dimension stones. In the course of time, methods and techniques applied before, during and after quarrying and extraction of dimension stones have developed from an empirical state to automated and computerized instrumentation, which provides a detailed analysis and efficient interpretation. Innovative modern instruments and methods are contributing to control, monitor and improve stability and safety conditions during exploitation of dimension stones. At the same time attention is paid to ongoing research and development, and the potential future trends in this and other relevant sectors of the stone industry.



Focus/Topic	’70s	’80s	’90s	Present	
Supply of Minerals (‘Scare of scarcity’)	🟩				*(“Limits to Growth”) public funding of mineral exploration*
Environmental Improvements (Reactive: “site” and technology focused)	🟩	🟩	🟩		*Technical* *Changes in operations, “end-of-pipeline” clean-up*
Safety, Health & Environment (SHE) (Internal: integrated management of SHE)		🟩	🟩	🟩	*Loss control, loss prevention, risk prevention, Active Reporting on SH &E management*
Corporate Social Responsibility (Proactive and external: global and community-oriented)			🟩	🟩	*Community relations, stakeholder engagement; Beginning “Corporate Citizenship”*

Figure 42. Mineral Resources Management towards Sustainability/maintaining Competitiveness. (Source: Prof. Dr. F.W. Wellmer, BGR, Euromines Conference on Sustainable Resource Policy for Europe, Brussels 2002)

Rock stability controlling and monitoring methods are mainly related to mechanical, structural and hydrological characteristics of the host rocks. Various instruments are used for the definition of the geophysical interpretations, RMR index, geotechnical surveys, topographic measurements, natural stress determinations, piezometric and in clinometric measurements, monitoring of rock – mass displacements and settlement measurements. Of course the main objective is to integrate the output of this multifunctional data into a potential tool enabling and supporting a high recovery quarry planning, safe working conditions and a sustainable management of the environment.

Excavations for stone exploitation, both underground and open pit, inevitably cause a series of disturbances in the host rock mass that affect its pre-existing natural state of stress, which is dependent on its nature and morphology. The extent of the perturbations is usually unknown and is related to the excavation structure, the methods used for the excavation and the interference these two factors have with the mechanical, structural and hydrological characteristics of the host rock. A stable excavation is based on a new configuration of the acting stresses compatible with the rock mass strength features. The stability of the excavation, the excavation methods used, the duration and the recovery of the quarry are all fundamental objectives that have to be accomplished when planning a quarrying activity, despite the many difficulties involved.

Remarkable technological advances have fostered the development of new methods and techniques in the quarrying activities. These are characterised by a high degree of mechanization and automatization of the excavation processes, combined with the development of new analytical and numerical design methods.

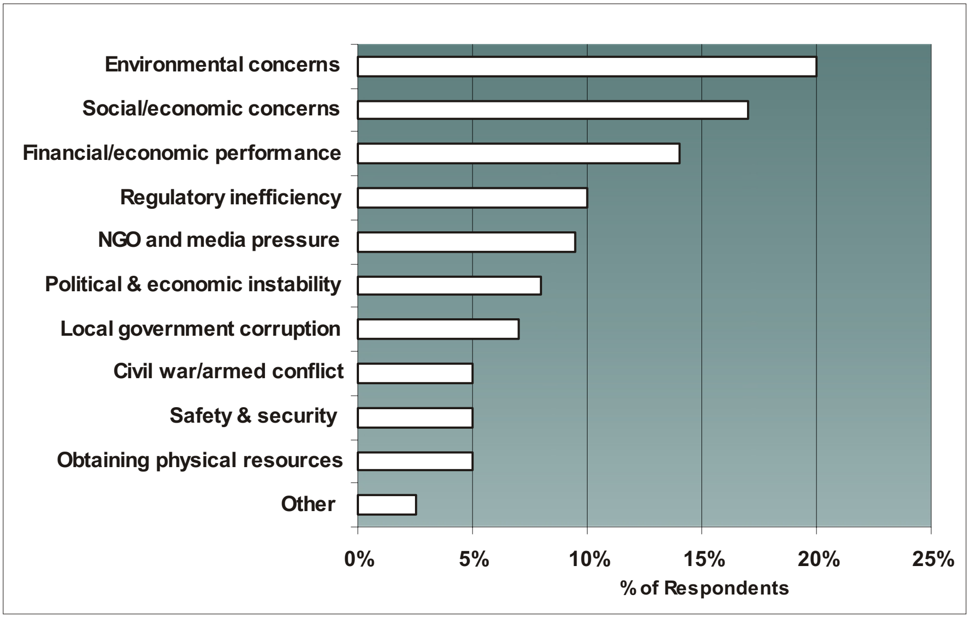


Figure 43. Key Issues Facing the Industry, (Source : Survey KPMG during GMI Conference Toronto, May 2002)

The theoretical methods developed to analyse the stability conditions of the excavated rock mass have been improved, both by considering more realistic models of the stress – strain rock behaviour and visualising the rock mass as a discrete blocky system in a three-dimensional field.

Latest developments on the methods applied *in situ* and in laboratory, on the physical-mechanical characterisation of the rock and of its "weak" areas (discontinuities), have also contributed to the definition of the mechanisms determining the stress-strain behaviour of discontinuous rock masses. On this basis the redistribution of the stresses around the underground excavation over time can be computed in a more realistic way. The rock mass of the excavation area can be considered as self-supporting medium, in relation to the different kinds of foreseen interventions during the excavations and according to the state of the rock fractures.

The last fifty years an evolution has been observed from an occasional qualitative observation of the physical phenomena involved in the opening of a quarry (convergence, settlement, collapse, rockburst, swelling, drainage) to the establishment of a scientific methodology that theoretical and interpretative supports the increasing number of observations acquired through methodical measurements and experimental controls. The target of this new approach is the minimisation of the geological risk, which in engineering terms is the achievement of the best safety conditions in the working area at the lowest cost, and the improvements in the safety conditions of underground excavations. The prevailing methods applied, mostly empirical, have therefore been integrated with new design procedures. These procedures connect the results of methodical measurements and geomechanical controls, carried out *in situ* and in the laboratory, in pilot or excavation stopes, with the planning and working adjustments of the excavation in order to optimise the working conditions.

The basic characteristic of modern design approaches of stone exploitations, therefore, is a geognostical - geotechnical investigation carried out before, during and after the execution of the excavation.

Investigations are performed before the excavation to collect the project data, during the excavation to verify the plan hypotheses, and after the excavation to check the effectiveness of the employed excavations methods over time. It will then be possible to formulate a comprehensive description of the possible relationships between the planned excavations and the pre-existing natural state of stress, and afterwards to evaluate the environmental impact of the underground exploitations. Accordingly it is necessary to identify and determine the physical-mechanical quantities, essentially the stresses and strains, which define the possible mutual interferences between the elements of the excavation.

Unfortunately, at present, the application of design methods based on experimental campaign, for the exploitation of ornamental and dimensional stones, is still occasional and essentially connected with particularly difficult conditions. It is then advisable for the control and verification interventions already applied to classical mining activities, to be introduced and performed in quarry exploitations, according to existing norms and technical regulations. In this view, the costs of the geomechanical controls are not seen as part of the overall exploitation costs, but as an investment for the safety of the workers.

This edition is especially dedicated to describe the most common methods and devices utilised to measure the state of stress (natural and induced by the excavation), the groundwater pressure and the displaced around the excavation both during the design phase (chapter 10) and during the excavation (chapter 11). In chapter 12 a description of the most promising development in the monitoring field is reported. In chapter 13 and 14 some well documented cases where the excavation design has been supported by in situ measurements and monitoring are reported

A series of tables summarizing the geomechanical investigations and control methods described here can be found in Appendix A of the present report.

Finally, Appendix B is devoted to the description of a study on application of geophysical methods.

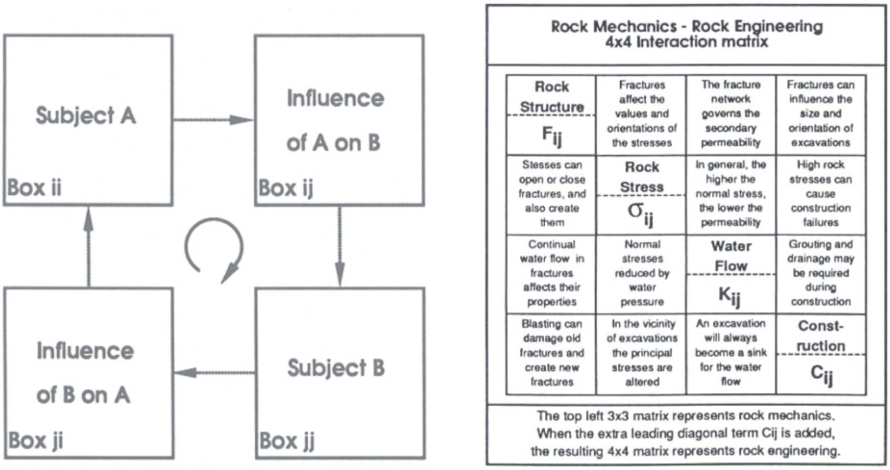
10

Geotechnical investigations during the design phase

ANNA MARIA FERRERO, GIORGIO IABICHINO

The design of an ornamental stone excavation needs the definition of the geological and geotechnical characteristics of the rock mass that has to be based on a series of investigations which are already applied, as a common procedure, in the mining industry of first-rate minerals. These include surface survey of the site, survey of the rock mass structure, measurement of the stress conditions, either or both absolute and relative, and performance of geophysical surveys, coring and laboratory tests. These kinds of data can supply useful information on the superficial and deep morphology of the rock mass, as well as the hydro-geological and thermal conditions of the excavation areas. They contribute to a comprehensive description of the possible influences between the excavation and the pre-existing natural state of stress and of the possible environmental impact of the projected exploitation.

A more accurate geomechanical characterisation results in a better correspondence between the chosen design method (empirical, analytical and numerical) and the actual working conditions in the excavation, together with the control of the costs of the excavation. This objective will not necessarily be achieved through the determination, in laboratory and *in situ,* of all the measurable characteristics of the rocks in the excavation area but through the identification and definition of the physical and mechanical characteristics of the rock mass specifically directly involved in the mutual interferences between the different elements of the excavation. The use of the “Rock Engineering System” (Hudson, 1992) has recently introduced a methodical approach to the study of the possible interferences between the rock of the excavation area and the engineering works, such as exploitation void and re-profiling of natural slopes. This method is based on the use of a square matrix of interference (Figure 44) composed of the elements which describe the excavation problems, shown on the diagonal, and their reciprocal influences, represented by elements outside the diagonal.



Rock Mechanics - Rock Engineering
4x4 Interaction matrix

Rock Structure F_{ij}	Fractures affect the values and orientations of the stresses	The fracture network governs the secondary permeability	Fractures can influence the size and orientation of excavations
Stesses can open or close fractures, and also create them	**Rock Stress** σ_{ij}	In general, the higher the normal stress, the lower the permeability	High rock stresses can cause construction failures
Continual water flow in fractures affects their properties	Normal stresses reduced by water pressure	**Water Flow** K_{ij}	Grouting and drainage may be required during construction
Blasting can damage old fractures and create new fractures	In the vicinity of excavations the principal stresses are altered	An excavation will always become a sink for the water flow	**Const-ruction** C_{ij}

The top left 3x3 matrix represents rock mechanics.
When the extra leading diagonal term Cij is added,
the resulting 4x4 matrix represents rock engineering.

Figure 44. Schematisation of an excavation process through a Rock Mechanics – Rock Engineering interaction matrix (Hudson, 1992).

On a first simplified approach the matrix can be composed of only four elements of which the first two constitute the main diagonal ("characteristics of the rock mass", "characteristics of the excavation", "influence of the characteristics of the rock mass on the excavation", "influence of the excavation on the characteristics of the rock mass"). With the insertion on the main diagonal of further elements characterising the issue under examination it is possible to identify, at least in qualitative terms, the connections between them and the investigations and controls to be carried out in laboratory and *in situ*. The connection matrix of the elements for the project gives a full account not only of all the factors required in the planned excavation, but also of those essential for the choice and optimisation of the excavation method (Hudson, 1993).

Independently from the design approach, the study of the stability conditions of an excavation (open pit or underground) has to be based on an all-scale preliminary investigation (anthropical, topographical and geotechnical) of the characteristics of the rocks in the excavation area.

For this purpose, direct and indirect studies are carried out in detail according to the kind of excavation to be undertaken, and to the phase of planning (preliminary, final or executive). The first kind of studies includes topographical surveys (Figure 45) integrated with aerophotogrammetrical and surface photogrammetrical GPS (Global Positioning System) techniques, which are employed for mapping the site (and of the existing structures and infrastructures) and to the fixing of a reference basis for the determination of horizontal and/or elevation displacement of points (Table 2, Appendix A).

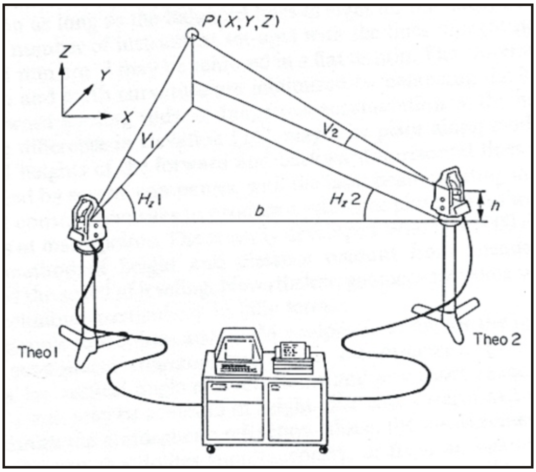


Figure 45. EDM (Electronic Distance Measurement) survey of mechanical and/or optical reference points and their plano-altimetrical positioning in an appropriate reference plane (Chrzanowski, 1993).

The use of electronic devices (possibly robotised) for the measurement of distances (EDM) and angles (Figure 45), “Total Stations”, gives a high degree of accuracy in the definition of the rock mass topography that is subsequently used as a reference for geometry. The delimitation of the projected excavation, together with the definition and control of the reference points located in the area, are defined with an accuracy of 0.01% over 200 metres (Chrzanowski, 1993). On this basis, it is therefore possible to identify and define the approximate interference areas between the projected excavation and nearby structures or pre-existing conditions.

The data acquired with the topographical survey are usually compared with those derived from the geological and geo-structural surveys that are also carried out on a regional scale. These surveys identify the main geological units in the excavation area, together with debris or landslide areas, principle faults, and the characteristics and distribution of the areas with a higher degree of disturbance (Canmet, 1977). Furthermore, it is possible to detect the presence of anomalous stress situations, free or under pressure layers, rendering impermeable structures and impluvia.

Despite the prevailing qualitative nature of the data acquired in the course of this phase, the International Society for Rock Mechanics (ISRM, 1978) had proposed a method for a preliminary information organisation. Since a relevant national regulation has not yet been introduced, the Society designed a series of procedures in order to determine the geotechnical parameters and the minimum requirements that a geo-structural survey should have in order to be employed in the geotechnical design.

No technical advice is given about the methods of statistical analysis of the data resulting from the geological-structural survey (Cravero & Iabichino, 1992; Priest, 1993). The acquisition in underground excavations of the data measured on the surface must be verified. The assumptions about the possible underground structure can be confirmed or questioned by the employment of direct methods for the underground survey - such as geotechnical coring, or indirect methods based on geophysical techniques. The planning of a series of coring is usually connected with a further investigations phase. These can be carried out by using the entrance gallery to the underground excavation for the collection of rock/ground specimens or fragments.

When the cores have a minimum diameter of 54 mm (NX size) they may be used for the description of lithotypes, intercepted discontinuities and their frequency, possible fillings and percentages of the coring results (Rock Quality Designation). When the coring is orientated it is also possible to extract information on the orientation of joints and on the spacing of the different families of joints.

In common practice, the cores are also used to define different indexes, for example the Franklin index (Is) or the sclerometric index (L-Hammer, Schmidt rebound number), which are determined with a point test with conic point (Point Load test) or a sclerometric test, respectively (Broch & Franklin, 1984). Both these indexes are employed in the indirect determination of the resistance to uniaxial compression of the rock matrix. The sclerometric index in particular is employed not only to determine the wall resistance of the discontinuities but also to estimate the rock elastic modulus (Stacey & Page, 1986). Suitable preparations of the cores acquired can complete the mechanical characteristics of the rock matrix (Table 1), by determining the relevant deformability and resistance parameters resulting from different stress conditions (ISRM, 1972; Vutukuri et al., 1976, 1978).

Table 1. List of the laboratory measurements of parameters and indexes of rock resistance and deformability according to specific international techniques or norms (ISRM, 1972; Vutukuri et al., 1976, 1978, modified).

Suggestions of the International Society for Rock Mechanics (ISRM)	Provisions of the American Standard for Testing and Materials (ASTM)
Petrographic description Water content, porosity, density, absorption Hardness and abrasivity Determining sound velocity Uniaxial compressive strength and deformability Tensile strength Strength in triaxial compression Shear strength Fracture Toughness Laboratory testing of argillaceous swelling rocks	Dimensional and shape tolerances of rock core specimens Laboratory determination of pulse velocities and ultrasonic elastic constants Creep in uniaxial compression Creep in triaxial compression Direct tensile strength Strength in uniaxial compression Strength in triaxial compression Unconfined compressive strength Permeability measured by flowing air Thermal expansion using a dilatometer Elastic modules of intact rock in uniaxial compression Specific heat Thermal expansion using a dilatometer

The acquisition of the data so far described allows the application of design methods for the planning of surface or underground excavations (Table 9, Appendix A). This can be carried out through the employment of rock mass classifications such as the “Q System” (Barton, 1976) or the “RMR” (Bieniawsky, 1984) or GSI (Hoek, 1994).

At a very early stage of the study, is possible to collect information about the stability condition of the excavation and about the self-supporting characteristics of the rocks especially when working underground, referring to abacuses specially designed for this purpose (Houghton & Stacey, 1980, Bieniawsky, 1984).

Any further evaluation of the stability conditions of the surface or underground excavation requires the determination of the deformability characteristics of the rock mass, the definition of the natural stress conditions, and also the influence of the hydraulic situation of the area under examination.

10.1. Measurement of the state of stress

The measurement of the acting state of stress within a rock mass can be very important for many different reasons: the natural state of stress is a starting point to evaluate the stability conditions of an excavation; the stress variation in the supporting structures (i.e. pillars), indicates the influence of the excavation on the safety degree of the supporting system. The natural stresses must be measured when studying the stability of both open pit and underground exploitation and the stability, for instance, of blocks possibly lying around the excavation area.

The measurement of the *in situ* stress strain behaviour of the rock mass can be very useful since it is difficult to be predicted by theoretical methods and impossible to be measured in laboratory conditions since the specimen volumes are too small when compared to the REV (Representative Elementary Volume) of the rock mass. The *in situ* measurements of the stress-strain behaviour of a rock mass usually becomes essential when the degree of fracture intensity of the rock mass is high and, consequently, can significantly affect the deformability and resistance characteristics of the rock matrix. Thus, a compromise between the need to test a significant rock volume and the possible necessity to repeat the tests in different positions has to be found in order to acquire representative data about a larger number of areas that present an interest for excavation works in different time periods.

In the case of dimension stone exploitation the *in situ* stress in the rock mass can be measured by two different methods. When the rock is directly accessible, the measurements are carried out through load tests performed on the excavation wall (ISMR, 1979) while if the area is not accessible, the tests can be performed with suitable coring boreholes (ISRM, 1987).

Stress can vary in the rock mass from point to point according to the depth level and also to the discontinuous nature of the rock. Since the acting stresses can not be measured directly they are determined only indirectly by measuring the values of physical quantities (such as strains, displacements, etc.) (Table 4, Appendix A).

At a first evaluation the maximum principal stress is often hypothesised to be vertical and with an intensity equal to the weight of the overburden, while the minimum principal stress is considered horizontal and lineal linked to the first, for example, by the elasticity theory. However, in many cases, experimental results have shown that at depths varying from 0-200 m the prevailing natural stress is the horizontal stress.

Due to the inner structure of the stress tensor that is represented with a rank two tensor whose definition requires the knowledge of six independent parameters, its measurement can be heavily affected by technical faults. The methods described below have different ability to measure the six parameters of the tensor as a consequence of the testing procedures.

Moreover, the different methods are based on different techniques with different operative procedures that have to be chosen in relation to the local situation of the rock in the measurement area in order to minimise unreliable measurements.

Table 2. Methods for the measurement of the natural stress condition of rock masses (ISRM, 1987)

Methods	Tests
Relaxation measurements (*stress release)*	Wall relaxation Under-coring In-hole relaxation (overcoring, borehole slotting, etc.) Relaxation of great rock volumes (bored raise)
Pressure cells *(stress restoration)*	Flat pressure cell Curved pressure cell
Hydraulic	Hydraulic fracture

Table 2 presents the different methods applied for measuring the natural state of stress in the rock masses.

In the last forty years several methods for the measurement of the natural state of stress acting in the rock masses have been studied. These methods are based on different principles (pressure restoration in cuts and boreholes, relaxation of a rock nucleus, hydraulic fracture, soft or hard inclusions, etc.) and the most accurate ones have been the subject of specific international techniques (ISRM, 1987).

All stress measurement techniques perturb the rock to create a response that can then be measured and analysed, with the use of theoretical models, in order to estimate part of the *in situ* stress tensor (Goodman, 1987).

In the hydraulic fracturing technique, the rock is cracked by pumping water into a borehole; the known tensile strength of the rock and the inferred concentration of stress at the well bore are processed to yield the initial stresses in the plane perpendicular to the borehole. In the flat jack test, the rock is partly unloaded by cutting a slot, and then reloaded (stress restoration); the *in situ* stress normal to the slot is related to the pressure required to null the displacement that occurs as a result of the slot cutting. In the overcoring test, the rock is completely unloaded (stress release) by drilling out a large core sample, while radial displacements or surface strains of the rock are monitored in a central parallel borehole. In each case stress is inferred, but displacements are actually measured.

The instruments used to perform such measurements can be divided into two general categories: soft and hard inclusions. Soft inclusion gauges have small stiffness relative to the host rock and stress determination requires knowledge of the rock properties and constitutive behaviour. These gauges therefore offer minimum resistance to rock deformation, so that gauge readings depend on rock stress and elastic properties but are independent of the modulus of the gauge. Rigid inclusion gauges are designed to be stiff relative to the host rock, and stress determination requires knowledge of the rock properties and constitutive behaviour only within broad bounds. Rock deformations are resisted by the gauge so that strains in the gauge have minimum sensitivity to rock modulus. Rigid inclusion gauges are usually referred to as “stress-meters”. Soft and hard inclusion gauges can be applied to measure the absolute state of stress and /or the stress changes.

Soft inclusion gauge

Stress change measurements can be performed using soft inclusion gauges of different types: flat and cylindrical pressure cells, borehole deformation gauges, biaxial and triaxial strain cells.

These devices can be applied in a wide variety of rock types; in some cases stress determination requires knowledge of the rock properties, while in other cases it does not.

One kind of soft inclusion device is the flat and cylindrical borehole pressure cells. A borehole pressure cell consists of a flat or cylindrical metal chamber, filled with a liquid and fitted with pressure regulation and monitoring capabilities. The term borehole pressure cell is normally used for a flat cell and the term cylindrical pressure cell for a cylindrical cell (Figure 46).

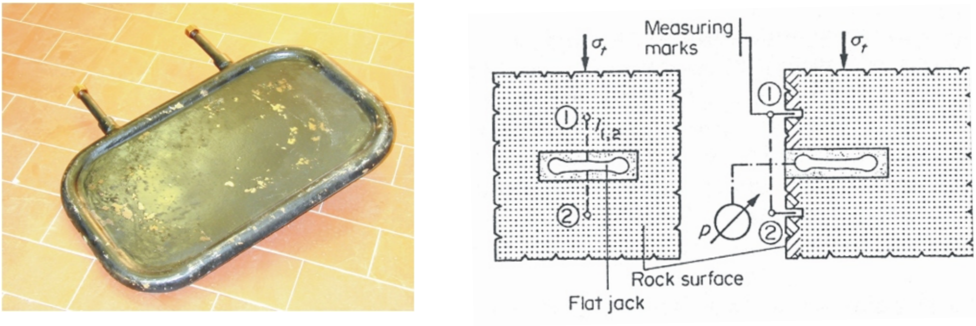


Figure 46. a) flat pressure cell for the measurement of the natural stresses by restoration of the stresses; b) scheme of the measurement displaying the cut executed in order to position the pressure cell and the measure bench marks (Fritz & Kovari, 1999).

A borehole deformation gauge is designed to measure diametric changes in a small diameter borehole where the gauge is inserted. The CSIRO (Commonwealth Scientific and Industrial Research Organization) gauge is used to measure changes in three diameters 120 degree apart. CSIRO has been used for stress change monitoring in more cases than the other cells.

Another well kwon deformation gauge is the USBM (U.S. Bureau of Mines) instrument, allowing measurement of chances in three diameters 120 degree apart. The USBM was developed for the determination of the absolute *in situ* stress by using overcoring procedure.

Biaxial and triaxial strain cells (also called doorstopper strain cell) are designed by the CSIR to measure strain on the wall or end of a borehole (Figure 47). The cells include electrical resistance strain gauge transducers and are bonded to the rock. Their primary application is the determination of the absolute *in situ* stress by using the overcoring procedure (Figure 48).

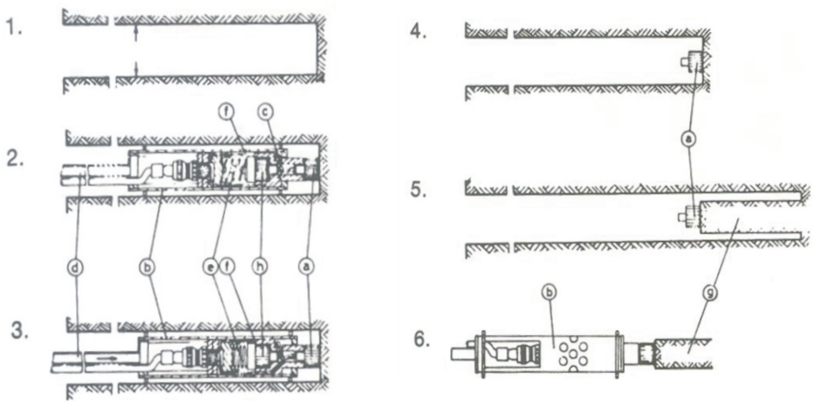
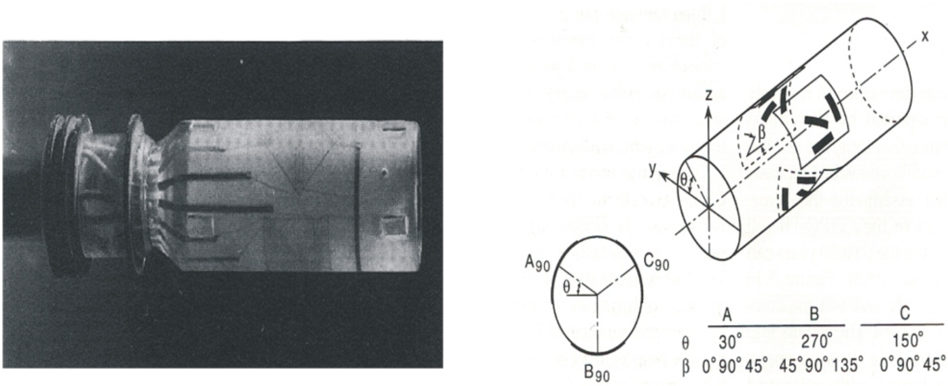


Figure 47. Scheme of the measurements by means of over coring technique; this example describes the CSIR (DOORSTOPPER) mono-axial technique (Leeman, 1969)



a) b)

Figure 48. a) CSIRO cell for the measurement of the natural stress condition with the stress release method; b) positioning of the three sets of extensometers for the three-dimensional measurement of the strains caused by the over coring (Worotnicki, 1993).

Rigid inclusion gauges

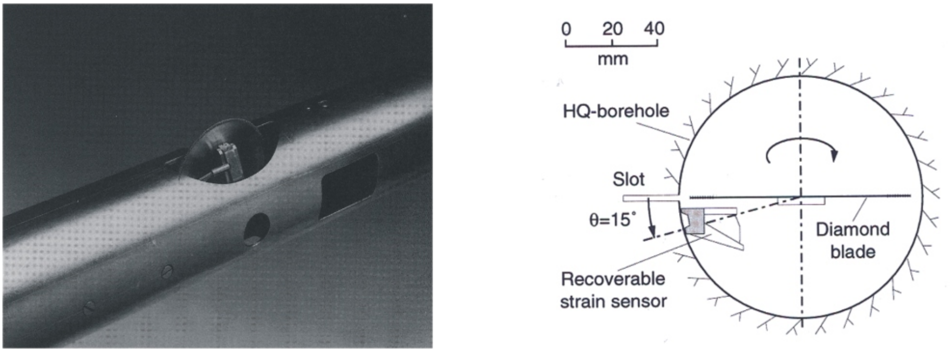
Rigid inclusion gauges, usually referred to as stress-meters, are designed to be stiff relative to the host rock and that stress determination does not require accurate knowledge of the rock properties and constitutive behaviour. The definition of a rigid inclusion gauge sets a practical upper limit of intact rock modulus of elasticity for which rigid inclusions remain "rigid" as one-third the modulus of the gauge. Steel, which has a modulus of elasticity of approximately 200GPa, is the most practical raw material for manufacturing rigid inclusion gauges. When used in rock with a higher modulus, the gauge must be calibrated in the host rock if maximum accuracy is required.

Rock pressure measurements are also made by hydraulic fracturing through hydraulic piezometers. Water is pumped into a section of the borehole isolated by packers. As the water pressure increases, the initial compressive stress on the borehole are reduced and at some points become tensile. When the stress reaches the tensile resistance of the rock a crack is formed and the pumped water pressure will fall as the crack will extend. The data can be interpreted in terms of initial stresses for known crack orientation. The orientation of a fracture can be observed by using down-the-hole photography or television or an impression packer.

The previously described methods are of interest for a standardisation process. Even if most of those methods are essentially employing coring boreholes to access the areas under examination, they have different characteristics basically depending on the rock volume involved in the measurement area and on the distance from the rock to the site which can be reached by men and vehicles. Actually, these elements may vary from a rock volume of 0.5 – 2 m^3 with a distance from the accessible area lower than 1 m in the flat pressure cell method (Figure 46) to a volume of $10^{-3} – 10^{-2}$ m^3 at a distance of 60 m in the USBM, CSIRO (Figure 48) and in the "Borehole Slotter" (Figure 49) methods, and still to a volume of 0.5 – 50 m^3 at a distance of several hundred metres in the methods based on the hydraulic fracture.

It is also important to have in mind that, in the best possible working conditions, such as when the rocks are all compact, homogeneous, with well defined geological limits, and with a stress-strain behaviour of linear-elastic type, the natural acting stresses can be measured with an error of ± 10% ÷ 20% for intensity and of ± 10° ÷ 20° for orientation (Amadei & Stephansson, 1992). These values are related to the volume directly involved in the measurement.

Even though the operative and economic details characterising each of these methods will not be thoroughly investigated in this text, it is worth pointing out that the definition of all the elements of the stress tensor in a single coring borehole can be carried out exclusively by means of the CSIRO or 3DCSIR methods. In fact, the flat pressure cell, hydraulic fracture and the USBM methods carried out with a single borehole allow the definition of only one, two or three elements of the unknown tensor, respectively.



a) **b)**

Figure 49. a) Borehole slotter for the measurements of the natural state of stress by relaxation in borehole; b) ideal section of a coring borehole in which a cut is executed for the stress release (Bock, 1993).

10.2. Measurements of groundwater pressure

The *in situ* state of stress is directly or indirectly affected by the local hydraulic situation, such as the presence of water tables, artesian layers, and the permeability characteristics of the ground, especially at low levels and when the rocks are weak, soft or highly fractured. The resistance of a rock mass is strongly influenced by its hydraulic conditions since it results in the reduction of the effective stresses that follows from the pressure increase in the pores of the rock. The definition and the analysis of the hydraulic situation and of its possible variations in an area where open pit or underground excavations are performed is therefore essential in order to determine the stability conditions of the exploitation and, in case of an underground excavation, of the possible influences on the surface. The hydraulic conditions of the rock mass vary from point to point depending on the local fracture intensity degree of the rock and on its state of natural stress, as well as on the presence, in restricted areas, of materials with a high permeability difference. It should be noted that underground excavations can meet aquifers under pressure with hydraulic heads in the number of a few dozens MPa.

The hydraulic characteristics of the rocks (Tables 5, 6, Appendix A) under exploitation are usually defined by means of installed piezometers and phreatimeters sufficient to cover the area under examination. The piezometers can have free heads or can consist of a porous cell connected with a hydraulic circuit and are employed to survey the position of the water table or the extent of the local interstitial pressure at a specific depth.

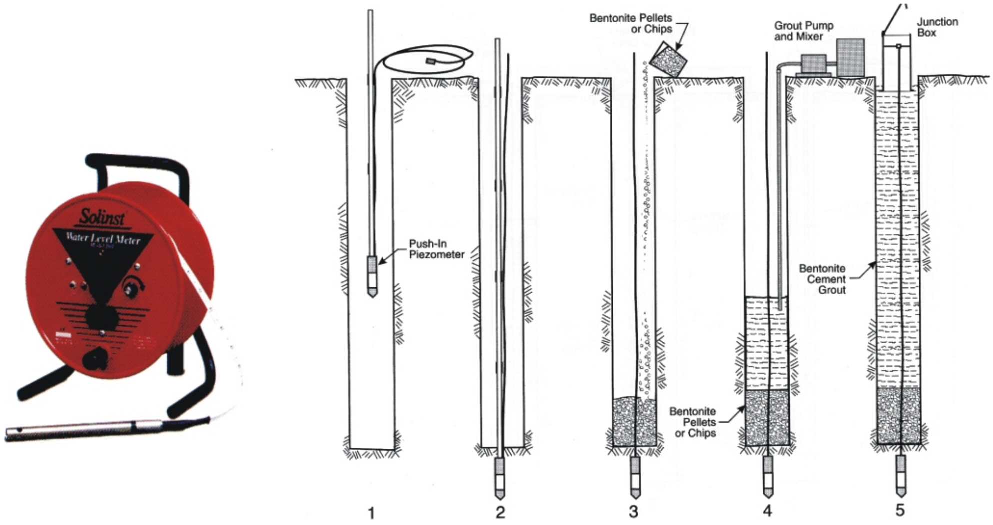


Figure 50. Piezometric probe of the "Casagrande" type and scheme of its on-site installation (Slope Indicator Appl. Guide, 1994).

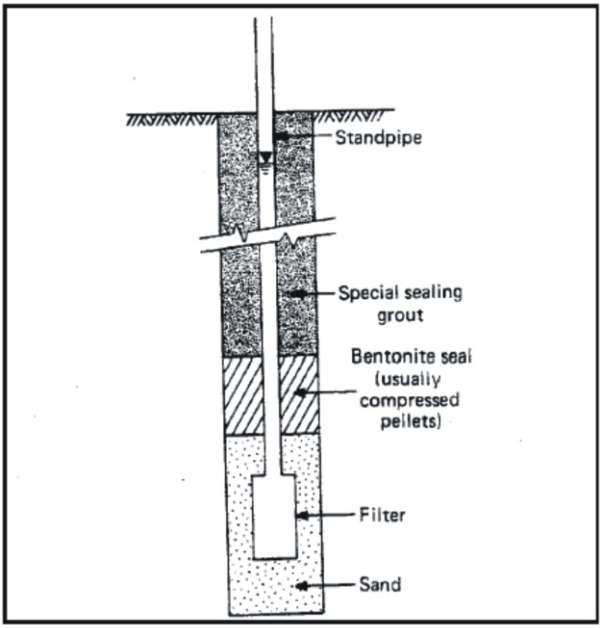


Figure 51. Piezometer of Casagrande type (Dunnicliff, 1993).

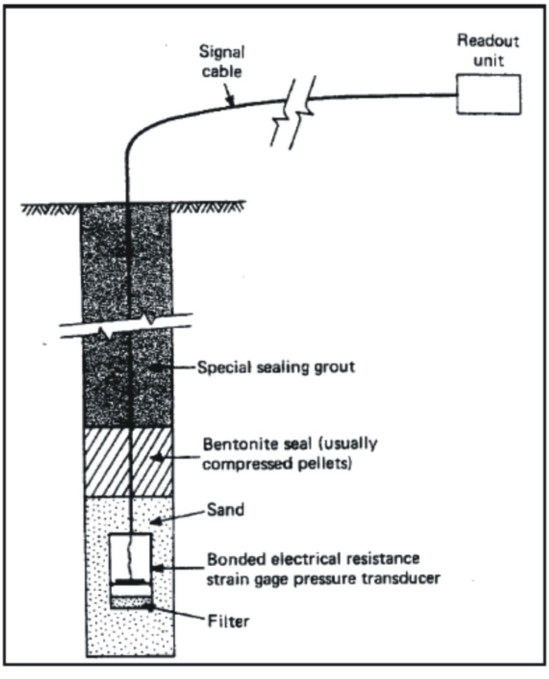


Figure 52. Piezometer with porous cell equipped with pressure trasducer and scheme of its on-site installation (Dunnicliff, 1993).

An observation well is a device that has no subsurface seals and it creates a vertical connection between strata. Because observation wells create a connection between strata their only application is in continuously permeable ground in which groundwater pressure increases uniformly with depth. “Casagrande” piezometer, (Figures 50, 51) is an open standpipe piezometer sealed so that it responds only to the groundwater around the filter element. Since it requires a significant volume of water to register a change in head, the response time can be very slow.

Piezometers can then be grouped into those that have a diaphragm between the transducer and the pore water and those that do not. The interstitial pressure is measured with different kinds (pneumatic, hydraulic, electric, etc.) of transducer devices connected with the porous cell. Instruments of the second type are open stand pipe and twin-tube hydraulic piezometers.

Piezometers are employed to determine the interstitial pressure in both saturated and unsaturated grounds (Hanna, 1973) by means of measuring cells with different characteristics. The cells employed for saturated grounds (low presence of air) have pores with an average diameter of 60 μ and a permeability degree of 3×10^{-4} m/s; those employed for unsaturated grounds (high presence of air) have pores with an average diameter of 1 μ and a permeability degree of 3×10^{-8} m/s.

When a piezometer is installed and the groundwater changes, the time required for water to flow into or out of the piezometer to effect equalization is called the hydrodynamic time lag. It depends primarily on the type and dimensions of the piezometer and the permeability of the ground.

Open standpipe piezometers have a much greater hydraulic time lag than diaphragm piezometers because a much greater movement of pore pressure is involved. The time lag can be minimised by using a minimum diameter standpipe, but since a minimum diameter stand pipe can nullify the self de airing feature of the piezometer diaphragm, piezometers can be used as an alternative. Several methods of estimating time lag are available (Viggiani, 1999).

Since the results obtained by a piezometer can only be confirmed by those of another nearby piezometer it is advisable to have a high number of installations, equipped with detectors of different kinds in order to improve the accuracy of the control over time.

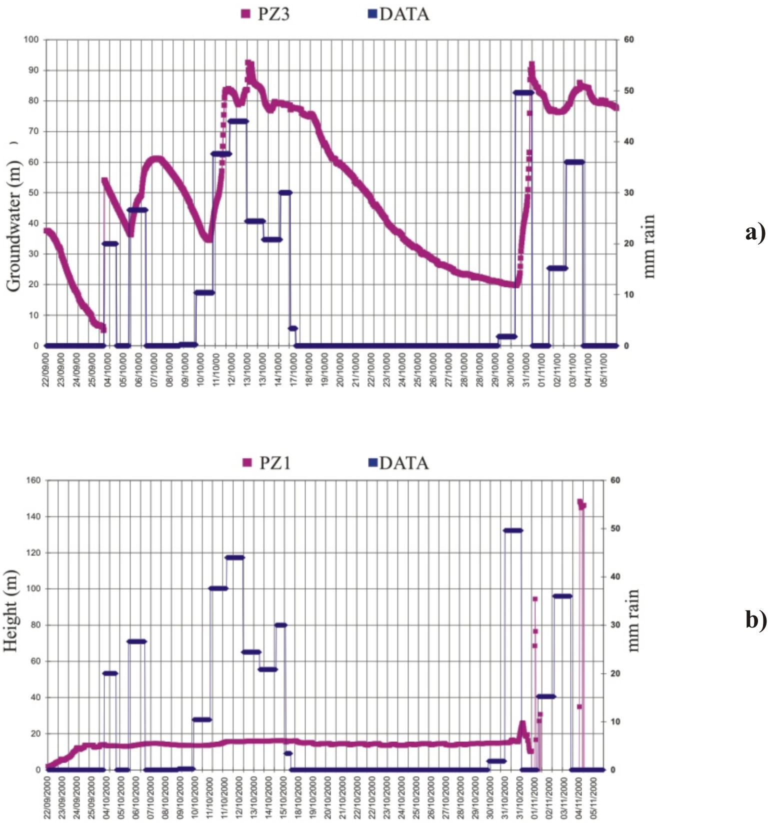
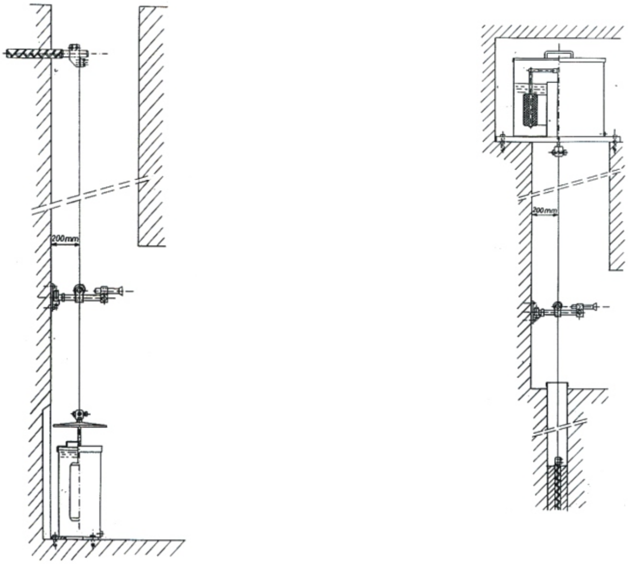


Figure 53. Examples of correlation between pluviometric and piezometric data according to time. a) Direct dependence between the water pressure and the intensity of the meteoric event; b) absence of dependence between the two checked measures.

10.3. Measurement of displacement

The measurement of displacements (vertical, horizontal and rotational) induced by an excavation can be a useful tool for understanding the rock mass mechanical behaviour and consequently, to investigate possible interference with structures located in the excavation area. The methods applied to the execution of these measurements depend strongly on the type of excavation (open pit or underground) and on the different characteristics of the area. In order to control the excavation behaviour specific devices should be installed at a very early stage of the excavation or, possibly, in pilot sites or tunnels developed to gather information to be utilised during the design phase. For this reason these kinds of measurements are introduced in this chapter, although, they will be carried out during the excavation. An initial set of displacement measurements, essentially referred to the surface, can be carried out by employing the already mentioned topographical techniques. For subsoil, the installation of pendulums (Figure 54), clinometers, inclinometers or extensometers has to be foreseen.

For the former, mechanical and /or optical reference points have to be fitted in the points of interest and their plano-altimetric position has to be inserted in a suitable reference plane (Figure 45). The evolution of the displacements over time can be controlled with optical topographical devices which, though subject to errors due to the weather conditions, allow the precise measurement of the spatial coordinates even in areas where direct access is difficult.



a) **b)**

Figure 54. Measurement on a horizontal plane of the displacements of the vertical from its initial position by means of direct (a) and inverse (b) pendulums (GIF Catalogue 1996).

For the latter, pendulums of different length must be installed in suitable locations and their possible displacements from the initial position on a horizontal plane must then be measured. A further set of measurements can be performed applying the previously mentioned geotechnical methods that are based on the observation of the displacements by means of clinometers, inclinometers and extensometers (Tables 7-10, Appendix A). These measurements can be carried out either by means of brackets, which will adjust the sensor to the element to be controlled, or by means of coring boreholes equipped for this purpose.

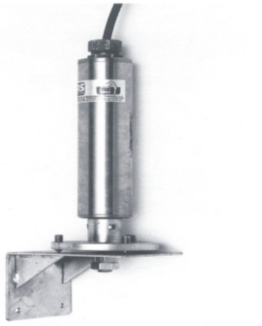


Figure 55. Clinometer for the measurement of angle deflections from the original zero position (SISGEO Catalogue 1998)

Clinometers and inclinometers for the measurement both on the vertical and horizontal axis can detect any angle deflection from the vertical. The method is based on the direct proportionality between the angle deflection of a pendulum and the current intensity necessary to the supply circuit of a magnet, adjusted to the instrument covering, to force the pendulum (servo-accelerometer) back to its original, vertical, position.

For inclinometers, the structure of the pendulum movements measured at different levels and on two respectively orthogonal planes allows the definition of the axis deformation of the reference hole over time and to the deepest point to which it is considered as fixed.

The diagram of the deformation velocity of the whole axis versus time is considered as a good safety indicator since a constant acceleration of deformation always corresponds to the breaking of the reference hole (Dutro, 1984).

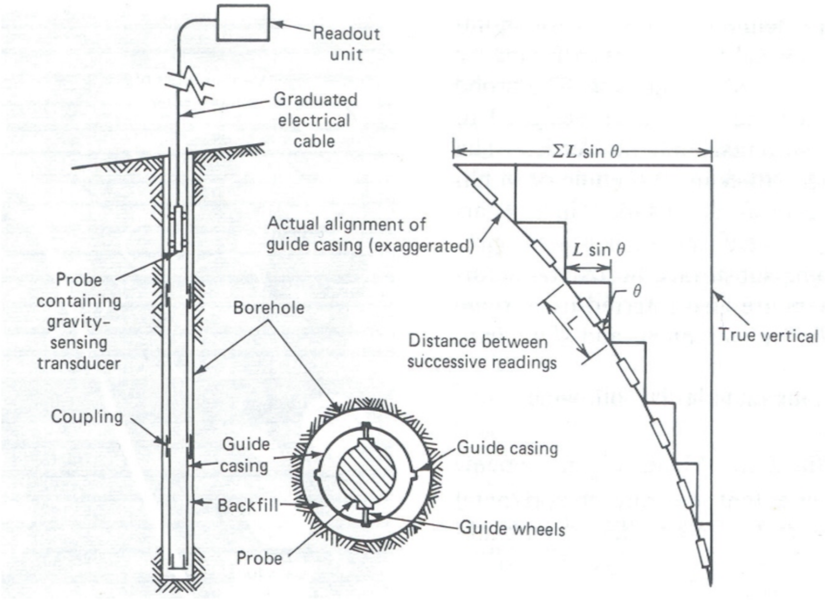


Figure 56. Recoverable inclinometer – the inclinometer probe can be seen inside the borehole (its section is shown) with the slide which enables the "torpedo" to cover the entire length of the hole. On the right the deformation of the hole axis is illustrated by consecutive segments (Wilson & Mikkelsen, 1978)

The diameter of the probe, and consequently of the coring borehole, is chosen according to the rock toughness. For example, higher diameters are employed for rocks with poor characteristics. The inclinometers can be of two types: recoverable and fixed. The former are employed in coring boreholes in which plastic tubes have been inserted covering their full length. On two pairs of respectively opposed and orthogonal generators, two semicircular slides are placed along the tubes. In this case, the measurement is carried out by running the inclinometer (called a "torpedo") along the entire length of the hole once on each of the two orthogonal planes predetermined by the slide position and by surveying the position of the pendulum by consecutive segments. Fixed inclinometers are composed of various servo-accelerometers (one for each component of the deflection under measure) permanently installed at different levels of the reference hole.

Figure 56 shows the normal principle of inclinometer operation for near-vertical guide casings. After installation of the casing, the probe is lowered to the bottom and an inclination reading is made. Additional readings are made as the probe is raised incrementally to the top of the casing, providing data for determination of initial casing alignment. The differences between these initial readings and subsequent sets define any change in alignment. Provided that one end of the casing is fixed from translation or that the translation is measured by separate means, these differences allow the calculation of absolute horizontal deformation at any point along the casing.

Most inclinometers provide casing inclination data in two mutually perpendicular near-vertical planes. Thus, horizontal components of movement, both transverse and parallel to any chose direction, can be computed from the measurement.

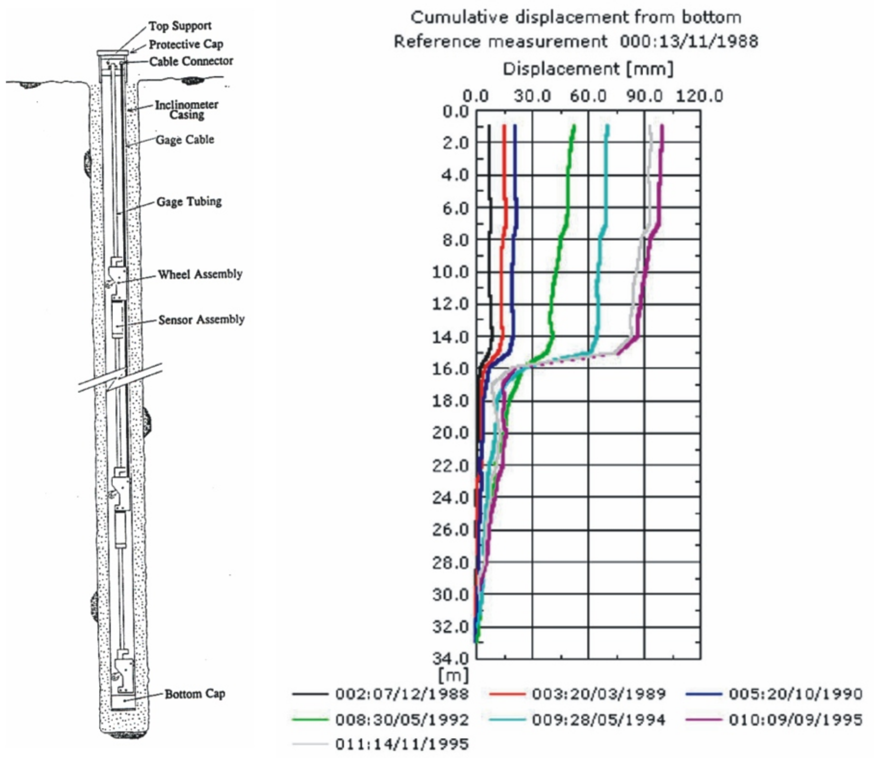


Figure 57. Fixed inclinometer chain – The diagram shows the chain of servo-accelerometers along the entire hole so as to measure the inclinations at different levels and to define the displacement of the hole axis (Slope Indicator Appl. Guide, 1994).

The measurement and the acquisition of data are identical for the two instruments and, in both cases, any possible translations of the entrance head of the inclinometric borehole can be determined by optical and topographical measures.

Extensometers (Tables 9, 10, Appendix A) can surv ey at a good degree of sensitivity (0.1 mm on a base of 10 m) the distance variations between two or more points distributed along the same axis in any direction. Extensometers belong to two types: removable and fixed. The first (Figures 58-61) are generally employed on measure baseline not over 25 – 30 m and they are composed of bars or graduated bands (convergence bands). These employ displacement transducers of various types (mechanical, electrical, etc.) to survey the distance variations of the reference points, which are usually directly accessible and are adjusted within the rock under examination. These measurements allow the control of the wall convergence around the excavation especially when working underground.

Fixed extensometers (Figure 62) are employed with the same degree of precision even on a measurement basis of several meters and are composed of bars. These employ displacement transducers to measure the distance variations between the reference points that are adjusted to the rock under examination along a coring borehole and with a measuring head placed at the end of the hole. Possible displacements of the accessible bench marks or of the measuring heads can be surveyed by optical topographical type measurements.

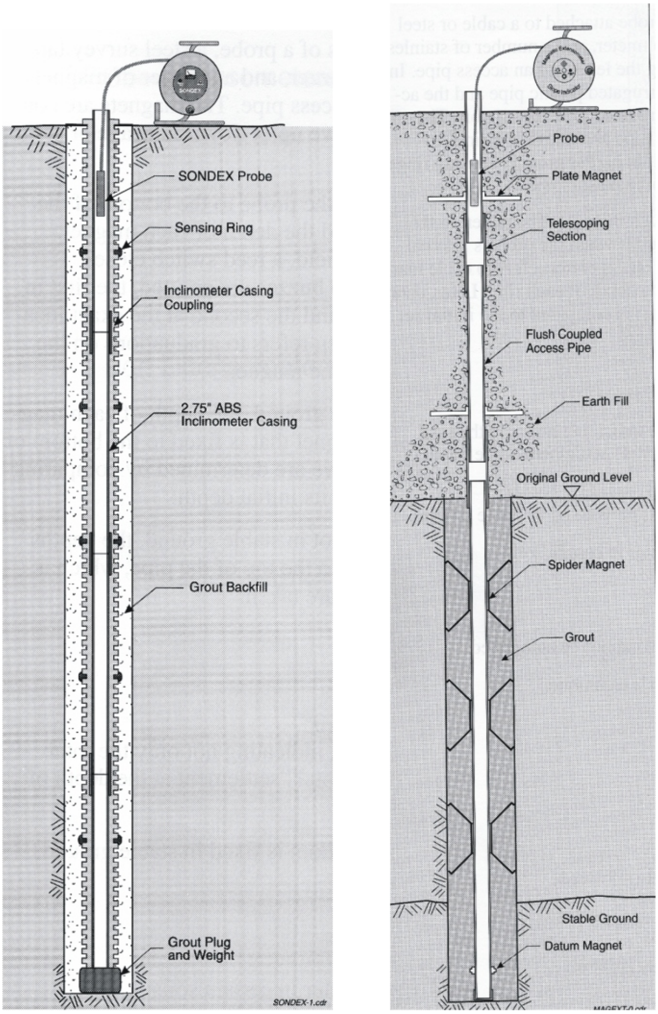


Figure 58. Fixed extensometer of an incremental type with a removable measure head (Slope Indicator Appl. Guide, 1994).

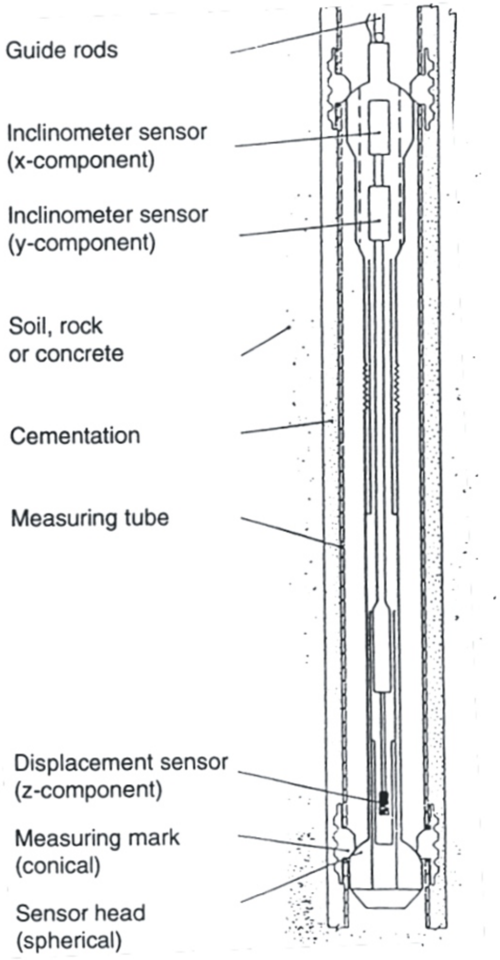


Figure 59. Inclinometer – extensometer (“Trivec”) of an incremental type (GIF Catalogue, 1996).

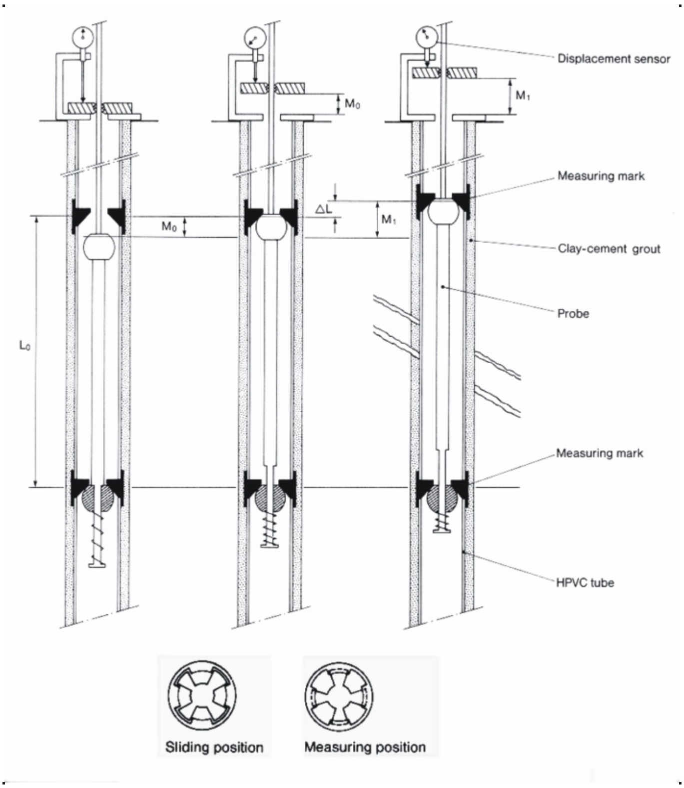


Figure 60. “Slide Deformometer” removable extensometer (GIF Catalogue, 1996).

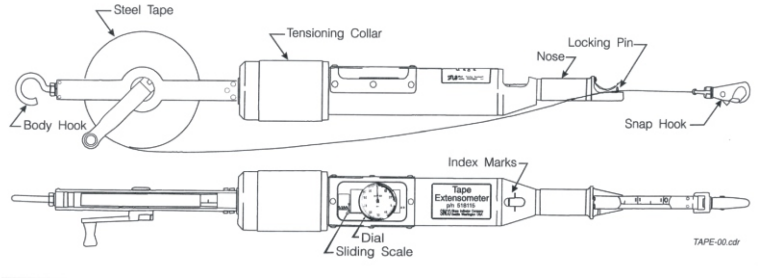


Figure 61. Removable extensometer: graduated band (convergence band) equipped with displacement transducers (mechanic, electric, etc.) employed on measure bases not over 25–30 m (Hoek & Bray, 1974).

Both kinds of extensometers require suitable reference points (anchorages) whose type (with mechanic, hydraulic, chemical clamping) varies according to the resistance characteristics of the rock to which they are adjusted. In particular, when borehole extensometers are employed the positioning of the furthest reference points from the measure head is usually performed on a part of the rock which will not be affected by the excavation works (Cording et al., 1985).

Recent technological improvements in the measurement methods applied to geomechanical problems have allowed the realisation of hybrid devices. These devices can determine at the same time and with the highest degree of precision both the deformation of a borehole axis and the incremental distance variations of predetermined measurement bases along the hole (Koppel et al., 1988).

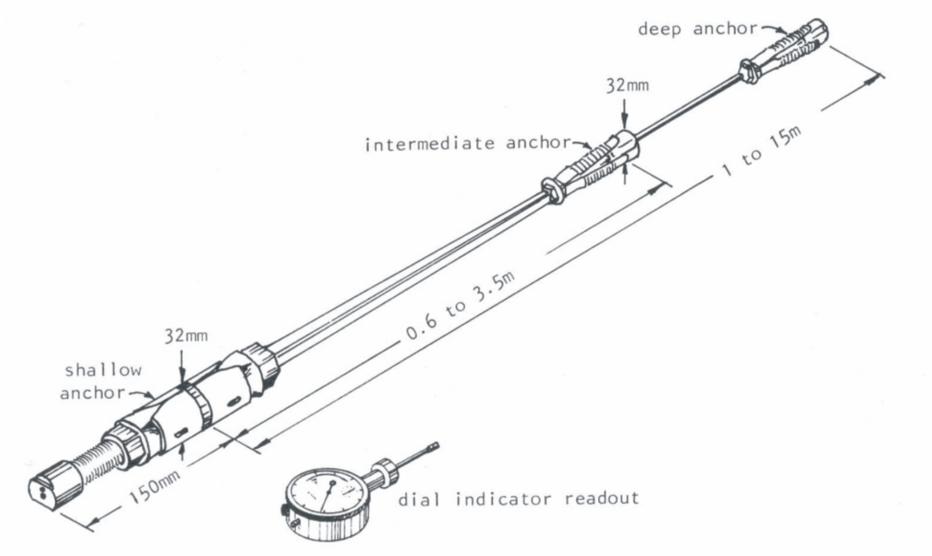


Figure 62. Multi-basis fixed extensometer for the measurement of the measure head displacements in relation to several reference points placed inside a coring borehole (Hoek & Brown, 1982).

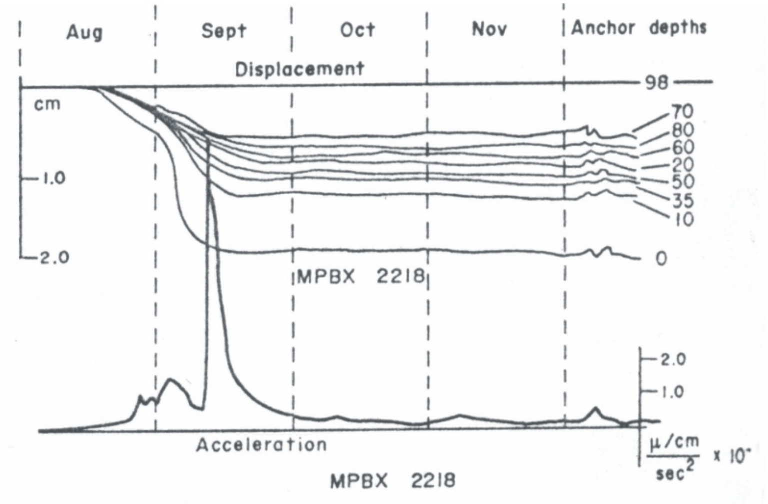


Figure 63. Evaluation of the displacements measured over time and diagram of the accelerations (Dutro & Dickinson, 1974).

The analysis of the acquired data is carried out by diagrams that present the relative displacements of the reference points versus time (Figure 63).

The normal purpose of inclinometer measurements is to define the location of any deforming zone and to allow an evaluation of that zone as time progresses, rather than to survey an exact profile of the casing. The deforming zone is often of the order of only a metre thick, and the sum of the changes over a few adjacent reading depths will usually be representative of the magnitude and rate of the entire movement. Thus, the most useful plots are generally plots of deformation at a few selected depths versus time. The cumulative change plot may in fact be misleading because, although the instrument may be operating within its range of precision, it may suggest tilting back and forth over a period of time.

Analysis of the deformation accelerations can provide a useful early indicator of potential instability phenomena.

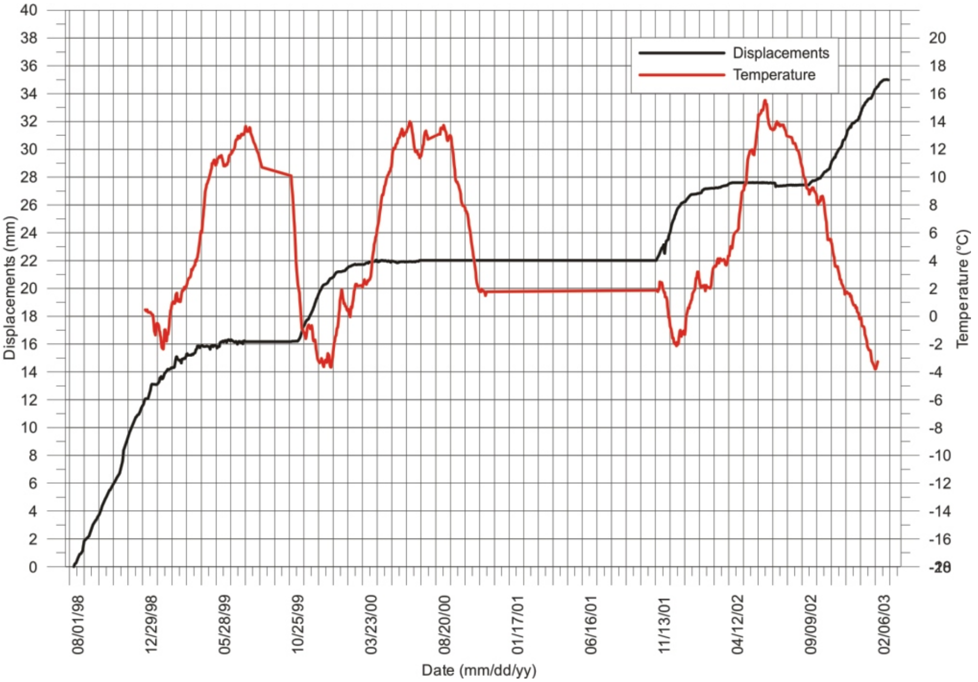


Figure 64. Example of the temperature effect on the measured displacements. Temperatures lower than 0°C corresponds to a macroscopic displacement increase.

Figure 64 shows the effect of temperature on the measured displacements. Since temperature can affect displacement it should be controlled during the monitoring period.

11

Geotechnical measurements and controls during the excavation

ANNA MARIA FERRERO, GIORGIO IABICHINO

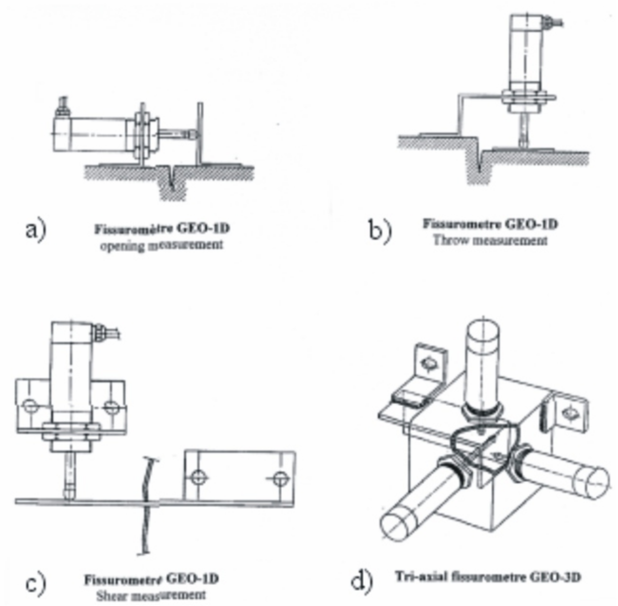
The excavation can be started after the definition of the project lay out and choice of methods for the acquisition and interpretation of data derived from the monitoring stations which are suitably positioned in the area of the exploitation. During the excavation further geotechnical measurements and controls are usually carried out independently from the method chosen for the excavation: mechanised or with explosives or mixed. The objectives of this procedure are to ensure the safety of workers and to verify the hypotheses formulated during the design phase.

Since a standard operative procedure has not yet been introduced, the person in charge of the project must choose among the different interventions according to the various requirements of the stope and the measurement method.

The systematic control, topographical measurements of the displacements of the surface and of the underground wall can be carried out through the installation of devices for the survey of rotations, displacements, strain and/or stresses in appropriate sections of the excavation. These are usually located near the areas where the rock behaviour is more uncertain, such as high fracture areas, paying particular attention to the kind of working operations carried out in those areas. In the case of underground excavations they can also be located near roof support structures, such as pillars and walls.

Besides the control of the relative displacements of the surface created by the excavations, measurements of the wall convergence over the extent of the disturbance area around the excavation should also be performed, especially when working underground. The devices employed for the displacement measurements are of the same kind as those adopted at the design stage. They are small or long-basis extensometers, called fissurometers and extensometers (with wire or in-hole) respectively. The first are of a mono or three-dimensional type and are adjusted by appropriate screw anchors to opposite edges of discontinuity in order to control their relative movements (Figure 65). The positioning of the extensometers usually requires the coring of boreholes, which are extended to the limit of the rock masses that might be influenced by the excavations.

The reference points are located inside the borehole taking into account the possible presence of disturbance areas of the excavation the distance from the surface. The measure heads are usually set in suitable holes in the excavation walls as a precaution.


a) Fissuromètre GEO-1D opening measurement

b) Fissurometre GEO-1D Throw measurement

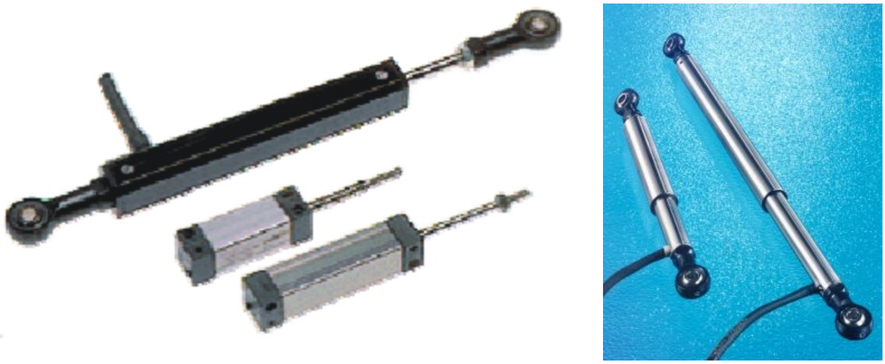
c) Fissurometré GEO-1D Shear measurement

d) Tri-axial fissurometre GEO-3D

Figure 65. Fixed fissurometers for the control of the displacements in correspondence of discontinuities – they can be of one-dimensional (a, b, c) or three-dimensional (d) types (TELEMAC Catalogue, 1999).

Devices for the measurement of strains and pressures around an excavation, or in the supporting structures of an underground excavation, have a limited response capacity and the transducers have a high sensitivity. The measurements could therefore be influenced by various specific external factors, such as uncommon temperature conditions, electric disturbances, etc., whose extent is such as to impede or to amplify the measurements of interest (stress effect). This can lead to confusing, contradictory or even incorrect conclusions. In order to reduce the influence deriving from the chosen method, the number of the control installations and measurements is increased, measuring several parameters such as displacements and rotations in the same equipped section of the excavation.

The strain measurements are usually carried out by devices with a high sensitivity (0.01% f.s.) over small distances (2 – 20 cm). The strain transducers and the displacement ones have different functioning principles (mechanical, electric, with vibrating wire, etc.) (Figure 66). They can control more than one direction at the same time and are usually welded or incorporated into the rock without any damage. Their measurements are usually made according to procedures which relate the resistance characteristics of the rock to the model of the structure under examination.



a) **b)**

Figure 66. Transducers of potentiometric (a) and inductive (b) type for strain measurement on a small scale (Novotechnick Catalogue, 2002).

Another kind of measurements that is usually carried out during the excavation is the monitoring stress change in rock by means of:

1. *Repeated measurements of in situ stress:* can be made *in situ* by using one of the absolute stress measurement techniques such as borehole over-coring. However, this approach is not often used because its cost is high, the absolute accuracy is low, and there is a possibility that important data may be missed between measurements.
2. *Measurements in a borehole or in a surface rock cut:* a device can be installed in a borehole to measure displacement, strain, or pressure caused by changes in the near-field stress. As described in the previous paragraphs they can be divided into soft or rigid inclusions. Hard inclusion devices are often use for this scope.

The measurement of the loads and the pressures on the supporting and structural elements of an underground excavation (such as supporting or reinforcing systems) is usually carried out with two specific kinds of instruments, which are called “load cells” and “pressure cells”, respectively.

Both are equipped with transducers, functioning using different methods, and have multi-shaped cases with different protections, so that they can be used in even very difficult conditions. Load cells are essentially employed to measure the loads on tie rods, anchorages and other supporting elements underground. Pressure cells measure the total pressure, that is the sum of the effective and the interstitial pressures, in grounds and structures of different nature, and also, at the interface of different media, such as supporting structures applied to rock mass (Figures 67-69). These measuring devices share a high sensitivity (0.01% f.s.) and they are mainly employed in fixed installations without any further access.

However, this can result in vulnerabilities to the required connections (hydraulic pipes or electric cables) between the measuring instrument and the devices used for the reading and the acquisition of data (Figure 70). All the appropriate precautions should therefore be taken.

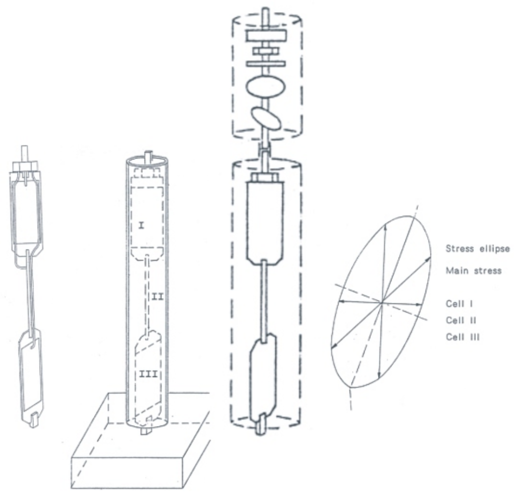


Figure 67. Pressure cell with hydraulic system for the stress measurement (Glφtzl Catalogue, 1991).

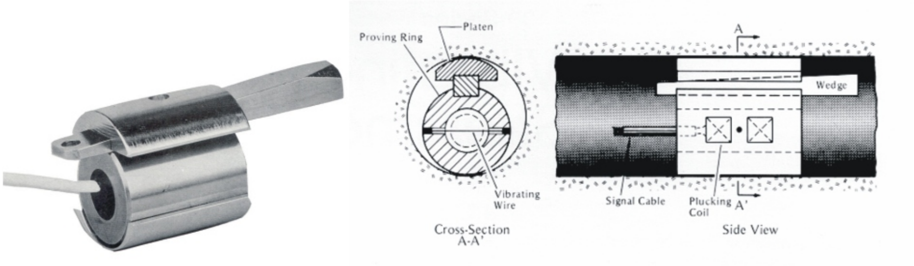


Figure 68. Hard inclusion pressure cell with vibrating wire sensor (Geokon Catalogue, 2002).

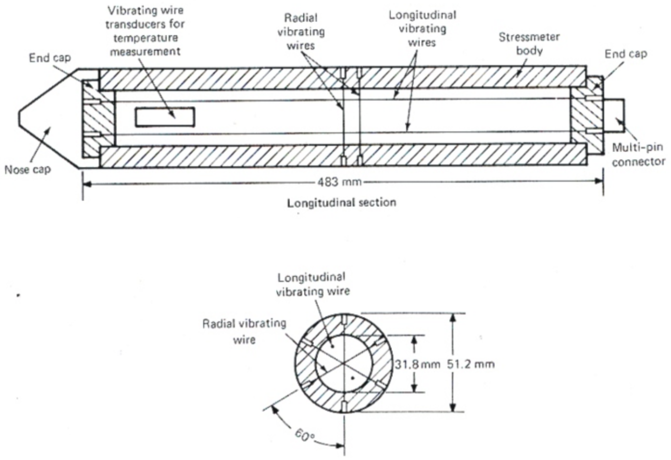


Figure 69. Soft inclusion pressure cell with vibrating wire sensor (Geokon Catalogue, 2002).

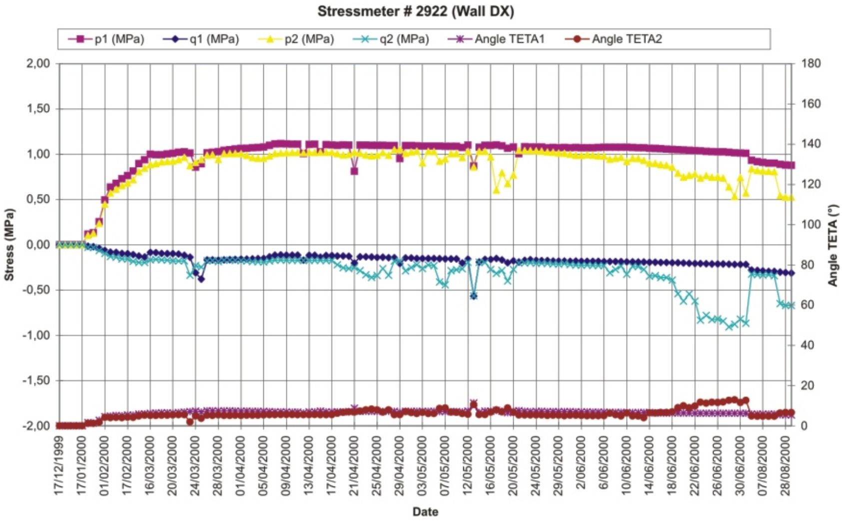


Figure 70. Drawing of the maximum and minimum (p1, p2) principal stresses surveyed in the measurement plane, orthogonal to the axis of the instrument versus time. The direction of the p1 is reported in the same chart.

12

New advances in geotechnical measurements and control

ANNA MARIA FERRERO, GIORGIO IABICHINO

The control and monitoring of a surface or an underground excavation can also be undertaken using new and innovative methods. These, however, are still at an experimental stage and their effectiveness has yet to be confirmed by researchers and experts. The different types are acoustic emission, time-domain reflectometry (TDR) and variants, optical time-domain reflectometry (OTDR), and low-coherence interferometry, as well as the unconventional employment of the radar. Although these control methods are not usually applied in geomechanics, their functioning and possible employment should be mentioned. The methods have advantages and disadvantages when compared to the classical methods reviewed in the previous section that have to be evaluated according to the situation in which they will be used. In any case, they can all automate both the acquisition and the transmission of data at a distance which is a basic requirement for the performance of controls in difficult conditions and over long time periods.

Acoustic emission (Figure 71) methods are realised by employing the localisation of the acoustic emission source as an index of the propagation of any possible fracture in the rock volume under examination. This is based on laboratory experimental results that have identified a direct connection between the stress exercised on a sample specimen and the emission from the specimen of energy in the form of vibrations in the range of audible frequencies, called the Kaiser effect. The acoustic emissions obtained are of different types (compression, shear, etc.) depending both on the sensor features and on the geotechnical and geometrical characteristics of the material they pass through.

The most commonly employed sensors, transducers that can convert mechanical stresses into electric signals, are piezoelectric accelerometers of the resonant type, with resonance frequencies of 30 kHz, 60 kHz, 150 kHz and 300 kHz.

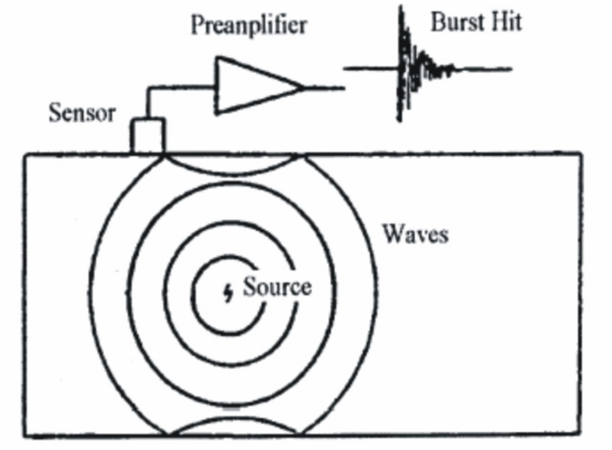


Figure 71. Scheme of a device for the measurement of acoustic emission sources in an element (Pazdera, 2001).

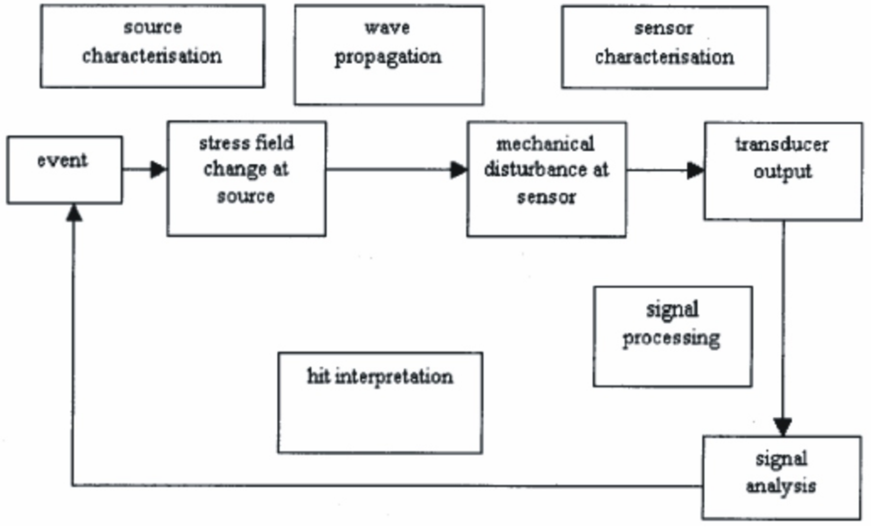


Figure 72. Ideal sequence of the analysis method applied to any single acoustic emission identified by the control geophones (Pazdera, 2001).

In open pit and underground excavations, the acoustic emission method is usually applied to situations where there is potential fracture propagation along sliding surfaces of walls or pillars. The external surfaces of the wall or pillar under examination are equipped with a network of geophones connected to a fast data collector that can localise the position and the characteristics of each micro crack almost in real time conditions. In order to obtain the clearest and optimum acoustic signal it is essential that the sensors are installed in direct contact with the rock walls.

As the obtained signals are always affected by background noises of different nature and intensity they need to be filtered. This is done by using special software that can analyse, identify and exclude the external noises, such as work in progress and atmospheric phenomena. The temporal order of the events should then allow the localisation of the fractures propagating inside the rock volume under examination as well as the extent of disturbances. The interpretation of these events is displayed in Figure 72.

The classical inclinometric systems for the measurement of movements along the discontinuities at deep levels have been recently improved by the introduction of the new time-domain reflectometry method (TDR). This is based on the measurement of the travelling time and of the reflection speed of electric pulses with a suitable frequency inside a coaxial cable. The device employed to carry out these measurements is called a “Cable Tester”. The coaxial cable is characterised by nominal impedance that is related to the type of conductors it is composed of. A deformation of the cable deriving from its interruption or simply from a variation of its initial pattern causes a change in the geometric structure of the two conductors and also in the degree of impedance.

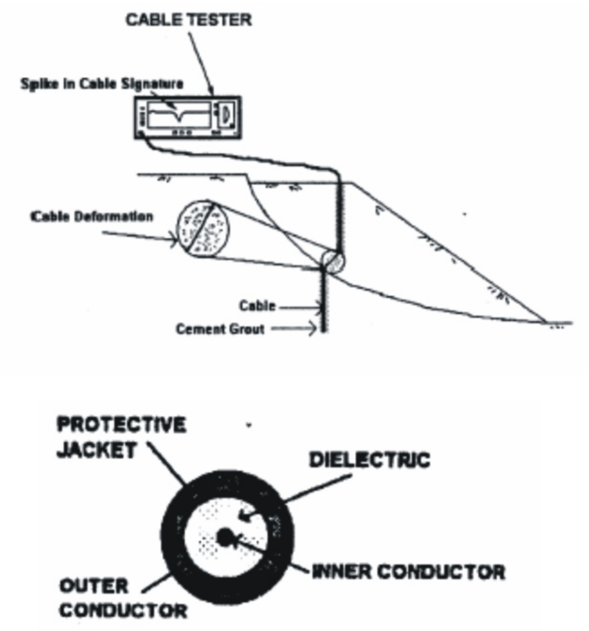


Figure 73. Device for TDR measurement and on the right a detail of the coaxial cable employed. Coaxial cables are composed of two conductors, one internal and the other external, and they are both covered by an insulator and protected by an external lining (Kane Geo Tech Catalogue, 2002).

When the pulse propagating along the coaxial cable meets a localised impedance variation, it is reflected towards the emission source. The reflected pulse can then be compared with that emitted and the coefficients of the reflection and of the wave propagation speed can be determined. When the nominal propagation speed of the pulse in the cable is known, the distance between the source and the reflection point can be determined with a high degree of precision. When landslide movements are being examined this method is carried out with the adjustment of one or more coaxial cables to the rock volume and with the measurement of the time of return of pulses appropriately modulated. Figure 73 shows an outline of a typical geotechnical application of the TDR method together with the standard section of a coaxial cable employed in the definition of the electric pulse travelling time.

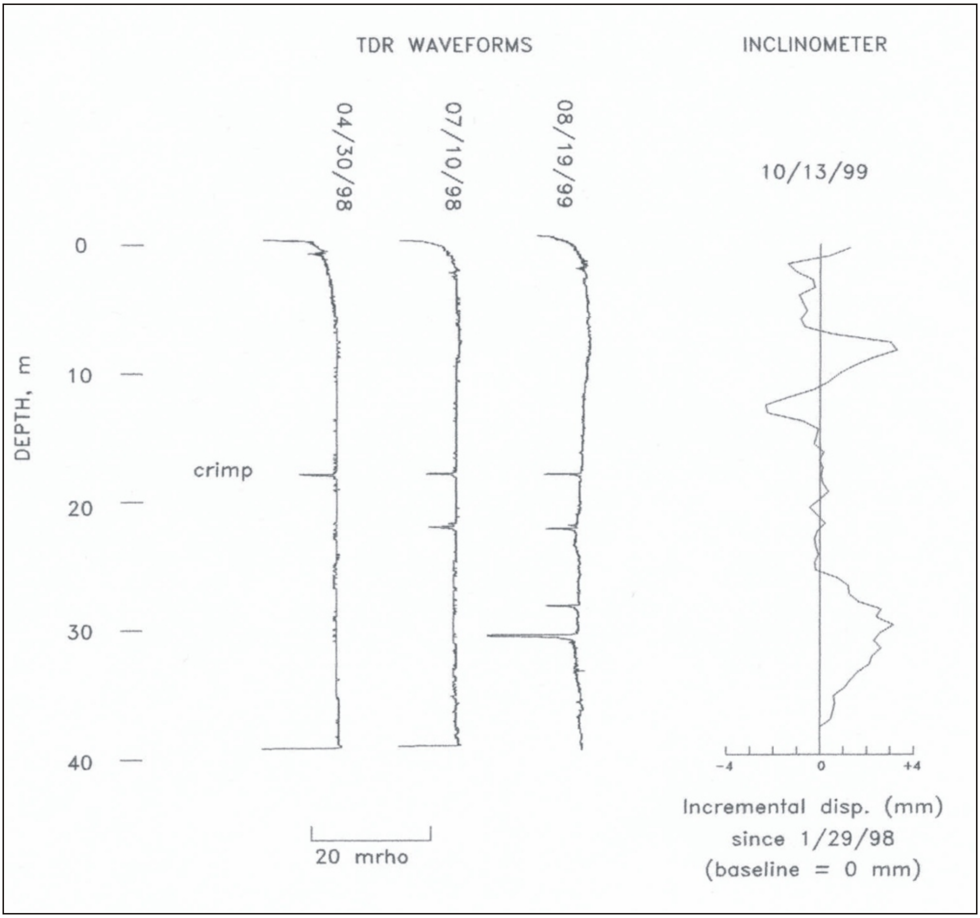


Figure 74. Typical drawings for the TDR test and the occurrence of a remarkably broad reflection (Kane Geo Tech Catalogue, 2002).

Optical time-domain reflectometry (Optical TDR or OTDR) is based on the same principle as TDR and is used in the same cases. Their only difference is that the applied sensor is an optical fibre cable excited by a light pulse with low coherence. The reflection or the fading of the light beam travelling along the optical fibre can therefore be related to distance. Compared to TDR, OTDR has the advantages of being practically free from electric disturbances (noise caused by stray static currents) and of being unaffected by the cable length. However the return signals, require a higher degree of interpretation.

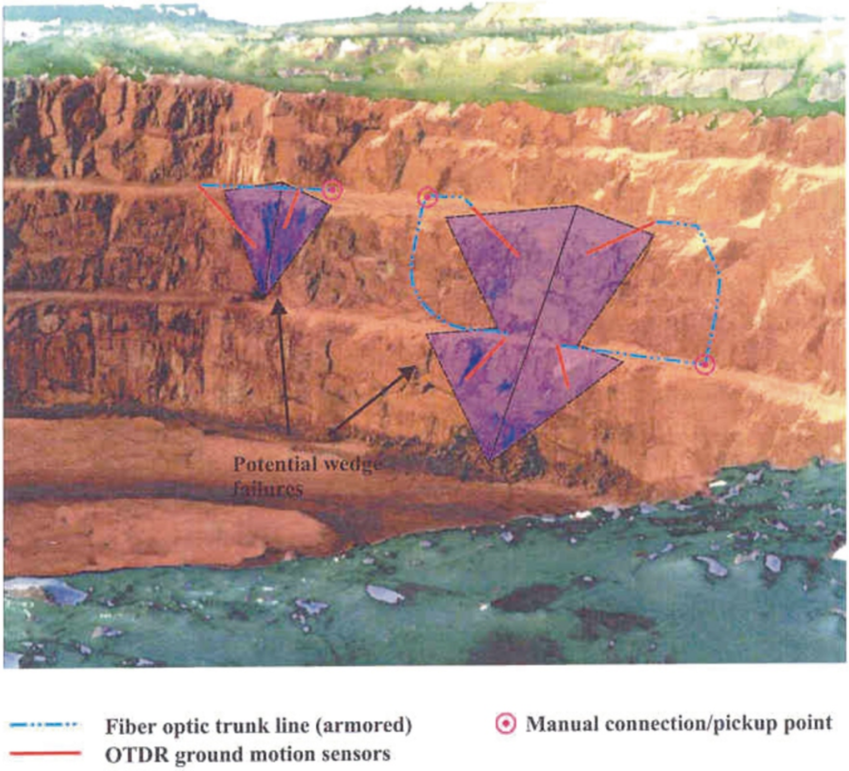


Figure 75. OTDR measurement device for a displacement survey in a terraced quarry (Zostrich Catalogue, 2002).

The measurement methods employing optical fibres and low-coherence interferometers can be applied in order to obtain an accurate survey of the displacements. These are usually used in civil engineering to monitor structures over time. They can survey with a high degree of precision the relative displacements of the structure under examination by comparing the interference fringes generated by two interferometers that operate at the same time on two pairs of optical fibres.

One of these is adjusted to the structure while the other is employed as a reference. They are installed in a small tube and adjusted to the structure under examination. One of them is called measure fibre and is anchored to the host rock in order to measure its strains. The other is called reference fibre and is free inside the tube. The difference in length between the two fibres surveyed over time detects the strains of the structure. The absolute measurement of this distance is carried out by a Michelson double interferometer with a low coherence and with a tandem pattern. The first interferometer is composed of measure and reference fibres placed in the structure, while the second is placed inside the portable measurement device (Figure 76) and can measure a well defined difference of length between the two arms of the reference system by means of a movable mirror.

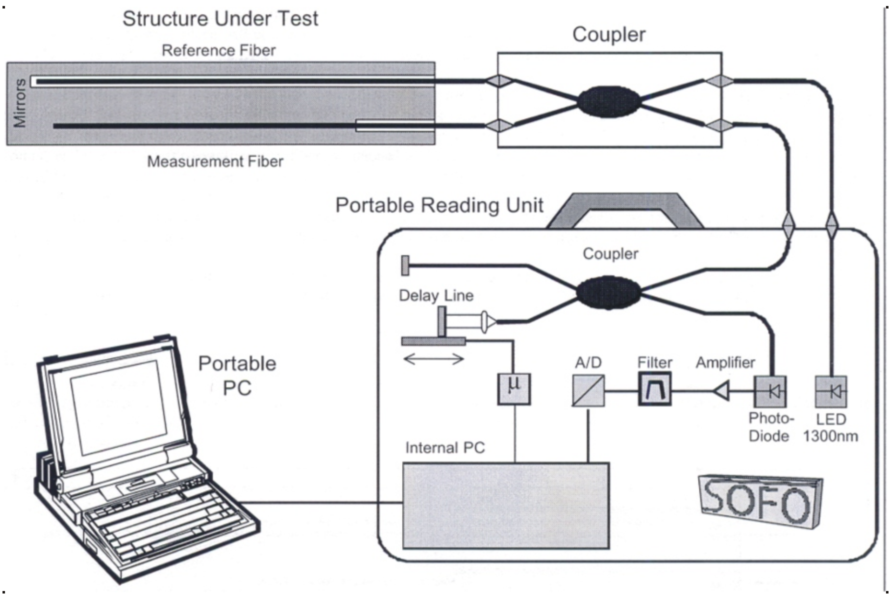


Figure 76. Interferometric measurement device with low coherence for displacement surveys (Smartec Catalogue, 2002).

Due to the low coherence (about 30 micron) of the source in the measurement device, the interference fringes can be detected only when the interferometer inside the device compensates for the difference of length between the fibres which are adjusted to the structure. The accuracy and the stability of this kind of configuration have been determined in laboratory and *in situ* and can reach 2 micron (2/1000 mm), independent from the length of the sensor and for a five-year period. Moreover, the precision degree is not affected by a variation in the transmission properties of the fibre as the displacement data are codified according to the light coherence and not to its intensity.

Some examples of the sensor application are shown in Figure 77. It is worth pointing out that at present the costs of the sensor and of its installation are competitive when compared to the costs of the "classical" instruments (multibase extensometers) employed for the same purposes.

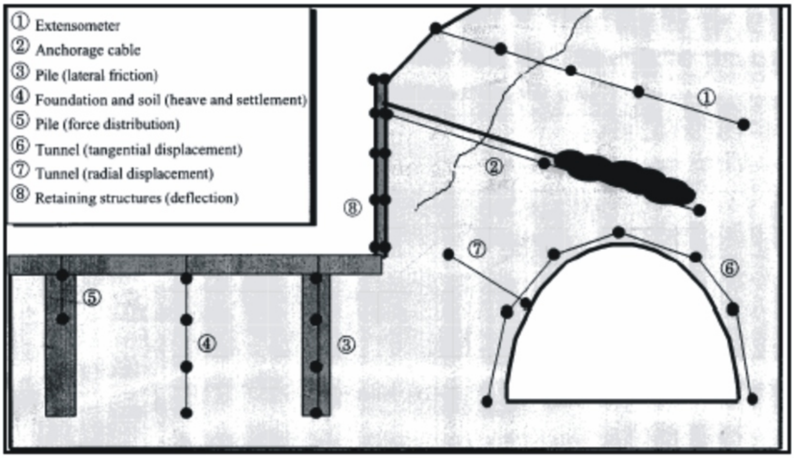


Figure 77. Scheme of the same practical examples for the employment in the geotechnical field of displacement transducers based on the application of the low coherence interferometry (Smartec Catalogue, 2002).

Synthetic aperture radar (SAR) differential interferometry is a remote sensing technique which is employed to evaluate the displacements of the earth surface with a high precision degree in the order of the wavelength of the transmitted signal, approximately one centimetre. The evaluation of the displacements is carried out starting from the calculation of the phase difference (called interferogram) between two SAR images of the area under examination acquired at different times and generally from different positions.

As a consequence, the phase difference of the two SAR images is linked both to the strains of the surface that occurred during the time interval between the two acquisitions, and to the topography of the area. These two factors must be thoroughly and separately investigated. The result of this operation is called the differential interferogram and the accuracy is of the order of the radar wavelength. The employment of this new method in the stability monitoring of rock walls, especially for high-wall open pit excavations, is an important innovation as the control of possible displacements can be carried out in the whole area under study, including also the displacements of small surfaces.

In detail, the technique employed is an extension of the satellite radar interferometry method outlined above, but it requires neither a satellite nor any instrument installations on the high-wall surfaces. The radar is positioned at a suitable distance from the wall under examination and automatic programmed scanning of the wall is made. At the same time the data collector connected to the radar analyses the graphs and systematically identifies the possible strains (Figure 78). The main disadvantage of this method is its relatively low precision. Laboratory tests have demonstrated that the measurements of the displacements cannot be carried out to the order of one millimetre, as they are affected by errors deriving from the environment and from signal transmission. The aim of the research in this field is the definition of a method to determine the displacements of the order of 10 mm per day.

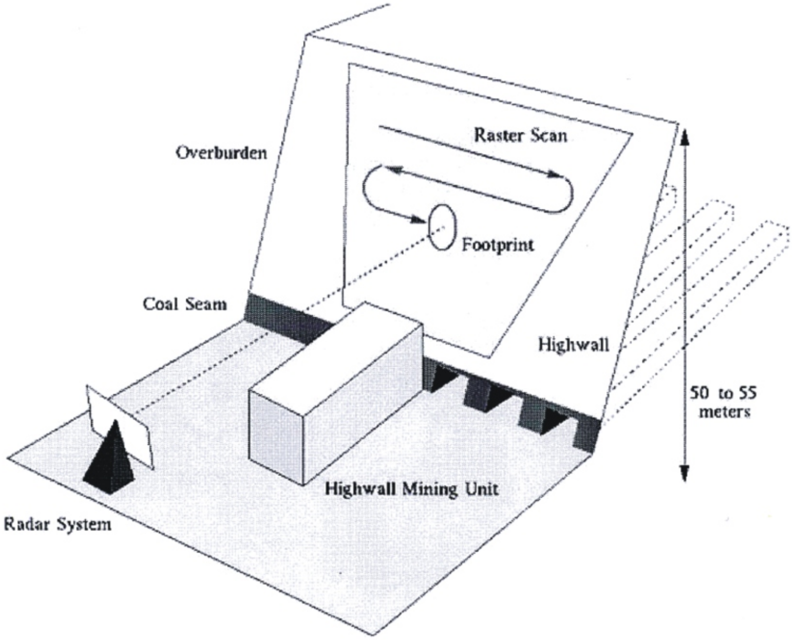


Figure 78. Scheme of the survey of displacements in exploitation walls using the earth radar interferometry method (Reeves et al., 1993).

13

Geomechanical and geophysical measurements in Lasa underground marble quarry

ANNA MARIA FERRERO, GIORGIO IABICHINO

A major consequence of opening up large cavities during underground quarrying is the need to check the stability of the remaining structures, in order to guarantee the safety of mining activities and to ensure their continuance into the future. As the works in the quarry proceed, a programme of *in situ* investigations should be composed in order to assess the evolution of the deformations and/or stresses resulting from the changing geometry of the cavities made during underground quarrying. However, an investigation procedure of this kind is rarely implemented in open stopes of ornamental stone quarrying. Both on account of the relative slowness with which such quarrying proceeds and on account of the degree of selection made during excavation, not always is adequate consideration given to the actual entity of the quantities quarried or to the final conformation of the remaining structures. Sometimes the result is a stope which presents a very irregular shape, on which it is practically impossible to carry out a calculation likely to provide a reliable assessment of the static conditions of the stope. For these reasons the overall carried out investigations are mainly conducted with the aim of checking particular local conditions and of providing estimates of the stability degree of the main supporting structures (pillars, slabs). The present work, which refers to an underground quarry of white marble, describes the programme of installations designed for carrying out checks over time on the deformations in a number of structures. In addition, the results are presented as measurements of relative stress and elastic wave velocity performed on some pillars with the aim of assessing the conditions of load and pillar integrity.

13.1. The Lasa underground quarry (Lasa, Bolzano, Italy)

The underground quarries of Acqua Bianca (Lasa, Bolzano) exploit a subhorizontal marble lens, of a mean width of approximately 40 m, embedded in the Lasa mica-schist unit. The marble lens constitutes the hinge zone of a vast fold structure, and the contact between the marble and the mica - schists that host it develops in general along a surface which is approximately concordant with the schistosity. The basic morphological arrangement is characterized by fold-type deformations, superimposed on which are mechanisms of a brittle, prevalently de-stressing type, consisting of fracture systems and occasional faults. Quarrying (Figure 79) is carried out by opening large cavities separated by pillars and proceeds in general in a series of descending steps starting from the galleries that mark the perimeter of the cavities.

The galleries have been driven using explosives in the upper section of the lens, leaving in place thicknesses (5 - 10 m) of marble "slab" to prevent the risks of rock failures owing to the excessive vicinity of the schists above the lens which present poor mechanical characteristics. Excavation in depth is performed by isolating large slices of marble by wire-saw cutting, the marble subsequently being cut into blocks using the same method. With the exclusion of the portion of quarry close to the two portals (northern sector), where quarrying was initially carried out, it may be noted that current extraction proceeds according to a geometrical pattern that entails the opening of long rooms with pillars at intervals, these having a fairly regular cross-section (central and southern sectors). With the purpose of identifying the particular lineation which may induce phenomena of instability in the remaining load-bearing structures, a geological-structural measurement has been conducted which has made it possible to ascertain (Cravero and Iabichino, 1990; Cravero et al., 1991) the major systems of discontinuity present in the quarry area (Figure 80):

1. Northern Sector; the dominant systems are those oriented 20° NW and 40° NW, steeply inclined and characterised by fractures, spaced 4 to 5 meters apart, with apertures of few millimetres and without any trace of infilling. Less frequent, though not less important as regards its potentiality for separation of large blocks, is the 60° NE system, with 60° NW dip.

2. Central Sector; this comprises the most tectonically disturbed part of the quarry: the 20° NW sub-vertical system, rather dense and frequent, the 60° NW system, with a dip of 70°-90° E or W indifferently and occasional fractures in a 40° NE direction, with inclinations 70° N - 35° N.

3. Southern Sector; the most widespread system, consisting of fractures spaced 5-10 metres apart, is oriented 30° N - 40° W and steeply inclined towards SW. A further system, in the 30° N - 40° E direction, with a NW dip, is clearly secondary.

13.2. In situ measurements

The complex geometry and the size of the underground cavities which constitute the rooms of the Acqua Bianca quarry have led to the decision to carry out measurements and checks in areas of particular importance for the development of the quarrying activity. The sitting of the measurement stations has been chosen on the basis of what is expected to be the future evolution of excavation works, and on the basis of the underground geo-structural conditions. In this respect, particular emphasis has been given to checks along the main access to the underground working places and inside the rooms themselves. Figure 79 also shows where the individual measurement stations are sited.

The measurement programme was devised to include three types of readings:

1. Check of relative displacements.
2. Determination of wall stresses.
3. Measurement of elastic wave velocities in the pillars.

These readings have been chosen with the aim of estimating, using simple and relatively inexpensive methods, the static conditions of a number of the remaining structures and their evolution in time.

Measurement of displacements

The systems for measuring relative displacements of rock include the use of special non-deformable steel measuring tapes, wires connected to sensors, or metal rods inserted and cemented into holes made in the rock in suitable points. The criteria followed in setting up the measurement stations was that of choosing fixed installations, but with retrievable sensors, rather than fixed datum points and mobile measuring instrument. In addition, to simplify the necessary procedures and to cut down the time required for reading the measurements, sensors of a single type (potentiometer) were adopted. These sensors were DC-supplied, having a high degree of stability and very easy-to-read.

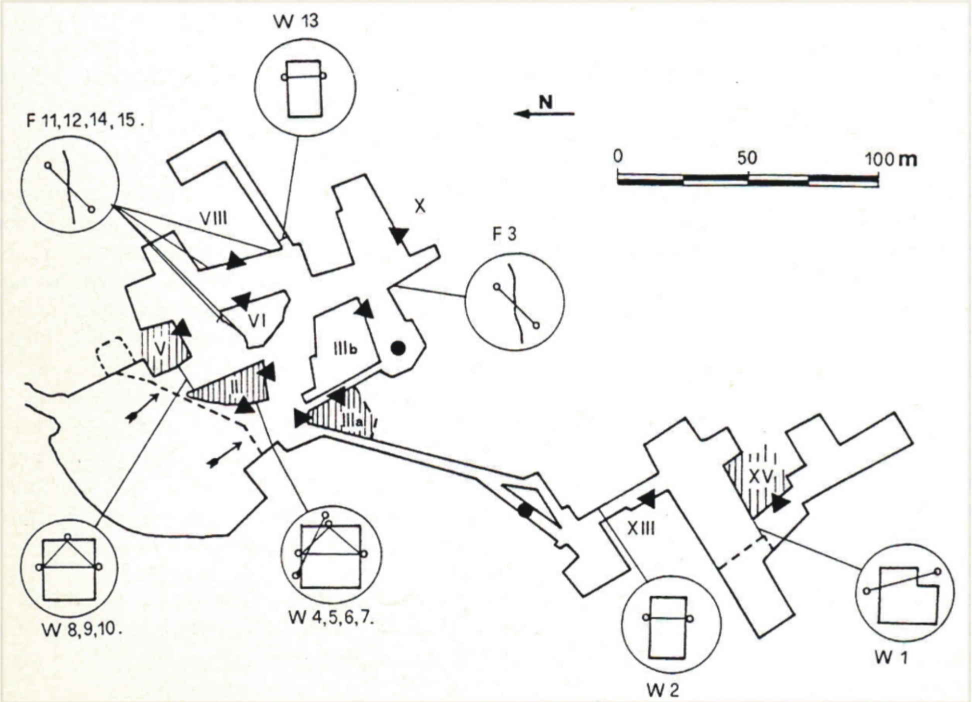


Figure 79. Plan of the Lasa underground marble quarry showing the locations of measurement station (Cravero et al., 1991). W = wire extensometer; F = crack meter; ♦ = doorstopper in the wall; • = doorstopper in the floor; ¦¦¦ = geophysical tomography.

During the installation of each of these stations, particular attention was paid so that none of the usual quarry operations (transit of vehicles or machines, wire-saw cutting, drilling) would be hampered by the presence of the measurement stations. In any case, the necessary measures were taken to ensure the continuity of the readings throughout. Any dislocations along the discontinuities were measured using crack meters which usually operate on the measurement bases of about ten centimetres and consist of the sensor and a special connecting rod. The convergence of the walls of the rooms was measured using long-base wire extensometers. The connection between the opposite datum points was, in this case, made by means of a non-deformable steel wire, one or two springs and a sensor. Consequently, it appears evident that the sensitivity of this type of extensometer is influenced by the number of tensioning springs used, as well as by the length of the measurement base. Finally, it is necessary to take into account that the precision of the measurement is further reduced by the catenaries assumed by the suspended elements.

In particular, for the two portals the choice has been to measure the relative displacements (convergences) of the opposite walls and of these with respect to the roof, creating a classical convergence measuring station with the coplanar reference points located at the vertices of a triangle of the most regular shape possible. Furthermore, the datum points were sited in portions of rock separated by discontinuities. All the instruments to be installed underwent laboratory calibration tests to achieve the linear relations which link the variations of potential difference, read on the sensor outputs, to the variations in the position of the slider of the potentiometer with respect to the potentiometer body.

The tests were conducted on different bases for equipment with one spring or two, as well as with supply voltages varying within the range of set values. In particular, the difference between the results obtained within the same measurement configuration, but with different power supply, provides an indication of the entity of the possible error due to the inevitable power output oscillations of the supply source.

The results of these tests have shown that:

1. In the case of the crack meters the relation supplied by the manufacturer of the potentiometer is valid; the full-scale expressed as potential difference corresponds to the full-scale expressed in mm of displacement.

2. In the case of wire extensometers, for the interpretation of the measurements, it is necessary to use the calibration curves obtained in the laboratory.

Furthermore, checks lasting a few days carried out in situ, using automatic means of measurement, revealed the almost complete insensitivity of the measuring instruments to temperature variations present at the entrances to the stope. As measuring instrument, an ordinary portable voltmeter was used.

Measurement of relative stress

Methods of relative stress measurement use techniques based on the determination of deformations resulting from the releasing or restoring of wall stresses. To this end, different types of sensors (e.g., electric, hydraulic, mechanical) may be used, as well as various configurations of the measuring base; these usually require the application of specific analytical formulae for their interpretation. In order to evaluate the static conditions of some structural elements of the quarry, deformation measurements were carried out applying the wall stress release method. The choice of the method of measurement was suggested by the particular stoping technique adopted in the quarry: in fact, as it has been already mentioned, quarrying is carried out using a wire-saw which does not cause appreciable disturbance to the wall, such as occurs, instead, in the case of blasting.

The sitting of the 26 measuring points is shown in Figure 79. The method chosen consists of recording the deformations which a sensitive element (four-component strain rosette) undergoes owing to the release of stress obtained by means of the peripheral cutting of the surface on which the sensor is glued.

The measurement point is prepared by performing a shallow coring (10-15 cm) followed by the smoothing of the bottom of the bore-hole. The sensitive element is then oriented vertically and glued to the bottom of the hole. Once the strain rosette has been firmly glued in place, an initial zero-setting measurement is made (using a strain gauge bridge), and then a drill-over of the sensor is performed and the subsequent measurement is carried out.

The readings were interpreted on the basis of the solution, which is valid in an elastic field, for strain rosettes in a single hole and using the stress concentration factors suggested by Van Heerden (1968). The reliability of the measurements was assessed by comparing the stress invariants.

Geophysical measurements

A method that makes it possible to obtain information on the integrity of the rock mass, on the lithological variations taking place therein and possibly on the state of stress, using non destructive measurements, is that of seismic tomography. Adopting this technique, it is possible to draw up a velocity map on a given plane, following on the two-dimensional processing of results obtained from seismic measurements. To carry out the geophysical measurements, a twelve-channel Geometrics ES 1225 with a maximum time resolution of 25 μs was used.

Figure 80. Density contours of discontinuity poles, collected in the Lasa underground quarry (Cravero & Iabichino, 1997).

The geophones, with a resonant frequency of 14 Hz, were set into the wall by means of rigid brackets and expansion bolts in order to guarantee a solid anchorage into the wall. As source of elastic waves, a six-kilogramme sledge-hammer was used, the wall of the pillars being struck at given points. The seismic signals thus acquired were transmitted onto a portable personal computer, on which, using appropriate software, the signals were displayed and the time breaks were picked up. A topographical measurement made it possible to identify the plane to which the velocity map thus produced was to be referred and to locate on the map with the degree of precision held to be sufficient (10 cm) both the struck points and the points at which the geophones had been placed. The recorded signals, the first arrival times and the coordinates of the geophones and the struck points, were subsequently transferred onto another personal computer in order to speed up tomography processing (Bois et al., 1971). Tomography processing, performed according to the A.R.T. method (Gordon, 1974; Peterson et al., 1985) involved the processing of about 170 seismic rays for each pillar under study (Figure 82), and produced maps, on average, from areas subdivided into 70-90 cells. The mean time taken carrying out the measurements on each pillar, considering a total of 14 sledge-hammer blows and the reception of signals on 12 geophones, was approximately 2.5 hours, including the topographical measurement; each team was composed of not less than three people. Data processing for each pillar kept one person occupied for approximately 1 hour. The overall cost of the instrumentation used to carry out the measurements and to process the data amounts to approximately 25,000 U.S. dollars.

13.3. Measurement results and their interpretation

The checks and measurements carried out in the stope of the Acqua Bianca quarry have together led to the acquisition of a set of data which make it possible to estimate the static conditions of the remaining supporting structures. The analysis of the data emerging from the preliminary geologic-structural measurements indicated the absence of conditions favourable to the formation of rock blocks important for the overall stability of the rooms (Cravero and Iabichino, 1990). Where, in fact, problems have arisen, the unfavourable structural arrangement emerges clearly, and in those areas suitable measures have been taken to provide the necessary support. Nevertheless, measurements were carried out to check the convergence of opposite excavation walls, and displacements located in correspondence with discontinuities were likewise measured. All these measurements, which have been performed continuously over a period of two years, have so far not revealed any appreciable deformations or signs of slip, as can be seen from an examination of some diagrams (Figure 81).

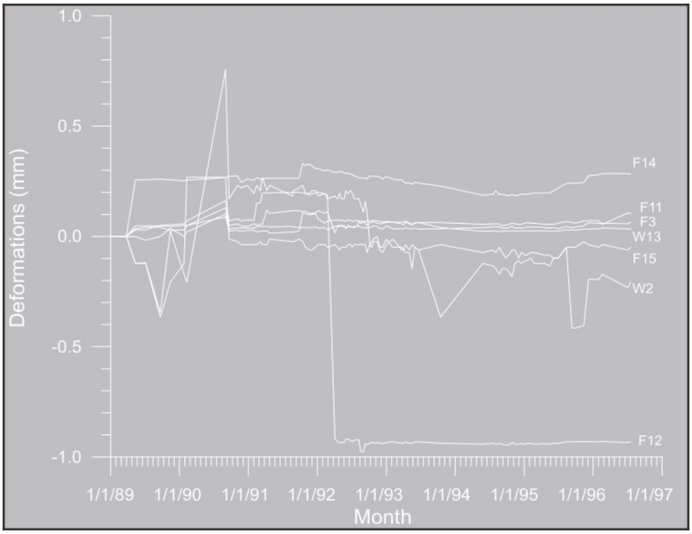


Figure 81. Diagrams of relative displacements from crack meters and from two extensometers (Cravero & Iabichino, 1996).

The results of the tomography processing are given in the form of an equal velocity line map. Some preliminary remarks are necessary to clarify the potentialities and limits of the method (Krajewski et al., 1989). The heterogeneous features present in the walls of the individual pillars can lengthen the first arrival times for some geophones, and consequently, since the tomography process is a sort of weighted mean, contribute to decreasing the overall velocities in the map of the particular pillar. The disturbances, which are present with varying degrees of intensity at the various times and places at which the measurements were performed, may also lead to considerable difficulty in comparing the absolute velocity values obtained in two pillars. Within any one map, however, the presence of bands of velocity gradients is of notable significance; such bands, in almost all cases, indicate the presence of weak zones and/or zones of fracturing (Ivansson, 1985).

An analysis of the individual maps thus makes certain observations possible:

1. Pillar IIIa (Figure 82a); two large areas may be identified: one to the south, with velocities of above 4 km/s, and one to the north, with lower velocities. Both of these present, within them, a distribution of minimum and maximum values which gives some reason to suppose that, in the passage from the former to the latter, there are present bands that are possible locations of fractures. The map was obtained with 204 seismic rays and 70 cells.
2. Pillar XV (Figure 82b); an extensive minimum area may be noted at the northern edge and a maximum one of lesser extent at the southern edge, this latter being the location of a saddle-type configuration and a very high gradient proceeding N-E from the most easterly maximum. The map was obtained with 180 seismic rays and 96 cells.
3. Pillar V (Figure 82c); a smaller mean velocity may be noted here compared to pillars IIIa and XV, and an elongated minimum value in the western zone of the pillar, surrounded to the north and south by two maximum values. Two other maximum value zones are present at the eastern edge and in the northern zone of the map. The map was obtained with 180 seismic rays and 70 cells.
4. Pillar II (Figure 82d); this pillar also presents a minimum velocity value below that of pillars IIIa and XV. Two elongated minimum bands are also to be noted in the N-S direction, with a band of maximum values between them. The map was obtained with 168 seismic rays and 70 cells.

The determination of the state of wall stress, carried out essentially on pillars and, in two cases, at the base of the cavities, was performed by positioning the measurement stations, as far as possible, in correspondence with the areas in which the tomography maps revealed the highest velocities. In general, it has been found that the single pairs of determinations, conducted in each measurement station, have shown a satisfactory degree of repeatability. The deformations recorded have been interpreted by applying to the various underground situations semi-empirical (Tributary Area Method) and numerical (2D Boundary Element Method) computing schemes.

A comparison was also made between the dynamic elasticity modules (deduced from the velocity of the elastic waves) and the static modules obtained in the laboratory, with the aim of circumscribing within the resisting elements areas of different deformability. Three dimensional modelling was not attempted, inasmuch as it was thought that a 3D schematization, even though articulated, could not represent adequately the complex actual situation and that, consequently, the level of approximation implicit in simpler computing schemes was acceptable. In this connection it must be borne in mind that the tributary area method, within the limits of its applicability, provides an explanation of the mean load acting on the pillars, while the BEM method allows influence of the difference in rigidity of the resistant elements to be taken into account and provides the wall stress values. The application of the two procedures has not taken into consideration the discontinuities present which affect the local distribution of the wall stresses.

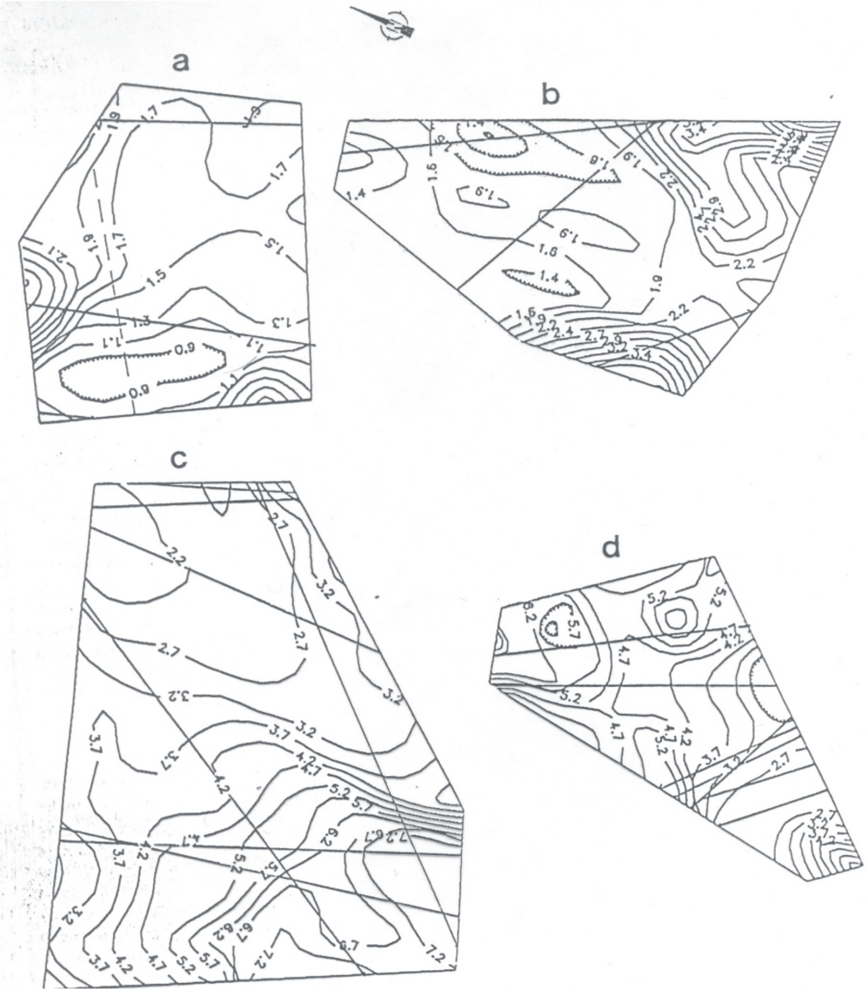


Figure 82. Tomography maps with main discontinuities superimposed; a) pillar V; b) pillar II; c) pillar XV; d) pillar IIIa (Cravero & Iabichino, 1991).

The results obtained from in situ experimentation and from calculation are brought together in Table 3. The upper section of the table refers to determinations made on the pillars, while the lower section refers to those carried out at the floor of the rooms. The characteristic mean values of deformability assumed for the interpretation of the measurements (E = 60,000 MPa, ν = 0.27) were obtained from laboratory tests conducted on samples taken from core operations carried out in situ. An examination of the table reveals that:

1. The maximum main stresses recorded are compression stresses, on average sub vertical and in general of high entity (a probable consequence of the concentration in the walls of the stresses acting within the pillars). The measurements carried out in correspondence with pillar X involved a de-stressed area and consequently are not given in the table.
2. The minimum main stress values reveal the existence of a non-negligible transversal state of confinement. In some cases the presence of tensile stresses was noted. The confinement effect recorded may be due to the position of the measurement points often sited in the lower part of pillars.
3. The mean vertical stresses, calculated using tributary area and BEM methods, have systematically revealed lower values than those actually recorded, but with concentration factors, compared to the lithostatic stress, comprised between 2 and 5. The comparison between the results obtained with the two methods of calculation, moreover, indicates a fairly good degree of repeatability.
4. The minimum and maximum stresses measured at the floor of two rooms prove to be variable in modulus and orientation, but of somewhat reduced entity.
5. The presence within the pillars of areas presenting different elastic wave velocities may be connected to the variations of deformability (on account of the presence of the discontinuities) and also local variations in stress. However, this link did not emerge with sufficient clarity.

The comparison of the stress measurements performed in the northern sector with similar measurements made in the past (Ribacchi, 1969) has revealed a substantial agreement between the sets of results. From this it may be inferred that the opening of new rooms in other sectors of the quarry has apparently not modified the stress conditions in the structural elements of the older rooms.

Table 3. Measured and calculated stresses in the Lasa underground quarry.

PILLAR & STATION	H (m)	σ_1 (MPa)	σ_2 (MPa)	θ_1 (°)	σ_c (MPa)	σ_m (MPa)	γz o $k\gamma z$ (MPa)
II	70	6.7-13.5	0.5-0.6	-81.2-85.3	6.1	4.3	1.9
IIIa	100	14.7-23.6	0.8-4.1	77.9-79.5	7.9	7	2.7
IIIb	130	13	2.2	84.6	8	7.1	3.5
V	40	5	2.1	53.6	3	4.9	1.1
VI	100	18.8	5.4	62.1	8.9	7.8	2.7
VIII	100	15.2	8.7	-59.2	4.5	8	2.7
X	160	-	-	-76.7	12.4	12.3	4.3
XIII	110	5.3	-2.2	76.9	4.9	7.7	3
XV	110	11.1	-0.6	65.2	7.2	8.1	3
D14	90	1	-3.6	-85.8	-	-0.8	0.9
D19	130	0.5	-1.4	51.3	-	-1	1.3
D20	130	2	-1.3	-43	-	-1	1.3

H = depth; σ_1 = maximum principal stress recorded; σ_2 = minimum principal stress recorded; θ_1 = angle between σ_1 and the horizontal, or between σ_1 and W (in the case of determinations at the floor), positive in a clockwise direction; σ_c = vertical stress (Tributary Area Method); σ_m = vertical stress (BEM); γz = lithostatic vertical stress ($k\,\gamma z$ = lithostatic horizontal stress) (Cravero & Iabichino, 1991).

13.4. Conclusions

The execution of an articulated programme of checks (geological-structural measurements, seismic tomography and measurement of displacements and of the state of wall stress) has helped, to draw a picture of the static conditions underground quarry for the case under examination. So far, the deformations that have been measured by the different sensors, where these have not been disturbed by quarry operations, have not indicated significant differences from the zero readings. It may, therefore, be inferred that, in the areas that were checked, no movements are in progress.

An analysis of the tomography maps indicated a fairly good correspondence between the minimum velocity values measured and the location of the fractures previously recorded. Furthermore, it has been possible to site the stress measurements in walls in points corresponding to the maximum velocity values found, where the rigidity of the pillars may prove higher. As regards the assessment of the state of wall stress, it is to be noted that the entire set of results obtained indicate a substantial variability connected to the specific situations of the stope (shape and geological-structural conditions). The observed values, in fact, present a lower limit close to the load condition estimated via calculation (Tributary Area Method, BEM), an upper limit equal to about three times those computed, and intermediate values equal to approximately twice those computed.

From the comparison of the measurement results with the determinations made in the laboratory, it moreover emerges that the wall stress conditions of the pillars reach, in one case, 35% of the mono-axial compression breaking load on test samples. These considerations confirm the observations of the aforementioned first set of measurements. The substantial differences between the observed stress values and the computed values - which have systematically produced an underestimation of the static conditions of the pillars - indicate that, where the underground situations are complex, it is essential to proceed by carrying out experimental checks and determinations, albeit of a simple and relatively inexpensive nature.

In this way, it is possible to make estimates which reflect more faithfully the actual situation, even though they are limited to a local scale.

14

Behaviour of experimental panels for underground marble exploitation by in situ monitoring and computation. The CAD-PUMA experience

ANNA MARIA FERRERO, GIORGIO IABICHINO

Safety and enhancement of productivity cannot be separately achieved in underground quarry exploitation of ornamental stone. This means that large ore production leads to large excavations, suitable technology, and increased speed in quarrying works. These, in turn, can adversely affect rock mass behaviour. Ground control should therefore be recognised as an integral aspect of quarry activities.

While past experience in underground excavation and careful analysis of failure records suggest design rules for specific mining operations (Salamon et al., 1967; Hoek & Brown, 1982; Brady & Brown, 1985) while monitoring is also a well established practice in classical mining (Bawden, 1993; Widsor & Thompson, 1993). The monitoring and adoption of consistent design is not yet common practice in ornamental stone quarrying, and the process of evaluation and field confirmation of suitable design guidelines (Iannacchione & Prosser, 1997) for against potential failure hazard is still underway. Furthermore, a relevant number of quarry operations develop very near to mountain slopes, often in the proximity of pre-existing exploitations; this situation is commonly found in many Italian quarry basins. This condition leads to a continuous and relatively quick increase of the stress state of the exploited rock mass, particularly around the newly created rooms. As a result, the stress-strain state of the abandoned support elements (pillars, diaphragms, roofs) and therefore also their stability condition varies with the progress of the exploitation. The role of the rock mass joints is also of fundamental importance for the stability assessment of the natural supporting structures. This involves the knowledge of the jointing geometry and strength, above all when the discrete features intersect support elements or room surfaces.

The evaluation of the performance of the underground excavation therefore implies the need of continuous monitoring which is the only way to obtain a perception of the effectiveness of the ground control (Dunnicliff, 1993) and use of consistent computation schemes (Beer et al., 1982; Meek, 1993). In line with the previously mentioned motivation, this paper is aimed at giving information on some technical achievements obtained during the development of a CEE Brite Euram III research work CAD-PUMA "Development of an integrated computer aided design and planning methodology for underground marble quarries". Among the objectives of this three-year work were: monitoring, interpretation and synthesis of rock mass structure and 3D numerical simulation of an experimental room and pillar panel. It involved the co-operation of industrial and scientific partners so as to make it possible to excavate the experimental panel and carry out the analysis of the observed behaviour.

Three different quarry sites (two in Italy, one in Greece) were selected as pilot sites and the experimental panels were excavated following the general layout shown in Figure 83, which also allowed for modifications according to specific site conditions. In the following paragraphs, an account is given of the panel layout, of the guidelines followed for setting up the monitoring system, of the rock mass numerical modelling of the newly created stopes and a presentation of monitoring and modelling results.

14.1. Exploitation panel layout and monitoring system

Following the general layout, the quarrying of the experimental room and pillar exploitation panel was performed in three main excavation phases. The first phase requires the excavation of four 3 m high and 9 m span rectangular shaped drifts, orthogonally arranged in order to isolate a square 15 m side central pillar. The second phase involves widening of the drifts contouring the pillar to a span of 20 m. The decision to try to obtain a high ratio of the panel recovery, as suggested in the general layout agreed by the industrial partners, had to be made taking into account the state of the rock mass, the monitored behaviour and the results from numerical modelling of each pilot site, plus the operative conditions at each site. These two phases had to be completed before the end of the project. The third phase, which will follow the enlargement of the drift, consists of deepening the room floor to a maximum depth of 50 m. This phase has not yet been started at the quarry sites.

It should be pointed out that, performing the operative tasks for project execution each quarry applied some variations to the geometry of the exploitation panel, especially as far as the roof spans are concerned. The excavation is all performed by means of subsequent chain saw runs, each of which is 2÷2.5 m deep. The selected sites are: the Acqua Bianca (Lasa - Bolzano, Italy), the Tavolini-Alta (Levigliani - Lucca, Italy) and the Stomatovouni (Athens - Greece) underground marble quarries.

The monitoring project was conceived to satisfy the essential investigation requirements related to the three quarry sites and above all to investigate the stress and deformation state of the rock mass at selected locations around the experimental exploitation panels in order to detect possible geo-structural or even stress controlled trends towards failure during the experimental excavation. Taking into consideration the financial availability of the CAD-PUMA project, the executive scheme for monitoring the underground experimental panel was prepared, as shown in Figure 83. Useful information for the choice of measuring devices and their location was also available thanks to preliminary 3D BEM modelling of the expected stress and deformation induced by panel excavation, as described in paragraph 14.4.

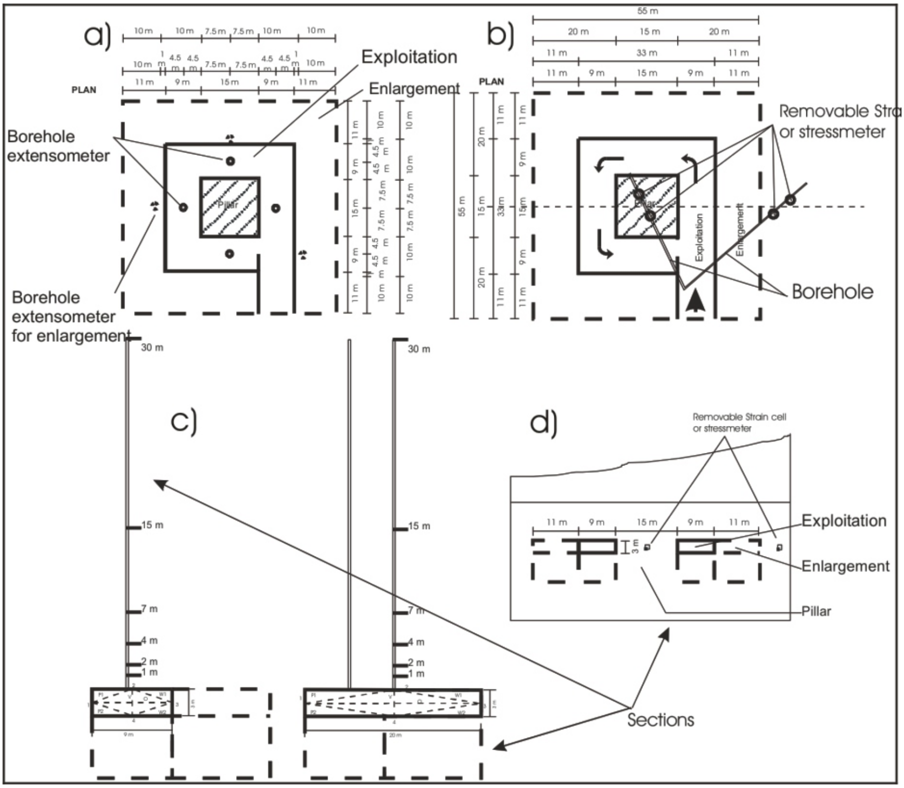


Figure 83. General layout of the experimental panel: first phase exploitation (continuous line) second phase exploitation and floor deepening (dashes line); a), c) MPBX location and anchor depth; b), d) stress meter location(Cravero et al., 2000).

Two Borehole-Stressmeters (for the evaluation of the increase in the stress state) and two MultiPoint Borehole-Extensometer (MPBX, to evaluate displacements induced by the excavation), were chosen for the monitoring during the first quarrying phase. One of the two stressmeters was located in the centre of the future pillar, while the other one was located in the opposite rock wall in a symmetrical position to the crown line of the drift that had to be excavated and subsequently enlarged. As far as the two MPBXs are concerned, one was located in the roof crown line of a drift and at half pillar width while the other one was located in the roof at the midpoint of the line of intersection between two consecutive drifts. When the second phase was started, which involves the widening of the drifts around the pillar, the number of measuring devices was increased by two MPBXs in each measurement station.

The deformation state induced in the rock around the experimental room by progressive excavation, as suggested by BEM calculations, was presumably low, consequently, the relative stress state inside the natural supporting structures had to be controlled by high reliability sensors with suitable full scale and repeatability. Having considered different transducer types (e.g. hydraulic, mechanical, electrical or vibrating wire) the choice was made of vibrating wire sensors. Apart from the previously mentioned technical requirements, the choice was especially motivated by the foreseen evolution of the exploitation panel. The final size of the exploitation panel is in fact that of a room, contouring the pillar, with span maximum 20 m and a height reaching a maximum of 50 m, according to the different sites. This implies that, during each deepening phase, the cables from each sensor have to be collected at one easily accessible point (ground floor level) and this condition must be assured for a long period after completion of the panel itself. To satisfy this requirement, a very long cable length must be used. The fulfilment of these conditions rules out electrical sensors and hydraulic pipes (voltage decay or, accidental air introduction or sludge problems for long term operation of the hydraulic circuit) and would suggest the adoption of frequency measurements.

The sensor chosen for the monitoring of the stress increase is of rigid inclusion type. It consists of 10 pulsed vibrating wire transducers (6 radial, 2 longitudinal and 2 for temperature measurement), with a full scale of 70 MPa (repeatability ±0.01 ÷ 0.07 MPa). The radial strain measurements can be related to the state stress that acts on the plane orthogonal to the stress meter, through the theory of elasticity (Savin, 1961). A 60 mm (BX) borehole is required to install the device, while expansive mortar is necessary to guarantee continuity between the sensor and the borehole surface. The displacements of the roof are monitored using vertical 30 m long MPBX extensometers, each of which has 6 measurement points. All the vertical boreholes for the installation of the extensometers have a 76 mm diameter. Displacement sensors of the pulsed vibrating wire type were chosen with a 25 mm range (repeatability 0.02% full scale). The complete measurement layout consists of 24 transducers for displacement control and 16 transducers for stress measurement purposes. In order to assure continuous data collection from each transducer and to avoid the cost of a full real time data logging, the multiplexer technique was chosen using one data logger linked to three multiplexers with 16 channels each. In this manner the multiplexers collect the cables from all the sensors that perform data logging on a time schedule according to the data acquisition program.

This layout and monitoring program was used, with minor adjustments, in the experimental panels of the three underground quarries and was supplied by the industrial partners involved in the CAD-PUMA project.

14.2. Schemes for rock mass and exploitation panel modeling

This paragraph refers to the definition of the rock mass model that had to be set up to analyse the static behaviour during experimental panel exploitation. Three basic approaches are usually available depending on the rock mass structure and rock matrix features: continuous, discontinuous and equivalent continuous. Continuous model can be applied to soil and weak rock where the lithotype mechanical features rule the rock mass behaviour. When the rock mass shows higher strength, the other two approaches are adopted, depending on the rock discontinuity patterns. Basically, the discontinuous approach is indicated when the whole rock mass behaviour is ruled by the discontinuities, whilst the equivalent continuous is better at reproducing a material whose stress-strain behaviour is due to the characteristics of the rock discontinuity-rock matrix system. Discontinuous approach is typically deemed necessary when the discontinuity sets identify blocks with volumes that are not much smaller than the excavation volumes. Several analytical and numerical methods are available to develop the different described approaches. The complex rock mass structure and the excavation geometry often lead to the necessity of numerical method application.

Computer based continuous approaches (Gioda & Swoboda, 1999) are mostly based on Finite Element Methods (FEM) or on Boundary Element Methods (BEM).

Discontinuous approaches are mostly based on discrete block models like such as Distinct Element Method (DEM) (Cundall, 1971) and Discontinuous Deformation Analysis (DDA) (Shi, 1989).

A synthetic description of the relation between the rock mass structure and the most convenient modelling approach can be based on a rock mass classification system like the Q-system (Barton et al., 1974) which is illustrated in Figure 84 (Barton, 1999).

Marble exploitation usually involves high quality rock masses since intact blocks have to be extracted. Although the three, here reported, case histories are characterized by Q values of between 15 – 60, suggesting DEM modelling, both the equivalent continuous approach (BEM) and discontinuous approach (DEM), have been adopted within this work. BEM was selected, in a preliminary stage, to determine the stress and strain increase due to the excavation, which is useful to define a suitable scheme of the rock mass monitoring at the three quarry sites (Cravero et al., 2000). Model reliability is closely connected to the rock mass data quality, particularly when a blocky system has to be studied. Consequently, 3D DEM models were set up just after detailed rock mass surveys and geometrical modelling of the rock joint structure for each site were obtained. Furthermore, in a medium with a low degree of fracturing, the state of stress and deformation induced in the pillar by the excavation can be somewhat influenced by the joint pattern. Since obtained the results using the discrete approach have to be compared to the in situ measurements, knowledge of the joint location in the quarry sites has to be acquired.

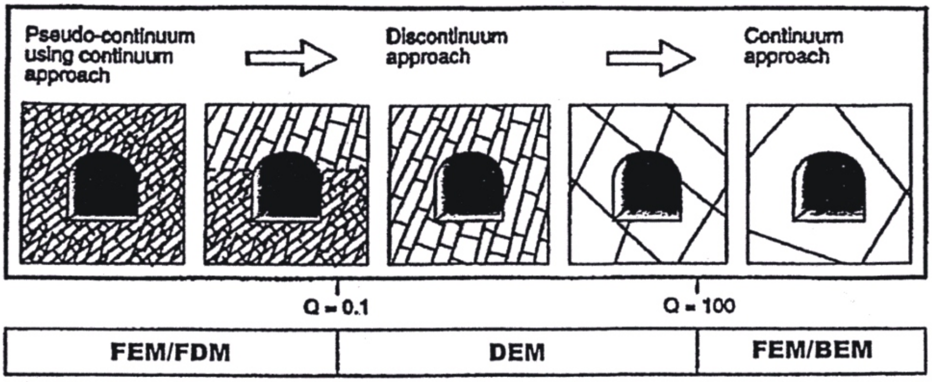


Figure 84. Schematic correlation between rock mass condition and modelling approaches based on Q-system (Barton, 1999).

DEM models, that show a reasonable fit with the monitoring results, can be used to validate the quarry exploitation layouts in discontinuous marble deposits.

BEM model

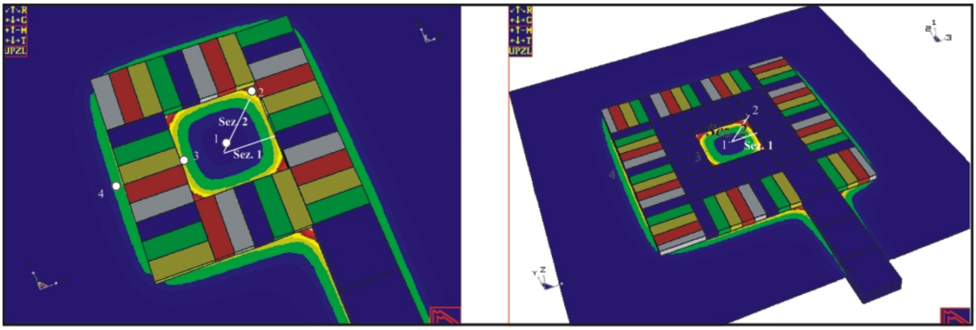
The purpose of 3D BEM modelling using the MAP3D code (Mine Modelling Pty Ltd., 1996) is to provide a preliminary assessment of the mechanical behaviour in the exploited rock mass due to the evolution of the excavation phases for the three experimental room and pillar panels. These analyses are based on the data gathered from classification schemes and assuming a natural stress state of a litho-static type. The geometry and exploitation of the experimental panel were assumed, at this stage, to be the same for the three quarries, according to the general layout (Figure 83), which involves two excavation phases.

Table 4. Litho-static stress state at the three exploitation panels. γ =specific quantity; σ_z= vertical stress component; $\sigma_x = \sigma_y$= horizontal stress components (Cravero et al., 2000).

	Acqua Bianca	Tavolini Alta	Stomatovouni
γ(MN/m^3)	0.026	0.026	0.026
σ_z (MPa)	4.3	2.2	1.0
σ_x=σ_y(MPa)	1.4	0.7	0.3

The rock mass deformability and strength of the equivalent continuum were derived from RMR and GSI schemes (Bieniawki, 1989; Hoek, 1994) and using the widely accepted empirical Hoek & Brown strength model (Hoek & Brown, 1982). The parameters are summarised in Table 4. Figure 85 a, b shows the modelling results, in terms of stress distribution, in the natural supporting structures (pillar and walls) for the Tavolini Alta quarry. Other similar results have been obtained for the other two quarries. Calculated stresses appear to be lower than the strength features of the equivalent continuum material and, in general, there is not evidence of plastic distressing in the rock mass.

However, in a blocky rock mass, like that which occurs at the quarry sites, the possibility of instability may exist under structural control. In other words, the location of rock joints, with respect to the voids, becomes important. To take these aspects into account, DEM modelling was performed on the basis of accurate in situ surveys.



a) b)

Figure 85. Modelling schemes and stress distribution in the natural supporting structures (pillar and walls) for one of the quarry site. a) simulation of the four orthogonal drifts excavation (phase A); b) simulation of the enlargement (phase B) (Cravero et al., 2000).

Table 5. Computed vertical stress increase inside the pillar induced by the two exploitation phases at each experimental site (Cravero et al., 2000).

Site	Centre of the pillar (MPa)
Acqua Bianca A	1.58
Acqua Bianca B	4.28
Tavolini Alta A	0.74
Tavolini Alta B	2.04
Stomatovouni A	0.3
Stomatovouni B	0.9

Table 5 reports the calculated stress increase inside the pillars at the different sites, while Table 6 gives the calculated displacements, induced at different depths which are representative of the measuring points, at the end of the two exploitation phases.

Table 6. Computed displacements at the end of the two exploitation phases, at different depths representative of MPBX anchors (compressive stress and roof settlement are positive) (Cravero et al., 2000).

	Acqua Bianca		Tavolini Alta		Stomatovouni	
Depth	A(mm)	B(mm)	A(mm)	B(mm)	A(mm)	B(mm)
30m	0.198	0.709	0.074	0.258	0.039	0.151
15m	0.422	1.259	0.161	0.487	0.089	0.277
7m	0.682	1.670	2.262	0.648	0.149	0.372
4m	0.856	1.928	0.331	0.751	0.190	0.433
2m	1.029	2.102	0.418	0.823	0.230	0.475
1m	1.152	2.214	0.448	0.865	0.259	0.500

The modelling results showed that the values of the physical quantities that had to be measured (stress and displacement) are within the capability of the selected instruments. For instance, the displacement calculated at a depth of 30 m is of low entity, confirming that a 30 m deep borehole extensometer can be acceptably chosen for displacement monitoring.

DEM models

The objective of 3D DEM numerical modelling, using 3DEC code (Itasca Consulting Group, 1998), is to assess the mechanical behaviour of the experimental room and pillar panel, explicitly taking into account the blocky structure of the rock mass and the exploitation phases. The models of the stope are constituted by deformable blocks and three representative horizontal sections are given in Figure 86 a, b, c. The models have been set up by taking rock jointing into account in two separate ways: firstly by using a random process for joint location and then by means of a conditional simulation of the joint location, taking into account the real joint appearance along the drift faces in each site. Conditional modelling of the joint pattern that are suitable for 3DEC input stream was performed using a special interface in RESOBLOCK code (Hıliot 1988). The step sequence that was followed to set up and run DEM analyses for each site consisted of: making the blocky rock mass structure (Table 7) using DEM input stream generated by RESOBLOCK (joint appearance along drift faces was used to constrain geometrical modelling of the joint network); tailoring the layout of the experimental panel geometry to the blocky model; mechanical parameters and in situ state of stress (of lithostatic type) assignment of the jointed rock mass (Table 8); simulating the two excavation phases for experimental panel exploitation, that consisted of seven different excavation steps, according to the exploitation program followed by each quarry site; comparing the modelling results with the in situ measurements.

a) **b)** **c)**

Figure 86. 3D models of the blocky rock mass and experimental panel at the three sites: a) Acuqa Bianca quarry; b) Tavolini Alta quarry; c) Stavatovouni quarry (Cravero et al., 2000).

Table 7. Attitudes and geometrical parameters of the joint sets for the three quarry sites (Cravero et al., 2000).

Acqua Bianca quarry				
J.Set	Dip	Dip. Dir.	Spacing	Persist.
K1	85	225	3.5	50
K2	80	260	4.2	50
K3	70	335	3.3	53
Tavolini Alta quarry				
J.Set	Dip	Dip. Dir.	Spacing	Persist.
K1	45	59	5.3	50
K2	73	107	6	30
K3	69	150	8.1	30
K4	74	209	6.7	30
Stomatovouni quarry				
J.Set	Dip	Dip. Dir.	Spacing	Persist.
K1	69	147	2.9	100
K2	69	210	2.3	100
K3	78	250	1.9	100
K4	63	68	4.3	50
K5	17	80	2.1	50

Different geometry schemes were generated for each site and analyzed with 3DEC. Only the final DEM models that give a reasonable comparison with monitoring data are here reported. The details of the three models shown in Figure 86 a, b and c are given below:

- Acqua Bianca uses a 110x50x110 m^3 model size made of 4328 blocks and 41968 contacts;
- Tavolini Alta quarry uses a 150x50x150 m^3 model size including 3252 blocks and 37620 contacts;
- Stomatovouni uses a 120x50x120 m^3 model size with 1658 blocks and 16290 contacts.

Table 8. Mechanical parameters of intact rock and rock joints: E = Young's modulus; ν = Poisson's ratio; c_{ir} = intact rock cohesion; φ_{ir} = intact rock friction angle; JKN = normal joint stiffness; JKS = shear joint stiffness; JRC = joint roughness coefficient; φ_j = joint friction angle; c_j = joint cohesion (Cravero et al., 2000).

	Acqua Bianca	**Tavolini Alta**	**Stomatovouni**
Intact rock features:			
E (MPa)	40,000	40,300	52,000
ν (-)	0.280	0.182	0.131
c_{ir} (MPa)	20.9	21.4	24
φ_{ir} (°)	34.3	42	36.2
Rock joint features:			
JKN	40,000	40,300	26,000
JKS	20,000	17,047	11,494
JRC (-)	13	12.57	12
φ_j (°)	29.5	32.3	31.2
c_j (MPa)	2.06	0.9	0.47

A comparison between monitoring and computation results is here given for each experimental panel.

Acqua Bianca quarry

This alpine quarry, located 1600 m a.s.l. in the Eastern Alps, exploits an on average 40 m thick marble lens fully embedded in micaschist under a highly variable rock burden. The experimental panel is located at a depth of about 200 m in a virgin area. Stressmeter data and computed vertical stress in the centre of the pillar and in the opposite wall show an almost uniform increase.

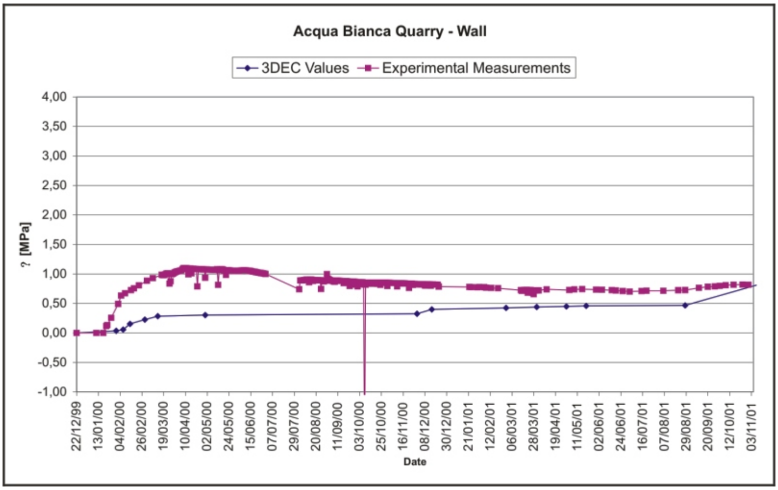


Figure 87. Acqua Bianca – comparison between measured (squares) and computed (diamonds) vertical stress increase in the wall (Cravero et al., 2000).

The maximum measured value at the end of the exploitation is about 1.6 MPa in the pillar and 1.1MPa in the wall (Figure 87), values which are in good agreement with the computed ones, while the computed centre pillar stress is 0.8 MPa. The trend of displacements from all the extensometers appears to be rather regular, reaching a maximum value around 0.5 mm. Although a similar value is attained by the computed displacement, some simulated trends, like that shown in Figure 88, are quite different in that the DEM reach the maximum displacement immediately after the beginning of the exploitation.

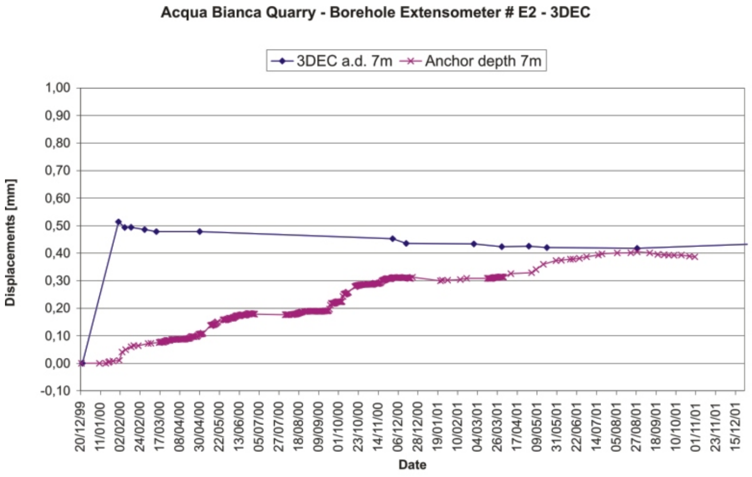


Figure 88. Acqua Bianca – comparison between measured (squares) and computed (diamonds) displacements for the 7m deep anchor (borehole extensometer E2) (Cravero et al., 2000).

Tavolini Alta quarry

The quarry, located 1500 m a.s.l., exploits the large marble deposit of the “Alpi Apuane” range. The experimental panel is under a rock covering of about 110 m, but very near to the mountain side and quarry entrance.

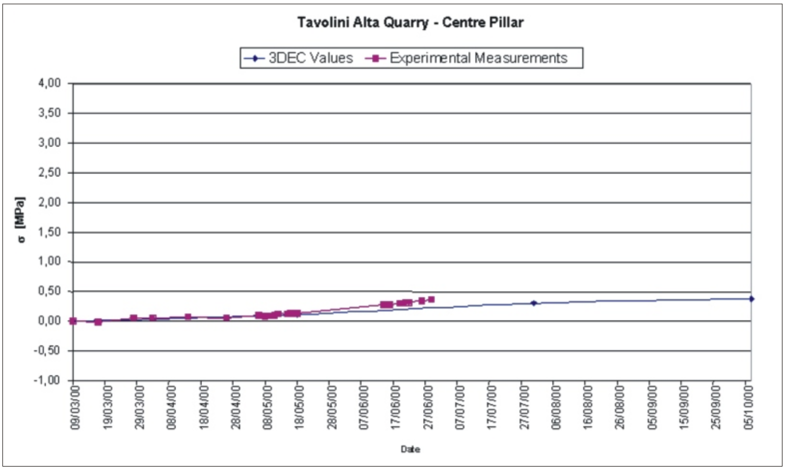


Figure 89. Tavolini Alta - comparison between measured (squares) and computed (diamonds) stress increase in the centre pillar (Cravero et al., 2000).

Stressmeter data were only collected in the first period of the panel exploitation because of electrical, not recoverable, damage that occurred to both the measuring devices (the quarry site is often subjected to storms and frequent lightning). Until that moment, the comparison with computations was satisfactory, with the maximum observed and computed value being about 0.4 MPa (Figure 89). The roof deformation appears to be very low, close to the instrument precision, with the computed values being within the same order or even smaller (Figure 90).

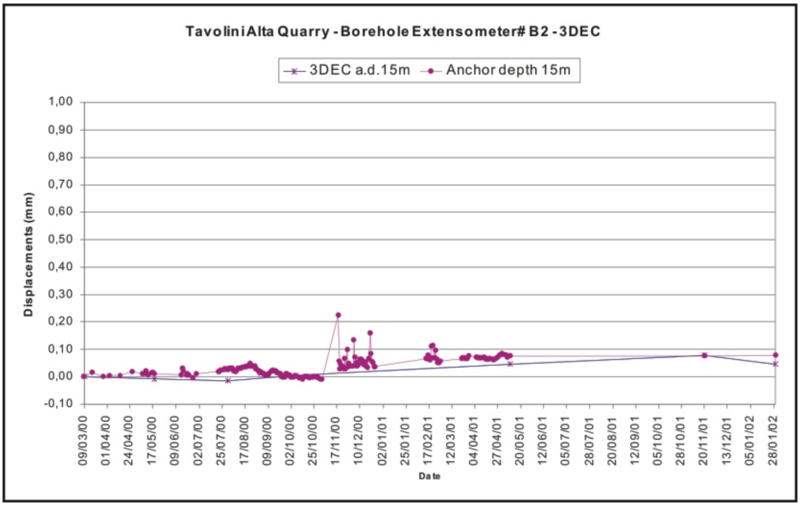


Figure 90. Tavoli Alta - comparison between measured (squares) and computed (diamonds) displacements relatives to the at 15m anchor depth (borehole extensometer B2) (Cravero et al., 2000).

Stomatovouni quarry

This quarry exploits a marble deposit located at 330 m a.s.l. on the Pentelikon Mountain. The experimental panel has an overburden of 40 m, the first 15 m of thickness being of marble and the upper remaining cover being of schist. Both the stressmeters give a stress increase that differs substantially.

The centre pillar stressmeter in fact showed an unsteady, strong increase of the vertical stress over a period of about one year (3.5 MPa), followed by a relatively quick decrease over five months. The value then settled at about 0.5 MPa and this steady stress level is comparable with the calculated one (Figure 91). One could observe that this behaviour was accompanied by roof supporting with bolts 3÷4 m long. On the other hand, the vertical stress measured in the wall increased with an almost uniform trend up to the value of 3 MPa at the end of exploitation, while the computed one did not show any appreciable increase in the initial stress state. All the extensometer readings show anomalous behaviour. While the superficial measurement anchors show a roof settlement of less than 1 mm, the anchors located at depths greater than 7 m show an opposite trend but with values up to 4 mm.

This unevenness of behaviour cannot be acceptably explained nor can it be reproduced using the DEM model, which however consistently reproduces the observed roof settlement (Figure 92).

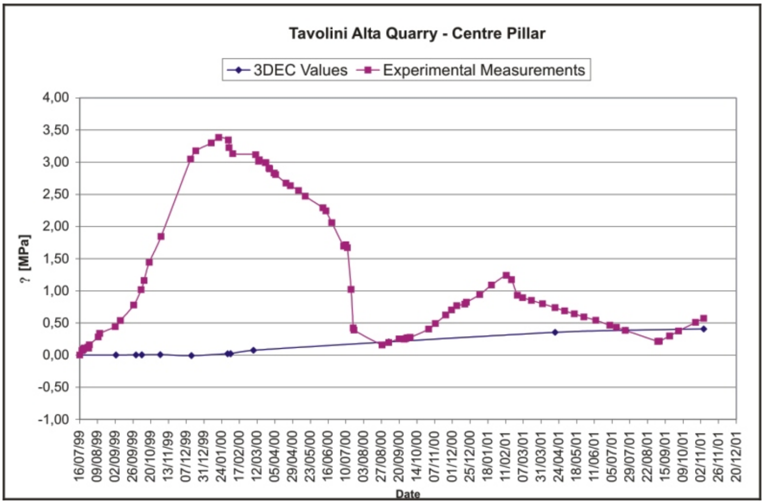


Figure 91. Stomatovouni - comparison between measured (squares) and computed (diamonds) stress increase in the centre pillar (Cravero et al., 2000).

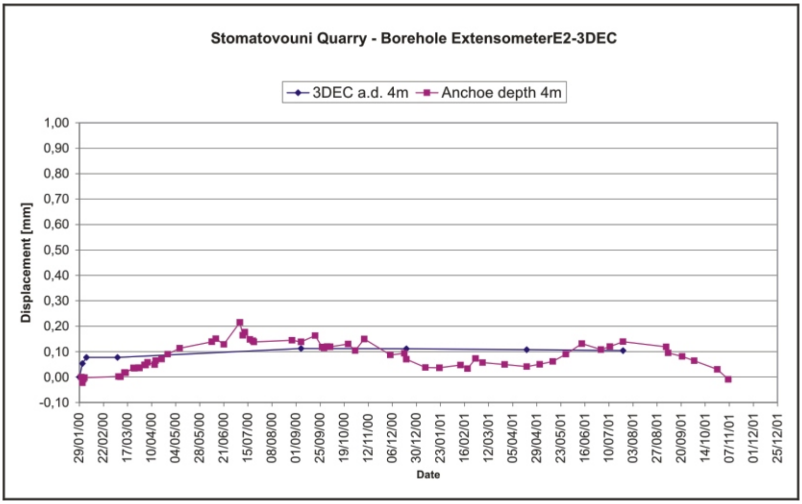


Figure 92. Stomatovouni - comparison between measured (squares) and computed (diamonds) displacements relatives to the at 4m anchor depth (borehole extensometer E2) (Cravero et al., 2000).

14.3. Conclusions

The geomechanical behaviour of the experimental room and pillar exploitation panel in three different marble quarries was evaluated by means of a systematic monitoring and modelling program. The geostructural layouts and the mechanical rock mass conditions of the exploited ore bodies are quite different as the morphology, thickness and overburden for all three experimental sites. This situation, in agreement with the experience of the quarry operators, gives rise to local adjustments of both the exploitation schemes and of the layout of the monitoring devices that have to be adopted at each site.

The set of measurement data and DEM results allow the following considerations to be made about the experimental exploitation behaviour:

The stress increment in the natural support elements (pillar and walls) in the Acqua Bianca site reaches about 40% of the supposed litho-static stress. This value, along with the almost regular evolution in time of the measured and computed stresses and displacements, points out that there is a substantial lack of relative joint movement and related stress portioning. Similar considerations can be drawn from the trends of the displacements in the Tavolini Alta site while the analysis of the stresses cannot be consistently validated due to the short monitoring period which, because of unrecoverable faults in the measuring device, only refers to the first stage of the exploitation. On the other hand, the jointing condition and the small rock overburden at the Stomatovouni underground quarry induce a state of rock mass loosening, as shown by the data logged by the monitoring devices. This appearance is underlined by the evolution of the measured pillar stress which shows a trend towards unstable behaviour. Such evidence suggested a timely action intervention of roof bolting, whose effectiveness was also monitored, as shown by the stress and displacement values. Although the numerical modelling does not consistently follow the observed stress and displacement history, it correctly reproduces the roof settlement and the stress level reached in the pillar at the end of the exploitation.

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APPENDIX A:

TABLES OF THE METHODS AND INSTRUMENTS COMMONLY EMPLOYED IN RESEARCH AND GEOTECHNICAL INVESTIGATION.

Table A1. Geostructural parameters required for the definition of the RMR index (Bieniawsky, 1984) referred to the rock masses

Characteristic	Measurement method	Core	Borehole wall via TV camera	Exposure
Orientation	**Compass-clinometer**	**M**	**G**	**G**
Spacing	**Measuring tape**	**G**	**G**	**G**
Persistence	**Measuring tape**	**P**	**P**	**G/M**
Roughness	**Against reference chart**	**M**	**P**	**G**
Wall strength	**Schmidt hammer**	**M**	**P**	**G**
Aperture	**Scale or feeler gauge**	**P**	**M**	**G**
Filling	**Visual**	**P**	**P**	**G**
Seepage	**Timed observations**	**P**	**P/M**	**G**
Number of set	**Stereographic projections**	**M**	**G**	**G**
Block size	**Three-dimensional fracture frequency**	**P**	**P**	**G**
G = good; M = medium; P = bad				

Table A2. Topographic measurements which can be carried out for the monitoring of the rock masses (Dunnicliff, 1993; Hanna, 1985; modified)

Method	Interval of measure	Accuracy	Advantages	Limits and Precautions
Offset from a beseline theodolite and scale	From 0 to 1.5m depending on the length of the reference basis	± 0.006 m to ± 0.015m	Simple and inexpensive; direct observation	It requires clear, relatively flat surface between points and stable reference movements. Corrections between temperature and slope should be applied. Standard chain tension should be used.
Laser and photocell detector		± 0.015m		
Triangulation		± 0.006 m to ± 0.012 m	Precise, long range, fast, usable over rough terrain	Accuracy is influenced by atmospheric conditions; accuracy at short ranges (<30 to 90 m) is limited for most instruments.
Photogrammetric		±1 /5000 to ±1 /50000 distance	Simple, fast, more precise particularly with self-levelling instruments	It has limited precision; requires good bench mark nearby. It requires good bench mark and reference points. Standard procedures have to be followed carefully.

Table A3. Geotechnical surveys which can be carried out on site (Dunnicliff, 1993; Hanna, 1985; modified)

	Rock material	Rock mass	On-site stresses	Elastic modulus	Empirical data
Overcoring cells and small flat jacks			Magnitude and directions of stresses	Deformation parameters	
Plate bearing tests and borehole jacks		Effect of joints on rock mass strength		Deformation parameters.	
Seismic/sonic measurements	Sonic velocity data from laboratory rock			Longitudinal and shear wave velocities and dynamic modules	
Convergence monitoring and borehole extensometers			Stress distribution.	Time-dependent rock mass movements around excavation	
Piezometers in borehole		Water inflow, pressure, and permeability			
Rock bolt pullout test		Rock	support data:		spacing, length, ….

Table A4 Methods for the definition of the natural stress condition of a rock mass (Dunnicliff, 1993; Hanna, 1985; mod.)

Method	Advantages	Disadvantages
Flat and cylindrical borehole pressure cells	Economical	Small measurement scale; rock deformability feature needed for pressure/stress conversion.
USBM borehole deformation gage	Recoverable; suitable for monitoring reductions in compressive stress.	Small measurement scale; low electrical output; lead wire effects; errors resulting from moisture, temperature, and electrical connections are possible; not proved for other than short-term monitoring; movement of gage causes false readings: expensive to grout in place; rock deformability feature needed for strain/stress conversion; not recommended for use.
CSIRO yoke borehole deformation gage	Suitable for monitoring reductions in compressive stress.	Small measurement scale; low electrical output; lead wire effects; errors resulting from moisture, temperature, and electrical connections are possible; rock deformability needed for strain/stress conversion; limited field experience.
CSIRO hollow inclusion triaxial strain cell	Triaxial data; strain gages encapsulated in epoxy resin; suitable for monitoring changes in tensile stress.	Small measurement scale; low electrical output; lead wire effects; errors resulting from moisture, temperature, and electrical connections are possible; rock deformability needed for strain/stress conversion; cementing difficulties in wet holes; potential errors caused by creep and moisture absorption of the epoxy; should be installed at least 1 month before requiring data.
Uniaxial vibrating wire stressmeter	Lead wire effects minimal; installation is relatively simple; can be used to monitor reduction in compressive stress of up to about 35 MPa	Calibration dependent on contact geometry and initial preload; calibration somewhat dependent on rock deformability in high-modulus rock; gage does not fill borehole completely; single measurement axis; risk of wedge slippage if blasting nearby. Cannot be used to monitor large reductions in compressive stress; no field experience in
Biaxial vibrating wire stressmeter	Biaxial; lead wire effects minimal; gage fills borehole completely.	rock.
Photoelastic stressmeter	Biaxial; gage fills borehole completely; poor cementing is immediately apparent; easy determination of the principal stress directions.	Cannot be used to monitor large reductions in compressive stress; lack of wide commercial availability; readings subjective; not amenable to remote readout.
Tapered plugs	Gage fills borehole completely.	Lack of wide commercial availability; custom drilling equipment required; low electrical output; lead wire effects; errors resulting from moisture, temperature, and electrical connections are possible; cannot be used to monitor large reductions in compressive stress; not recommended for use.

Table A5. Methods for the measurements of piezometric type (Dunnicliff, 1993; Hanna, 1985; modified)

Type	Interval of permeability	Accuracy	Advantages	Limits and precautions
Open-system	10^{-5} to 10^{-8} cm/s	It depends on the measure instrument employed.	Simple, inexpensive, and adequate for most earth problems.	Central observation system cannot be used.
Well points			Simple, inexpensive, and universally available; can be driven in place.	It has large time-lag in low porosity materials ($k<\mu m/s$) and metallic elements that may corrode; cannot measure negative pore pressures.
Casagrande			Simple, inexpensive; no metallic elements, long service life, and provisions for offset riser pipe and flushing tip.	It cannot measure negative pore pressures; requires borehole and carefully placed bentonite or grout seal.
Geonor			Can be pushed or driven into soft ground; can be placed in borehole with filter zone to reduce time lag.	It cannot measure negative pore pressure.
Cambridge			It has simple drivable piezometer with inexpensive tip and shield to protect tip during driving.	It cannot measure negative pore pressures; has metallic elements that may corrode.
Closed-system **USBR** **Bishop**	10^{-6} to 10^{-9} cm/s		Allows central observation system to be used; can measure negative pore pressures; is usable in low permeability soils. Simple, inexpensive, and readily available; has long experience record. Simple, and designed for less frequent de-airing than USBR type; can be pushed into soil from bottom of borehole.	It is more difficult to install than open system piezometer; requires frequent and careful de-airing.

Table A6. Measurement methods of the piezometric type (Dunnicliff, 1993; Hanna, 1985; modified)

Type	Interval of permeability	Accuracy	Advantages	Limitations and precautions
Diaphragm	10^{-9} to 10^{-11} cm/s	±1% of full scale	Small time-lag; is usable in low permeability situations; allows central observation system to be used; can measure negative pore pressures.	Costly and difficult to install and operate.
Pneumatic		It depends on the measurement instrument employed	It is not subject to freezing; uses smaller, less expensive tubing.	It cannot measure negative pore pressures; leakage and moisture in lines.
Hydraulic		±1% of full range	Simple and easy to seal against leakage. It can often be locally fabricated from	It cannot measure negative pore pressures; it requires constant volume pumps or flow control valves.
Electrical resistance strain gauge			commercially available parts; adaptable to automatic data recording; can measure negative pore pressures.	Often limited service life; susceptible to wiring damage.
Vibrating wire strain gauge			More reliable than resistance strain gauge type; adaptable to automatic data recording.	

Table A7. Measurement methods of the inclinometric type (Dunnicliff, 1993; Hanna, 1985; modified)

Type of inclinometer	Typical range	Approximate precision	Advantages	Limitations
Force balance accelerometer transducer	± 30°, optional to ± 90°	± 1-13 mm in 30m	Long successful experience record; most widely used type; version available with automatic readout, recording, data reduction, and plotting provisions; version available for use in 38 mm inside diameter grooved casing; version available for use in horizontal casing for monitoring settlement.	
Slope Indicator Series 200B	± 12°, optional to ±25°	± 8-25 mm in 30m	Long successful experience record.	Standard version is uniaxial; no provision for automatic readout; no longer manufactured.
Bonded resistance strain gage transducer	± 20° ± 20°	± 0.5-25 mm in 30 m	Version available for use in smooth 38 mm inside diameter pipe.	Errors owing to moisture, temperature, and electrical connections are possible; abandoned by most manufacturers.
Vibrating wire transducer		± 3-13 mm in 30 m	Long successful experience record.	Special manufacturing techniques are required to minimise zero drift; bulky transducer results in large probe; abandoned by most manufacturers.
Electrolytic level transducer	± 40°	± 50 mm in 30 m		Size of transducer limits use to near-horizontal holes; short experience record.
Shear probe	± 30°	Very crude	Simple, Inexpensive.	Poor precision; does not measure inclination; cannot determine curvature below point of smallest curvature.

Table A8. Measurement methods of the inclinometric type (Dunnicliff, 1993; Hanna, 1985; modified)

Instruments	Interval of measurement	Accuracy	Advantages	Limits and precautions	Measurement reliability
Fixed multipoint borehole inclinometers		±0.3mm in 3m	Precise; can be used to check horizontal movement at top of other devices, such as inclinometers.	Risk of electrical failure; limited application for tunnels	Good
Portable borehole inclinometers:					
a) Wheatstone bridge pendulum	±12°, optional to ±25°	± 20 mm in 30 m	Has long experience record; not sensitive to temperature.	It requires lengthy calculations; it reads one axis at a time; has no provisions for automatic readout.	Very good
b)Accelerometer	±30°, optional to ±90°	± 5 mm in 30 m	Reads two axes at a time; automatic readout and recording provisions.	It requires lengthy calculations without automatic readout; it requires manual check of data for errors with automatic readout.	Good
c)Vibrating wire	±30° or ± 20°	± 10 mm in 30 m	Available in single or double axis models.	It requires lengthy calculations. Errors due to zero drift are possible.	Good
d)Bonded resistance strain gauge	±20°	± 10 mm in 30 m	Adjustable range on some models; uses ordinary square tubing for casing on one model.	It requires lengthy calculations; it reads one axis at a time. Errors due to zero drift, temperature, or electrical connections are possible.	Fair

Table A9. Extensometers employed for the monitoring of rock mass displacements (Dunnicliff, 1993; Hanna, 1985; modified)

Type	Range	Accuracy	Advantages	Limitation and precautions
Tape	1 to 30 m	± 0.03 to 0.3 mm	Simple, precise, portable; good for measuring tunnel diameter changes	Accuracy limited by tension adjustment; it requires temperature correction
Portable rod	1 to 8 m	± 0.03 to 0.3 mm	Simple, precise, portable	Limited span; accuracy limited by sag; invar tubes can be used to minimize temperature corrections
Weight-tensioned wire	Variable	5 to 20mm	Simple	Creep in wire that leads to errors; vulnerable to damage in tunnel
University of Illinois rod	0.15 m	± 0.03 to 0.13 mm	Simple, precise, and large range; can be quickly installed; more blast installed and damage resistant; easily adjusted anchors.	Not adaptable to remote reading; it has two anchor units only.
Interfels rod		Variable	Simple, precise; can have multiple anchors; can accept remote readout transducers	Projecting head that is vulnerable to damage
Variable tensioned wire	15 to 90 mm	± 0.05 to 0.13 mm	Multiple anchors, up to 6 or 8 (some models are designed for remote readings with transducers using bonded resistance or vibrating-wire strain gauges)	Variable tension that requires varying calibration factors, wire friction and hysteresis that can seriously affect accuracy, risk of electrical failure, and projecting head that is vulnerable to damage.
Constant tensioned wire	50 mm	± 0.05 to 0.13 mm	Multiple anchors; designed for remote reading using potentiometers; has constant calibration factor	Wire friction and hysteresis that can seriously affect accuracy, risk of electrical failure, and projecting head; complex mechanically.

Table A10. Instruments for the settlement measurement (Dunnicliff, 1993; Hanna, 1985; modified)

					Reliability
Water level	± 0.3 m	from ± 0.0025 to ± 12.7 mm	Precision, easily and commonly employed.	High sensitivity to sudden changes in temperature and pressure. Both its ends must be placed at the same height.	Excellent
Probe for deep settlements					
a)With optical survey	Variable	Variable	Extremely easy to employ, low costs versatile, solidity.	Its installation and its maintenance require a great care. It requires some mechanical interventions on the bars for the adjustment to the automatic reading. It is less solid.	Excellent
b)With automatic reading and with references at deep levels	± 0.015 m	± 0.05 mm	Easy to employ, precise, versatile. It does not require a special maintenance.		Good
Telescopic equipment with sliding joints	± 0.015 m	from ± 5 mm to ± 20 mm	Easy to employ. It can measure horizontal and vertical displacements.	It requires specific slides for the lining fixed into the ground.	Moderate
Device with impedance measurement and with radio waves		from ± 2.5 mm to ± 20 mm	It is not influenced by the type of lining.	Possible errors of electric type. Rarely employed in the past.	Moderate
Of the magnetic type		from ± 0.076 mm to ± 0.25 mm	Easy to employ, it can be used with the piezometer lining.		
Modified extensometers	± 30 mm	from ± 0.025 mm to ± 0.25 mm	Easy to employ, versatile. It can perform absolute and automatic measurements	Risk of electric errors.	Moderate

APPENDIX B:

APPLICATION OF GEOPHYSICAL METHODS

Edited by Dr. Nikos Arvanitidis

1. Introduction

Cost effective and environmentally balanced exploitation of ornamental stones depends on the determination of the optimum excavation ratio in order to obtain proper economical recovery, while assuring safety at quarry workplaces. While the goals of quarrying are the same – to extract saleable volumes of different rock types - the route to achieve this varies considerably, with different impacts on the local environment and prevailing stability conditions in terms of waste production and visible scars on the landscape. The problem for the quarrying industry is to maintain its significant global market share while at the same time conforming to EU legislation and directives, which aim to reduce waste and visual impact from this industry. This can be done by introducing some consistency of approach into the fields of exploration – exploitation – and quarrying, so that best practises can be established for different situations, settings and rock types. This technical edition aims to introduce new methods in terms of controlling the stability conditions during quarrying operations, paying at the same time attention on improving the recovery rate and reducing the environmental impact.

A main targeted research action concerns the development of an integrated "cradle to grave" approach, from geological exploration based regional surveys, including where needed remote sensing, to better planning of the exploitation of a site with monitoring of a range of parameters during the lifetime of the quarry. This involves the evaluation of the structural health of a quarry excavation based on the knowledge of the rock mass geology and structure, the estimation of the strength and deformability features of the rock to be exploited and the evaluation of the natural acting stresses. Consequently, setting up a suitable rock engineering design of a quarry excavation requires preliminary in situ surveys and testing, and monitoring the behaviour of the excavated rock structure in order to control, calibrate and, possibly, modify the design on the base of the experimental observations. Underground quarrying as an option is also investigated in this sector. This can impact significantly on quarrying in the European Union, by enabling conformity with legislation and directives, while at the same time increasing productivity and long-term quarrying activities.

Methods of stone exploitation are linked to the specific site (hill, mountain or plain) of the ore deposit, and these methods are strongly affected by the geostructural and mechanical features of the exploited rock mass. Open pit quarrying is widely used, but there is an increasing trend towards underground quarrying. Sometimes these two options co-exist (Scandinavia). The economic implications of underground workings are evident, but the benefit of the underground option to the environmental impact is relevant and the spreading use of highly productive cutting techniques makes profitable underground stone exploitation. Large stone production leads to large excavations and increased speed in quarrying works. In order to achieve this, careful advance planning must be made, one of the topics addressed by the OSNET project. In this respect time and cost-effective monitoring methods are in great demand by the ornamental stone industry. The following paper presents the application of non-detractive geostatistical and geophysical techniques towards detecting and imaging of fractures and defects in marble and granite quarries.

2. Geostatistics

A review of the various geostatistical techniques is undertaken with a view of integrating the geostatistical data into a quarry-exploitation scheme and applying it at a quarry scale. Geostatistics can help with setting up new quarry sites, by providing the average quantity of extractable volume before opening of the quarry, simply by the simulation of a preliminary fracture study. Geostatistics may provide input of a supplementary nature to geophysical originated information and can be part of a data base for the characterisation of a quarry. The main points of the study are listed below.

2.1. Characterization of fracture geometry

The characterisation of fracture geometry is the first step towards quantifying the fracture network, i.e. expression in numbers. The main parameters studied are:

- orientation of fractures;
- length of fracture traces;
- spacing between fractures;
- density of fractures (number or length of fractures per surface unit);
- type of fracture limit (terminates in the rock, or cut by another fracture).

These parameters are calculated from fracture mapping studies carried out either on terraces, or on a horizontal bench in a quarry (Figure 1). This involves distinguishing different fracture families defined by their orientation. Figure 2 shows histograms of fracture length and spacing. Quantification of geometrical parameters provides a better knowledge, understanding and characterization of the fracture network. The main problem is to work out which is the best cutting orientation of the quarry face, which depends upon the recovery level of blocks. The parameters to be studied, therefore, are fracture length and spacing. Statistical parameters may then be adjusted according to statistical laws, a log normal law for example, applied to fracture lengths. These statistical laws are subsequently used in the simulation stage.

2.2. Characterization of blocks bound by fractures

Fractures delimit unflawed blocks within the rock mass. The following may be calculated for each such block:

- surface area;
- perimeter;
- radius of the circumscribed circle (smallest circle containing the unflawed block); radius of the inscribed circle (largest circle within the unflawed block).

These parameters are subsequently used to calculate various shape indices.

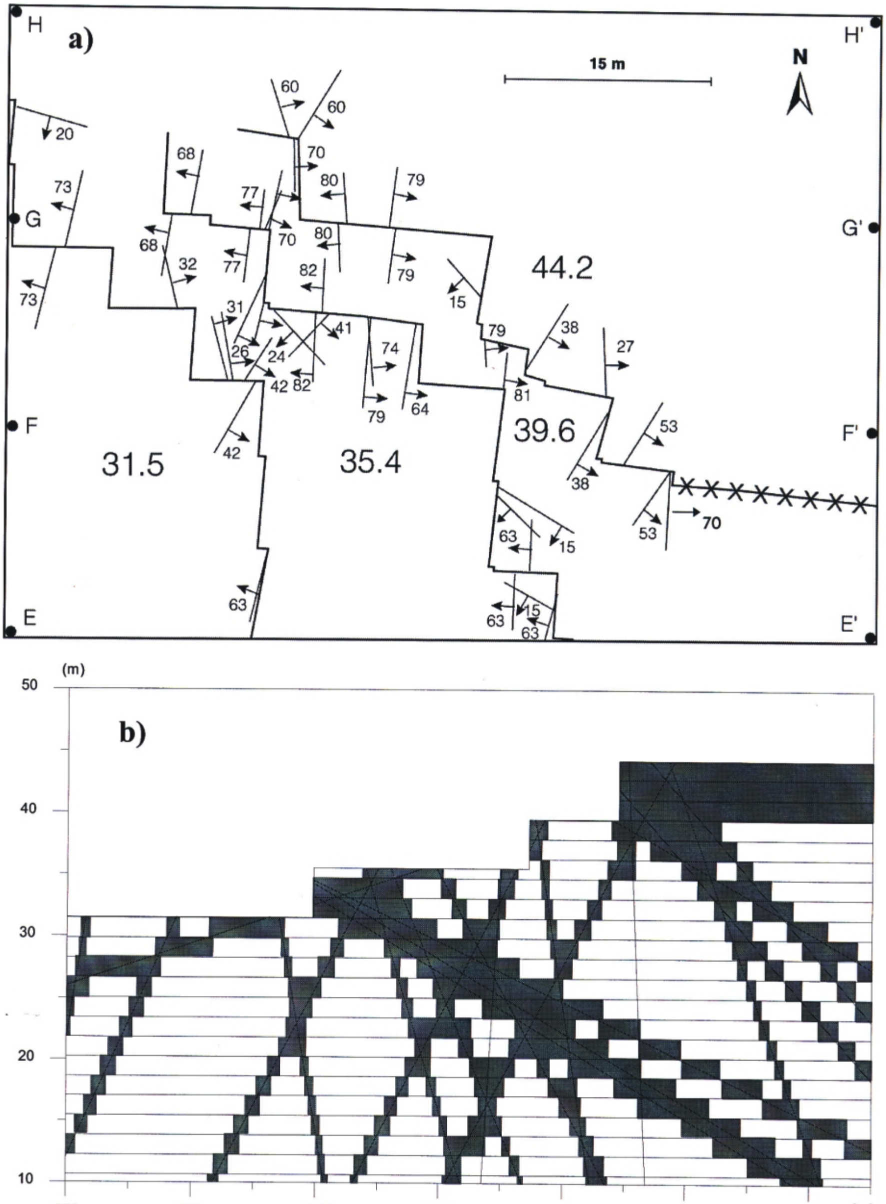

Figure 1. a) representative part of marble quarry showing the distribution of the joints (fractures of type 1). The face in the lower right part, market with X, is intensively micro-fractured; b) an example of a cross-section, F-F', showing the distribution of the joints. Shaded area represents non-excavated area. The upper right part is intensively micro-fractured (after Conquist and Sahlin).

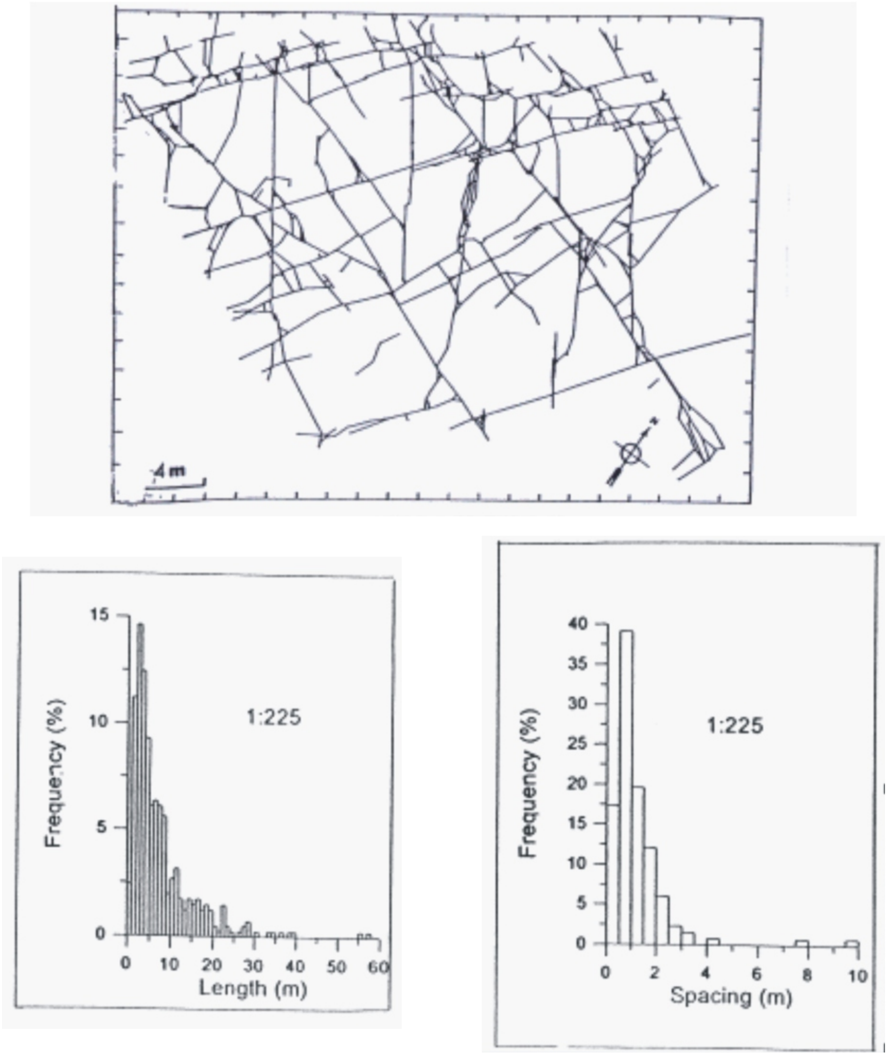

Figure 2: (a) Example of a fracture network (b) Histogram statistics for fracture length and spacing (Project No. 6086 – Final Technical Report)

The characterisation of blocks may be based either on data from a full fracture study, or on simulation results. In addition, it is also possible to determine the number of intact blocks and their volume, depending on the adopted exploitation method (orientation of the faces, spacing between saw lines, etc.). In this manner, the exploitation recovery level of blocks can be calculated.

2.3. Simulation of a fracture network

Simulation involves a numerical model that aims to provide an image of unknown reality, but without any direct contact with reality. The simulated network is set up so that it has the same properties as the real network, i.e. the same length, fracture spacing, block size, etc. Simulation is generally applied when only a partial fracture study is available rather than a full one. The laws of fracture distribution are assumed, either from full fracture studies undertaken in another zone, or from hypotheses and comparison. Parameters of these laws may also be calculated as a function of the available partial fracture study. The same calculations can be carried out with a simulated network as with a real one, i.e. determination of geometrical parameters, and the distribution of blocks. Different types of models may be used for fracture simulation, two of which are outlined below.

- Random disc model (Figure 3) – in that case it is assumed that the fractures are of finite extension and that they have a circular pattern. Model parameters such as disc orientation, fracture density, and disc radius, are estimated from results of a statistical and geostatistical study. This model operates in three dimensions, but each fracture never terminates against another fracture.

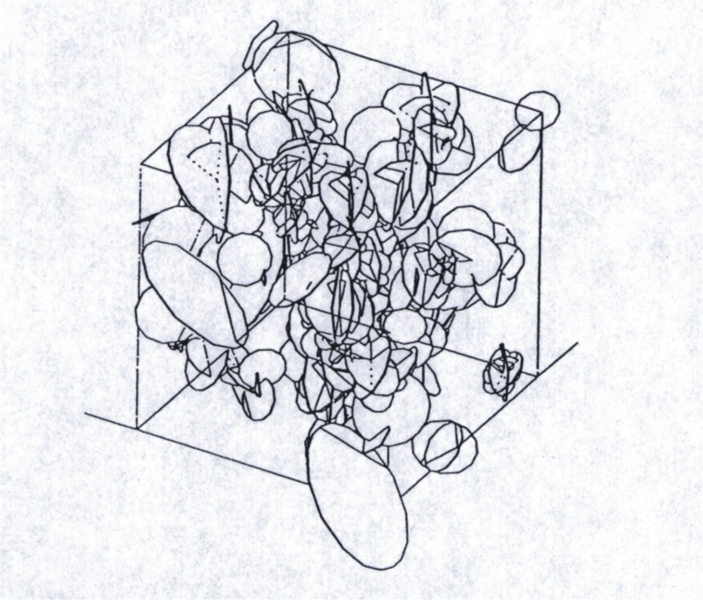

Figure 3: Random disc model with regionalised fracture density (Project No. 6086 – Final Technical Report)

- Dershowitz model; this model is better suited to rectangular fracture patterns which commonly intersect one another. It is quite difficult to work in three dimensions, and several versions are possible depending on the type of geometry to be modelled. At present, no standard software is available to enable simulation of all cases.

3. Geophysical methods

Several geophysical techniques are available to the ornamental stones industry and their application plays an important role to the increase of productivity and security. These techniques are an invaluable tool for prospecting new quarries to be developed in the future and evaluate quarries of potential interest. 3-D radar software capable of processing, interpretation and 3-D representation of the fracturing, borehole antenna and acoustic systems was proven to be successful. The critical factor determining the application of the methods is still the cost involved.

3.1. 3-D Radar Software

The 3-D detection of fractures in ornamental stones quarries has been tested and validated for resolutions of about a centimeter and with penetration depths of the order of 8 m. The data were processed using almost automatic (SU) procedures and transferred under Matlab for interpretation and 3-D representation. Interface between Matlab and other 3-D representation software is possible by programming. The processing sequence, developed entirely on a UNIX workstation, operates under development environments such as SU and Matlab.

The advantage of using such development software is the low cost; SU is supplied free of charge by the Colorado School of Mines (1994), and Matlab for UNIX is inexpensive compared to platforms like GOCAD or Strim 100.

Furthermore, the surface radar is extremely well-suited to quarry needs (Figure 4):

- at 900 MHz - resolution on a centimetre scale and a penetration depth of 5 m,
- at 300 MHz - resolution of 10 cm and a penetration depth of up to 12 m.

Processing time is very reasonable. Data from a Thassos quarry survey, i.e. 120 + 336 m^2 representing respectively 600 + 4000 m^3 of tested marble were processed in one week. The most time-consuming part of processing is the picking of fractures and other anomalies. The final development and adjustments to the radar images are done almost automatically.

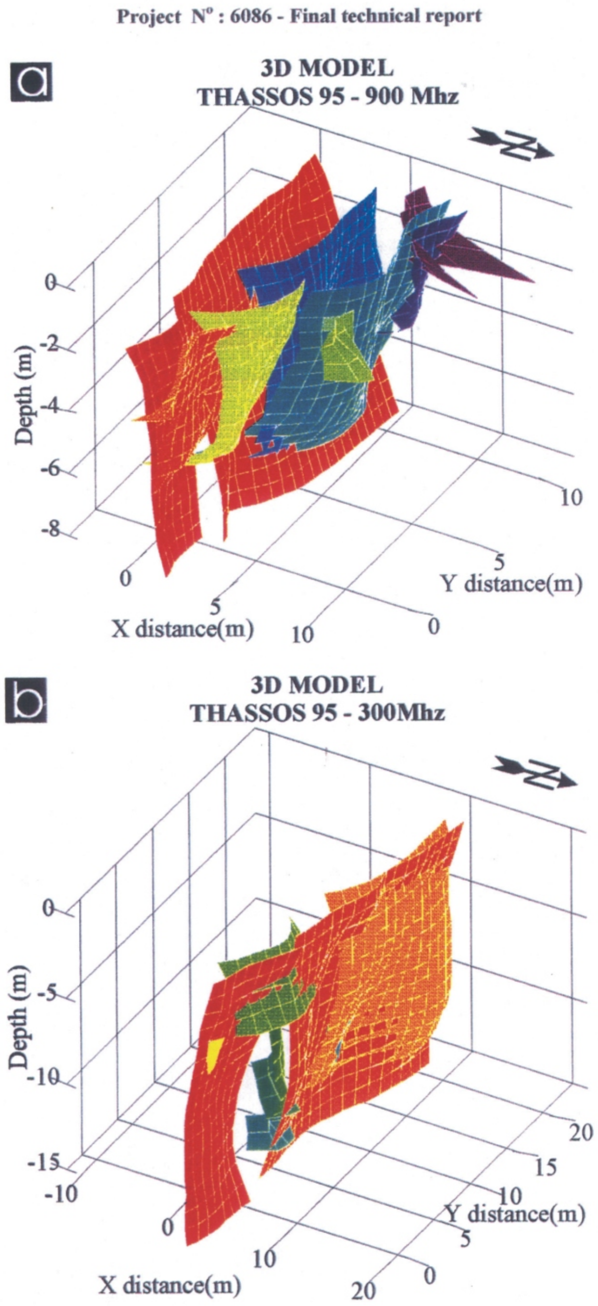

Figure 4. Final 3-D models for the (a) 900 and (b) 300 MHz profiles. Colors represent the different surfaces interpolated from interpreted fractures (after Karmis, 1996).

3.2. High-frequency borehole radar antenna.

The borehole radar (Figure 5) has shown obvious qualities of resolution and suitability to quarry work: it enables visualisation of fractures between boreholes at a required depth. Whereas the non-destructive surface radar possesses qualities adapted to a work face, the borehole radar can be used to estimate the value of an unexposed zone. The surface radar is very disappointing in such conditions because this technique is not capable of penetrating the weathered zone. Only a borehole can be used to penetrate this zone. High-resolution tomography, however, can be used to estimate the degree of fracturing in the surrounding the metres. Currently, only the 2-D tomography software is able to restore an image of the fractures. The 3-D reflection tomography (Figures 6, 7) is still being tested. Improvements still need to be made to the antenna regarding its adaptability to all logging conditions (pressure, waterproofing, logging cable, etc.). This is the final validation stage for this highly innovative tool.

Figure 5. Photograph of the borehole radar antenna

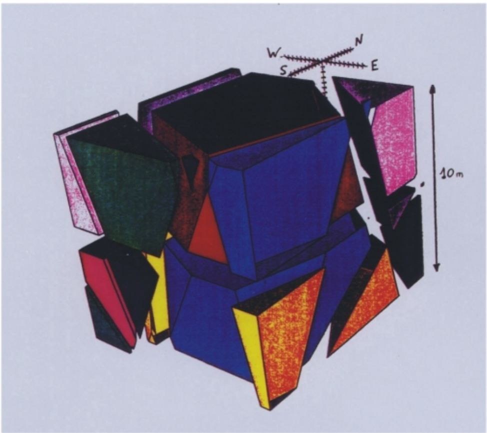

Figure 6. 3-D tomography results, Sardinia (Project No. 6086)

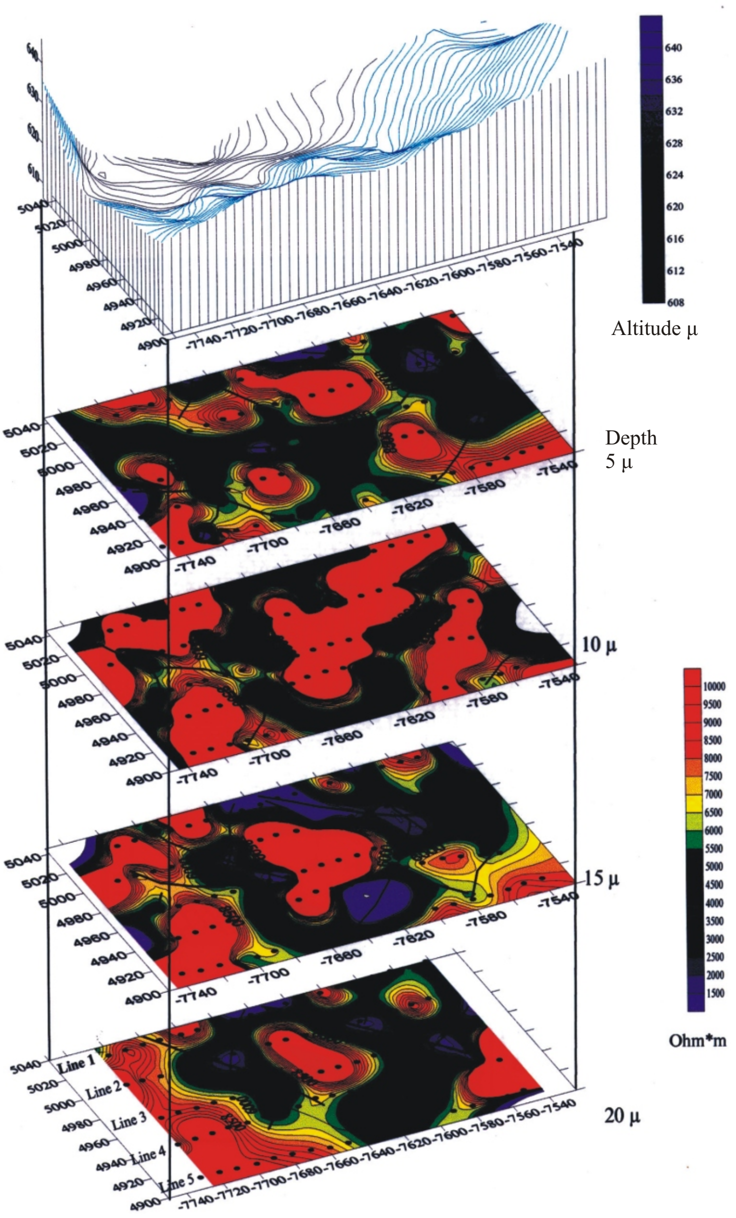

Figure 7. 3-D geoelectrical tomography showing the main structural discontinuities in a Greek marble quarry (after Karmis, 2001).

3.3. Acoustic system

The problem of detecting defects in a block can only be solved by a technique that does not involve overall costs exceeding the value of the blocks. Consequently, time spent on data acquisition and interpretation must be reduced to a minimum. The equipment best suited to this problem is an acoustic system (type Pundit), highly portable, which records measurements by transmission between two faces. It was shown that in most cases (narrow fractures) the resolution offered by this technique must be complemented with reflection measurements which are better for detecting discontinuities such as fractures. The system tested fully meets the needs for qualifying the blocks in terms of degree of heterogeneity: the more heterogeneous the rock (presence of fractures, cracks, karstic zones), the greater the variation in average velocity recorded between the two faces, and the higher the anisotropy. Very good results were obtained with this equipment, demonstrated by the correlation between the 3-D velocity tomograms and the mapped fractures. The main disadvantage with this method is the time-consuming measurement phase.

3.4. Geophysical methods evaluation

The geophysical methods provide new tools to solve the problem of determining fractures and karst zones in new ornamental stone quarries or operational quarries. The resistivity and the electromagnetic (VLF) methods can give useful results, employing fairly cheap instrumentation and are fairly quick in acquisition and processing time. They should be used as a reconnaissance tool on virgin areas and in operating quarries where the detailed reconstruction of fractures is not essential. For the 2D or 3D fracture imagery, depending on the scale of results required, surface and borehole radar should be applied for the assessment of prospective and operational quarries. Combined use of surface and borehole radar is in some cases needed. Three-dimensional acoustic tomography on blocks provides very good results.

A number of geophysical techniques were selected and listed below, considering their advantages and limitations.

Table 1. Geophysical methods assessment

Methods	GRANITE	MARBLE	Acquisition time	Processing – interpretation time	Effectiveness
Electrical	√	√	Average	Average	Average
EM (VLF)	√		Low	Low	Average
GPR (Radar)	√	√	Low	Average	High
Borehole tomogaphy GPR	√	√	Average	Average	High (when combined with surface GPR)
Acoustic			High	High	High
Borehole tomography seismics		√	Average	Average	Low

In **Granite** the problems of fracturing are less complicated than in marble and the aim is to detect the discontinuities and horizontal contacts. It is impossible to detect the mafic inclusions within granite.

- The application of Electrical and EM surveys can help in detecting the main structural elements with a high degree of confidence to a depth of about 15 m. The instrumentation is relatively cheap and acquisition cost in time is small for VLF and average for Electrical. This can be cut down by employing multi-electrode systems and multi-array configurations (Figures 8, 9). The processing – interpretation procedure can be elaborated, depending on the problem needs. Certain interpretation algorithms and routines used in other fields of geophysical investigation (engineering geophysics, mineral exploration) have been modified and applied successfully to granite and marble.
- GPR (surface surveys) can also be applied in granite, with superior accuracy and resolution than Electrical / EM. GPR has the advantage of rapid data acquisition, enabling coverage of large areas, but processing and interpretation time can be high, particularly when a detailed reconstruction of fracturing is required. It also calls for expensive instrumentation, advanced computer hardware and software and the necessary human expertise. Radar should be used in combination with borehole radar tomography, particularly in cases where the surface fractured / weathered layer masks the response of deep fractures.
- Seismic can be very helpful when used in the topography mode and when radar instrumentation is not available.

In **Marble** the situation is more complex and calls for integrated geo-scientific approach, involving structural geology mapping, borehole drilling and core logging along with the application of geophysical techniques (Figure 10).The geophysical methods for marble are listed following in order of effectiveness:

- GPR surface surveys. It has been demonstrated that the surface radar can provide very accurate and detailed information. Its resolution and penetration depend on the frequency used:
    - At 900 MHz – resolution on a centimetre scale and a penetration depth of 5 m,
    - At 300 MHz – resolution of 10 cm and a penetration depth of up to 12 m.
- Borehole GPR tomography, can be used to estimate the degree of fracturing at ten metres distance from a borehole, overcoming the problem of weathered surface layer.
- Geoelectrical surveys can provide a qualitative assessment of the fracturing extent of a site at a depth of about 20 meters. They can also detect fractures at a resolution of a few cm, at depths to 5 m, or decades of cm at larger depths.
- Borehole seismic tomography can also be used to asses the degree of fracturing.

VLF surveys in marble are less effective than in granite, due to the large number of discontinuities encountered but they can be applied as a reconnaissance tool to aid tectonic mapping.

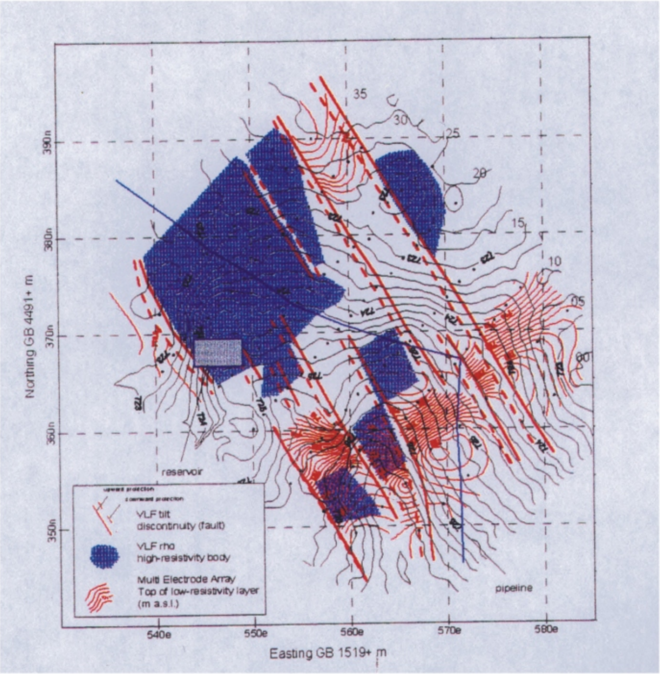

Figure 8. Budduso granite area, Italy. Final Interpretation Map.

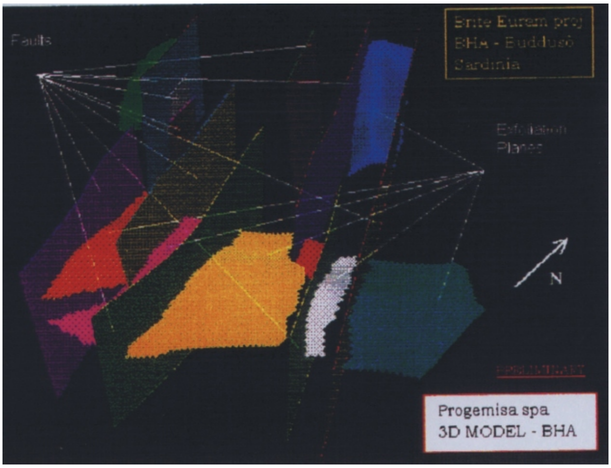

Figure 9. Budduso granite area, Italy: SE view of the three-dimensional model.

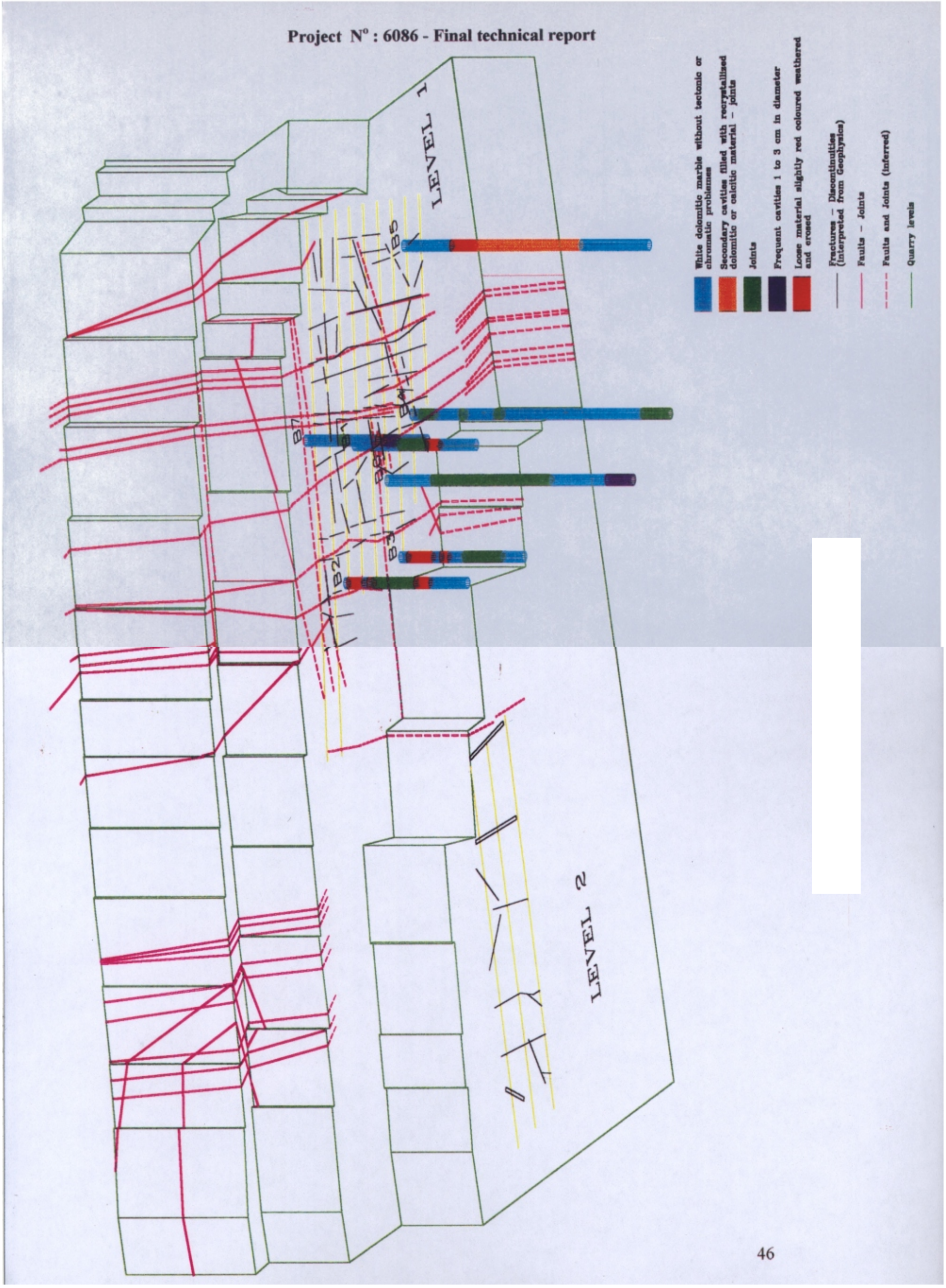

Figure 10: Iktinos quarry on Thassos Island. Greece.

The selection of the methods depends on the individuality of the problem and on the available funds. The GPR methods are usually more expensive, bearing the high cost instrumentation. Geoelectrical methods are cheaper but less accurate and resolving than GPR.

Micro fractures in marble. It has been ascertained and verified from quarrying activities, that none geophysical method can detect and delineate the micro fractures often found in marble, probably the most serious problem in quarries. These are less than 1 mm in thickness, hardly visible, but their existence in the rock mass result to the rejection of the site or block and can bring stability problems.

Even after a systematic geophysical survey the possibility of micro fractures being present cannot be ruled out.

Marble block investigation. The application of the acoustic technique suffers from high cost in terms of acquisition and processing – interpretation time. It has been shown that at present, time a number of two blocks can be surveyed per day, whereas the needs of the industry are a 10 times higher production rate. Thus the cost of the application of the method exceeds the market value of the block. The problem of detecting fractures of one mm in thickness can be resolved technically, but the method is not economically viable. However, it should be stressed that geophysics combined with other methods could contribute effectively to control the stability conditions during quarrying.

4. Application fields of geo-scientific methods

There are two domains of geostatistical and geophysical methods application.

The first involves the assessment of sites, planned to be developed as quarries. The application of the geo-scientific approach proposed above, would lead to the optimisation and planning of the site exploitation. The proposed approach would include a tectonic mapping of the area under development for the delineation of the best suited sector for further study in terms of economics and working safety. Geophysical investigation would follow, comprising VLF orientation surveys, geoelectrical surveys, borehole drilling GPR surface and GPR borehole tomography. The purpose of borehole drilling is exploratory and also operational. It will enable the application of GPR tomography, very fundamental in the case where the surface zone is fractured and weathered, not permitting the application of surface GPR. The results of the work would enable decision making on the implementation of the investment and planning of the quarrying activities.

The second domain is working within operational quarries. The assumption for economic viability of a quarry is the rational exploitation of the deposit. The success of the venture depends upon the procedure by which this exploitation plan is performed. The basic problem of this procedure is the difficulty to know the expected in situ material value, prior to its exploitation. In quarries the existence of developed levels and exploitation faces permits the very detailed tectonic mapping and the detailed application of surface GPR, and borehole tomography. The results of the work, including a comprehensive 3D picture of the fracturing of the site, would enable estimation of the reserves and would guide the planning of the quarrying activities to the most profitable and safe sectors. Combined with knowledge of extrinsic factors, such as commercial value of the particular type of material, this geo-scientific methodology could provide direct information to the management and the future development of the quarry can be planned on the basis of quantitative criteria, encompassing economical, working and security factors.

5. Pre-feasibility study

A cost/benefit analysis of the geophysical methodology is considered from both a customer and service supplier standing. The term “customer” represents the private enterprise, being the end user of the technological benefits. The term “supplier” refers to the company who will provide the relevant services. It is believed that the transfer of the technological benefits to the end user most probably can be materialised via a service supplier. The techniques involved require highly skilled personnel and expensive instrumentation, which can be only maintained by specialised servicing companies. The large majority of the industrial companies, operating in both marble and granite are small firms which employ a small number of people, less than 100 people, with their interest mainly on processing and trade. It is highly unlikely that these companies will be interested in developing their own in house technical teams for the application of the proposed methodology.

Out of a total of about 4.000 existing marble companies in Greece, producing more than 250.000 m^3 marble in blocks, only 10% are capable of undertaking the complete process from quarry to client (extraction, dressing and marketing). In Italy, the total amount of operating quarries is about 600. The market for processed marbles is more profitable than the raw marble market and this causes the trend towards the finishing and marketing rather than the whole process line. The proposed methodology is focused on the quarrying activities, the first step of the line and usually the riskier and less profitable. The following paragraphs describe two scenarios with possible involvement of the above methodology with the potential cost and benefits.

Case l: New quarry to be developed

We assume a company wishing to assess the exploitation potential of an area and use the means of destructive investigation. For a full scale operation it will take one month of work and a capital layout of more than 100.000 € before decision can be made on continuation or not of the work. This expense involves usage of the complete suite of machinery, wire-sawing, drilling etc. This type of operation is only undertaken by the major companies who wish to decide rapidly on the future of the investment. The majority of the quarry owners, being small producers, assign few people to the exploration of new sites, with limited machinery. They continue exploration activities for a prolonged period, often more than a year, before they can decide on future work. In most of the cases the expense is much higher than in the first case and the environmental damage is much larger, in view of the erratic, arbitrary and often illegal way of operation. There is very little hope the latter type of enterprises will be interested in investing on a geo-scientific exploration work of any kind. By continuing the first scenario we assume that the initial investigation workings encouraged continuation of the work. A new quarry needs between one to two years of preparation development works with an estimated cost of more than 500.000 € before producing.

Case 2: Quarry in operation

Operating quarries can run at a loss and close down, with a detrimental effect to the environment. The same quarries can be profitable, as known by experience, when the exploitation is taking place in an efficient and rational way. The annual cost of operating a small scale quarrying enterprise is estimated about 1 m€. It is evident that the capital allocated by the industry to opening new quarries is high and there is also a high risk of loss of investment. Also the high operational cost of a quarry is a self motivation for new means of increasing and secure productivity. The proposed methodology applied to a prospective quarry site extension of an operating quarry is the following:

- Tectonic mapping of an area of about 3 hectares, selection of the optimum sector (size about 0.5 to 1 hectare), detailed mapping of the chosen area.
- Geoelectrical/EM surveys for qualitative gross assessment of the site at 10 m interval lines over the same area.
- GPR surface techniques covering the area at 15 m spaced profiles.
- Drilling of 4 couples of boreholes at a depth of 20 m
- Borehole GPR

At this stage decision can be made on whether work will be continued or abandoning the site. If the results seem encouraging and this can be substantiated by destructive investigation, geophysical work can be continued on a systematic pattern, on closely spaced profiles aiming for high detail and accuracy. It is difficult to prove a exact cost for the exercise above, due to the different figures charged by the service providing companies. A gross estimate would be about 50-100.000 €. The time consumed for data acquisition-report writing will be 4 to 6 weeks.

Working on an operational quarry posses less difficulties in terms of access to the area but is more demanding in terms of the sought accuracy and resolution. The similar methodology will be applied, with the aim being to establish the fracturing pattern in 3D. The size of the investigation area will be smaller (1000 to 3000 m^2) and the spacing of the profiles will be at 1 to 2 m. Multi frequency GPR and borehole GPR tomography will be undertaken and multi-array Electrical surveys with the objective to detect as accurately as possible the fracturing pattern at a depth of at least about 20 m. As it has been shown the resolution is high at shallow depths (1 centimetre at a penetration depth of 5 m, 10 cm at 12 m depth and so forth. The results would be supplied in a 3D fashion to the customer enabling their proper utilisation.

Either type of operation can be provided at an estimated cost of 50.000 - 100.000 € depending on the service provider. This is between 15% to 30% of the overall development cost of a prospective quarry site and about 10% of the annual operation cost of a quarry. If the results of the investigations show that the prospective area is not suitable for quarry development, due to poor economic and stability conditions, there is a substantial saving in capital layout. If the results indicate good prospects for development and they can guide the exploitation in an efficient and safe way, this expense will prove to be negligible, compared to the profits of the quarrying enterprise. For comparison purposes, a small scale marble quarry can produce between 2,000 to 3,000 m^3 per year, with a turnover of about 1 to 1.5 million.

In economic terms the direct result of the successful application of the integrated geological - geophysical exploration strategy would lead to an increase of the recovery rate by at least 20 to 25%, at the most conservative scenario and contribute to improve the stability conditions during operation. At present the, calculated recovery of a medium sized quarry is of about 40% for granite. In the case of marble this is much lower, with some Greek quarries operating at a recovery rate as low as 5%, i.e. those producing the excellent quality pink marbles, with the majority running at 5 between 5 to 10%. The stability conditions are also not known enough to be able to take the proper measures.

6. Conclusions

Geophysical techniques are available to the ornamental stone industry and their application plays an important role to the increase of productivity, and the control and improvement of stability conditions. The main areas of project elaboration concerns (a) prospecting for new quarries to be developed in future and (b) evaluation of the rock mass in operating quarries. The present compilation of geophysical methods applied during stone exploration and exploitation involves the following innovative techniques and new products.

- Ground Penetrating Radar (GPR) and relevant software capable of processing, interpreting and 3D modelling fracture planes and karsts zones in terms of ornamental stone exploration, exploitation and quarrying operations. Processing techniques similar to those used in seismics are applied. The quality of the data enables a correct interpretation of the fractures, which can then be displayed in 3D.
- High Frequency Borehole Antenna, making an innovative technique which is able to provide accurate measurements and high – quality results. High – quality achievements are also obtained when the synthetic – pulse radar, and the 2D velocity and attenuation tomography software are applied.
- Innovative acoustic method data interpretation to increase the resolution of fracture detection.
- Resistivity and electromagnetic (VLF) methods can give valuable results, employing fairly cheap instrumentation and providing relatively quick acquisition and processing time. However, these methods should mainly be used in regional exploration of new target areas and in operating quarries where a detailed re-construction of fractures is not essential.

As a final conclusion it should be addressed that for 2D and 3D fracture imageries, depending on the scale of results required, the techniques of surface and borehole radar are suitable for the assessment of prospective and operational quarries, whereas acoustic testing fits for the delineation of microfractures in blocks. These methods have broad applications in the field of geotechnical studies. In the case of ornamental stones quarrying they are capable to fracture network detection in engineering geological structures, e.g. marble and granite rock masses, providing useful information on the prevailing stability conditions.

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