Using engineering geosciences mapping and GIS-based tools for georesources management: lessons learned from rock quarrying

Helder I. Chaminé, Maria José Afonso, José Teixeira, Luís Ramos, Luís Fonseca, Rogério Pinheiro and António Carlos Galiza*

The heterogeneity of the geological properties of rock masses is very important in engineering geosciences and rock engineering issues. The study of discontinuous rock masses has developed enormously. In particular, the assessment of in situ block size plays a key role in rock engineering design projects such as mining, quarrying and highway cutting operations. The application of Geographic Information Systems to engineering geosciences has become more common. In this article, the importance of an integrative comprehensive approach to rock engineering is discussed in the context of quarrying operations, i.e., from field mapping surveys to geomechanical assessment. This approach led us to a better understanding of the appropriateness of exploitation of raw material aggregates and to reduced uncertainty about sustainability of georesources in relation to their management and the environment.

L'hétérogénéité des propriétés géologiques des masses rocheuses est très importante dans les problèmes des géosciences de l'ingénierie et d'ingénierie des roches. L'étude des masses rocheuses discontinues s'est énormément développée. En particulier, l'évaluation des dimensions du bloc in situ joue un rôle clé dans les projets de mécanique des roches, telles que les mines, les carrières et les opérations de coupe de chaussées. L'application de systèmes d'information géographique à les géosciences de l'ingénierie est devenue plus courante. Dans cet article, l'importance d'une approche intégrative en ingénierie des roches a été discutée dans le contexte d'exploitation de carrières, c'est-à-dire à partir de la cartographie sur le terrain et jusqu'à l'évaluation géomécanique. Cette approche nous a conduit à une meilleure compréhension de l'adéquation des exploitations des agrégats de roches et à réduire l'incertitude quant à l'exploitation durable des géoressources en ce qui concerne leur gestion et de l'environnement.

La heterogeneidad de las propiedades geológicas de los macizos rocosos es muy importante en las cuestiones relativas a las geociencias de ingeniería e ingeniería de rocas. El estudio de los macizos rocosos discontinuos ha tenido un gran desarrollo. En particular, la evaluación del tamaño del bloque in situ juega papel relevante en proyectos de ingeniería de rocas, como: minería, explotación de canteras y desmonte en carreteras. La aplicación de los Sistemas de Información Geográfica en geociencias de ingeniería se ha hecho habitual. En este artículo, se discute la importancia de una perspectiva integradora de la ingeniería de rocas aplicada a la explotación de canteras; por ejemplo desde los trabajos de cartografía de campo hasta la evaluación geomecánica. Este enfoque nos ha llevado a una mejor comprensión de la relevancia de la explotación de áridos, reduciendo las incertidumbres en aspectos de sostenibilidad, medio ambiente y gestión.

Geosciences, Mapping and Georesources

The geologist Ruth D. Terzaghi stated this important issue: *"Because of the significant influence of joints on important engineering properties of hard unweathered rock, a description of such rock is inadequate for engineering purposes unless it includes reasonably complete and accurate information concerning the spacing and orientation of the joints."* (Terzaghi, 1965: 287). This remarkable quotation is the basis for the key role of geology in field site investigations for rock engineering purposes. Hopefully, nowadays any skilled professional (e.g., geologist, engineering geologist, engineering geomorphologist, geological engineer, geotechnical engineer, mining engineer, civil engineer, or military geologist/engineer) engaged in the practice of applied geosciences must keep this in mind to reduce all geological uncertainties and variabilities. According to De Freitas (2009) the safest way through such uncertainties relies on good case histories, which should be on the desk of every engineering geologist and used as frequently as the electronic calculator. Regarding this, ***Fig. 1*** represents a modern overview of the interdisciplinary and multidisciplinary scientific field called ***Geotechnics***, which can be practiced by several types of professionals and in most situations encompassing expertise teams with complementary skills. Engineering geoscience is concerned with the application of geology and geomorphology in engineering practice.

Geotechnics is the science that focuses on the mechanics of soil and rock to characterise and assess the engineering behaviour of the ground and the sustainable interaction design with the environment. Currently, this approach has become a standard practice for professional geologists and engineers aiming at the planning, design, construction and maintenance of engineering structures and works (e.g., foundations, slopes, dams, underground excavations, mining, quarrying, retaining structures, highway cutting operations, landfills, etc.),

* Laboratory of Cartography and Applied Geology (LABCARGA), Department of Geotechnical Engineering, School of Engineering (ISEP), Polytechnic of Porto, Portugal, hic@isep.ipp.pt

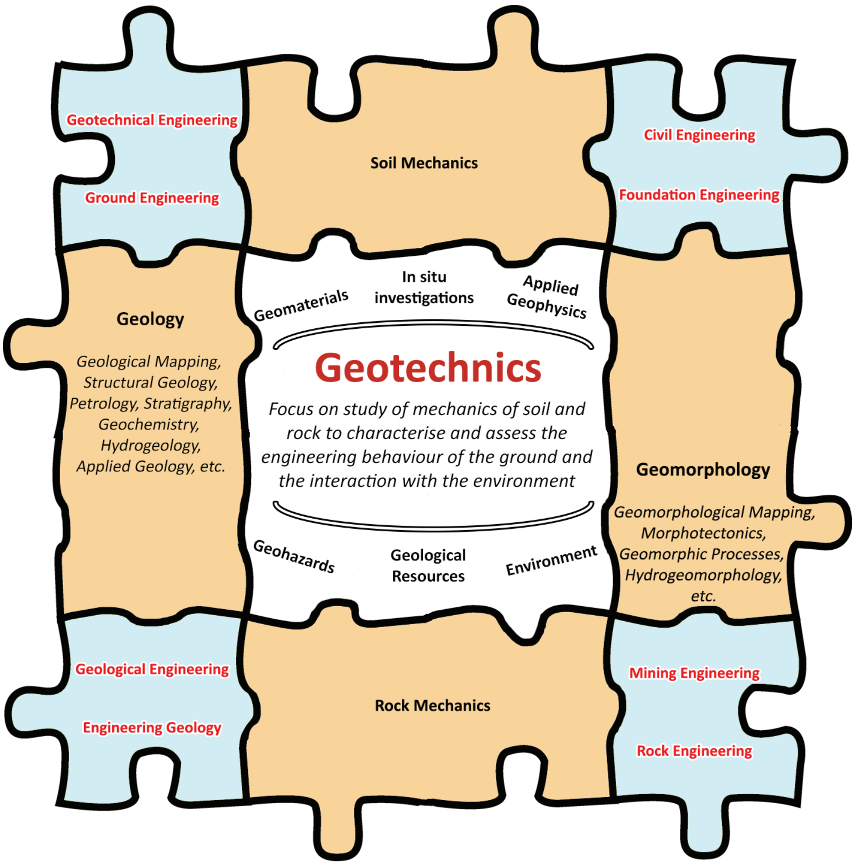


Figure 1: A modern overview of Geotechnics: major scientific areas – geosciences (geology and geomorphology), soil mechanics and rock mechanics – and practitioners.

as well as in exploitation and management of geological resources and environmental issues (***Fig. 2***). In short, all geotechnical practitioners aim to contribute to the correct study of the ground behaviour of soil and rock, its applications in sustainable design with nature and environment (McHarg, 1992) and to the development of society (De Freitas, 2009).

Understanding the complexity of Earth systems is possible through the use of ground models (Griffiths and Stokes, 2008). Thus, a typical site characterisation should be outlined based on Earth systems analysis which form the core for building models to create scenarios using different approaches (e.g., Hudson and Cosgrove, 1997; Griffiths and Stokes, 2008; Keaton, 2013 and references therein), such as: i) ***ground models*** (geologic and/or geomorphological models with engineering parameters); ii) ***geotechnical models*** (ground models with predicted performance based on design parameters); iii) ***geomechanical models*** (geotechnical models based on mathematical modelling (i.e., probabilistic, deterministic or stochastic). All the models must be robust, calibrated and supported on a permanent back-analysis scale based on a logical understanding of the real ground behaviour (Dinis da Gama, 1983). Particularly, rock engineering deals with jointed/faulted anisotropic material and fluid-bearing media, the so-called rock mass (Barton, 2012). The rock engineer must be able to predict the consequences of a particular excavation design. In addition, incomplete or inaccurate geologic and geotechnical site characterisation can lead to the selection of unsuitable models, geotechnical properties, and design values (Terzaghi, 1965; Griffiths and Stokes, 2008; Keaton, 2013; Dinis da Gama, 2013).

The potential for geology to support engineering occurs at every scale, from regional geological structures to molecules found on mineral surfaces and in the fluids passing over them (De Freitas, 2009; Price, 2009). However, the input of geological data for engineering purposes is only adequate if it is supported by the appropriate rock property values (Zhang, 2005 and references therein). The assessment based on engineering geosciences, geohydraulic and geotechnical features of rock masses involves combining parameters to derive quantitative geomechanical classifications for rock engineering design purposes (Barton, 2012, and references therein). Barton (2012) stated that discontinuous behaviour provides rich experience for those who value reality, even when reality has to be simplified by some lessons learned during the development of the empirical parameters.

Rock is a natural material that forms the crust of the Earth (Smith *et al.*, 2001). Rocks are formed in an continuous geodynamic cycle (involving numerous internal and external processes) throughout the geological time, that result for engineering purposes (e.g., Price, 2009; De Freitas, 2009) in ***hard rocks*** (unweathered, strong and durable), ***soft rocks*** (weak and easily

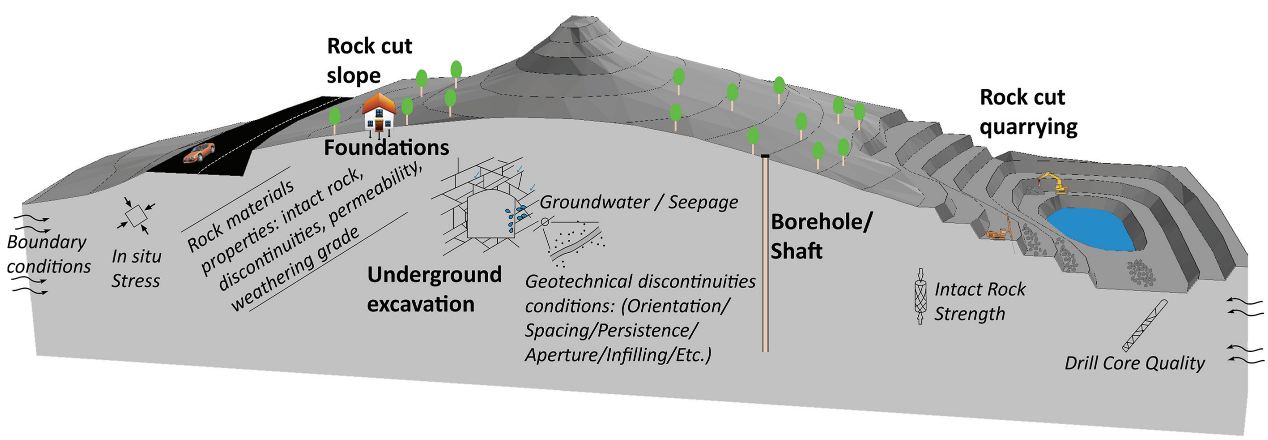


Figure 2: Typical rock engineering works and related ground behaviour.

deformable) and ***soils*** (unconsolidated sedimentary deposits overlying bedrock) (***Fig. 3***). Nevertheless, it does not cover the earthy materials forming the ground in which plants can grow ("soil" in a pedological sense; Smith *et al.*, 2001). Rocks may be surveyed in several backgrounds: i) at the surface and subsurface (outcrops, cliffs, quarries, etc.), ii) underground (tunnels, mines, boreholes).

Since the dawn of civilization, rock has been used as a construction material. Diverse constructions and structures have been built on, in or of rock, including houses, bridges, dams, tunnels and caverns (Zhang, 2005), as shown in ***Table 1***. Particularly, crushed rock aggregates are fundamental to the man-made environment and represent a large proportion of the raw material produced by the quarrying industries and used in construction (Smith *et al.*, 2001).

Rock engineers deal with large volumes of rock which will contain variable amounts of fluid in their network discontinuities, such as joints, fractures, faults, sedimentary or tectonometamorphic surfaces (bedding planes, schistosity, shear zones, folds, etc.) and vein structures. These natural rock structures render the fabric of the rock mass discontinuous (Zhang, 2005; Price, 2009). The general term "discontinuity" in rock engineering refers to any break in the rock continuum having little or no tensile strength (Hudson and Cosgrove, 1997). Intact rock refers to the unfractured blocks (ranging from a few millimetres to several metres in size) between discontinuities in a typical rock mass (Zhang, 2005).

According to Hudson and Cosgrove (1997) providing a clear structural geology framework is a key requirement for the investigation of all rock engineering projects. The geological structures of rock masses (discontinuities, *sensu lato*) significantly influence their hydrogeomechanical properties, such as permeability, cohesion, roughness, aperture and in situ stress. It is thus the structure, at several scales, of the geomaterials that controls the engineering behaviour of the ground. For this reason, it is fundamental in the mapping of rock exposures, whether outcrops, road and railway cuttings, underground excavations or quarry exploitations to collect discontinuity data. Conclusively, the success of a given construction or excavation is related to the accurate knowledge of the general framework of site investigations, particularly that associated with the geology and geomorphology of the studied area (Griffiths, 2002, and references therein). In that perspective, mapping (general or sketch maps, geological maps, engineering geology maps and geotechnical maps, at diverse scales) assumes a critical importance in further stages of geotechnical investigations and modelling. It is also important to emphasise also the value and cost-effectiveness of mapping for geoengineering, georesources and planning purposes compared with other activities (Griffiths, 2002; Price, 2009). Thus, mapping plays a central role as a standard technique in engineering geosciences for in situ geotechnical investigations, ground

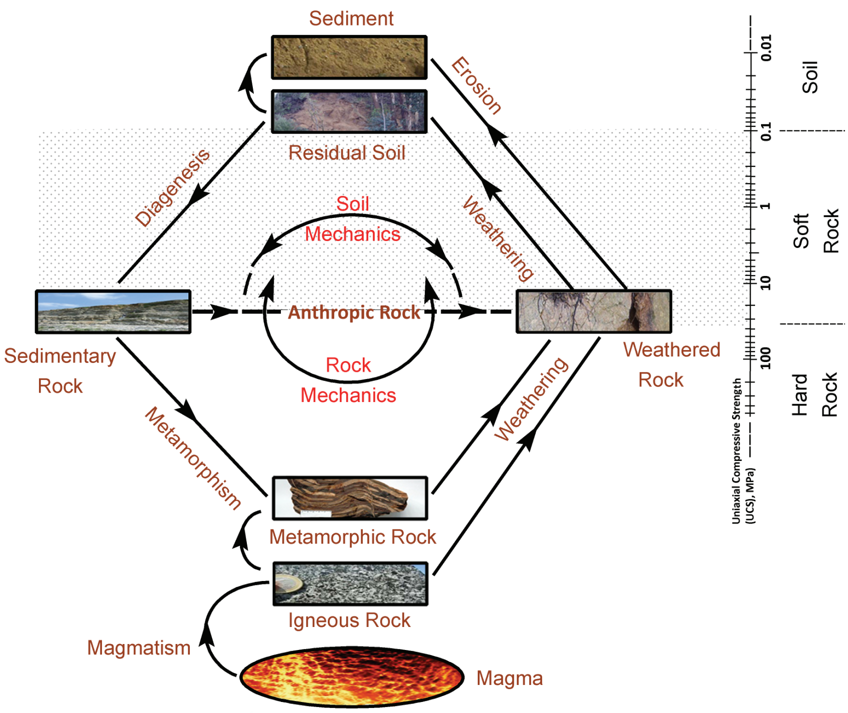
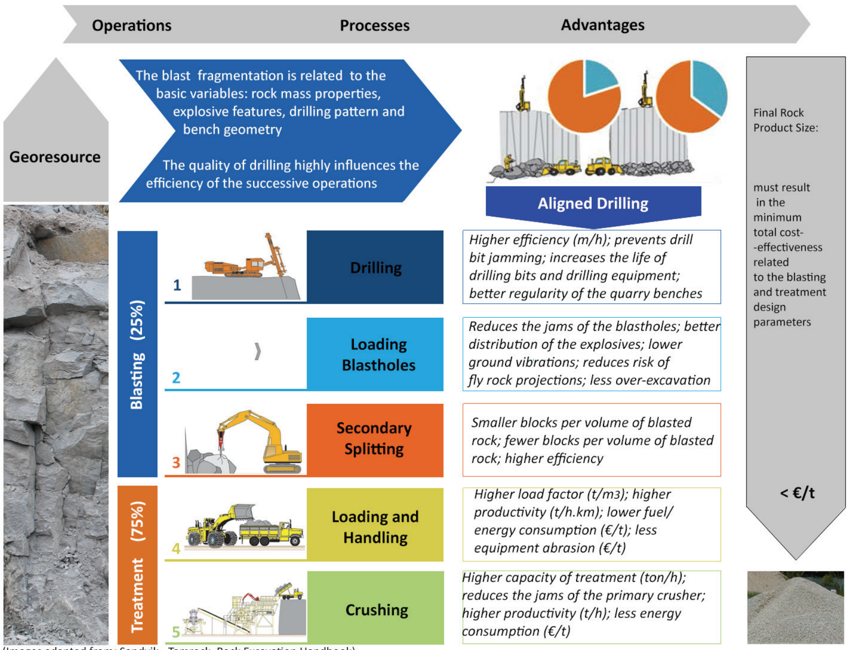


Figure 3: The rock cycle in the perspective of the engineering geosciences framework: an outlook for rock mechanics and soil mechanics issues (adapted from Dobereiner and De Freitas, 1986). Anthropic rocks is a collective term for those rocks made, modified or moved by humans (Underwood, 2001).

Table 1: Main types of structures built on, in or of rock (adapted from Brown, 1993; in Zhang, 2005).

Field of application	*Types of structures*
Mining	*Surface mining (rock slope stability and/or excavation; rock mass diggability; drilling and blasting; quarrying fragmentation);* *Underground mining (shaft, pillar, draft and stope design; drilling and blasting; fragmentation; cavability of rock and/or ore; amelioration of rockbursts; mechanized excavation; in situ recovery)*
Energy	*Underground power stations (hydroelectric and nuclear); underground storage of oil and gas; energy storage (pumped storage or compressed air storage); dam foundations; pressure tunnels; underground repositories for nuclear waste disposal; geothermal energy exploitation; petroleum development including drilling, hydraulic fracturing, wellbore stability*
Transportation	*Highway and railway slopes; tunnels and bridge foundations; canals and waterways; urban rapid transport tunnels and stations; pipelines*
Utilities and Environment	*Dam foundations; stability of reservoir slopes; water supply tunnels; sanitation tunnels; industrial and municipal waste treatment plants; underground storages and sporting and cultural facilities; foundations of surface power stations*
Building construction	*Foundations; stability of deep open excavations; underground or earth-sheltered homes and offices*
Military	*Large underground chambers for civil defense and military installations; deep basing of strategic missiles*



(Images adapted from: Sandvik - Tamrock, Rock Excavation Handbook)

Figure 4: Illustration of the blasting and treatment processes of rock quarrying development for raw material aggregates: a general overview.

modelling, geological resources assessment, and military works and operations (e.g., Kiersch, 1998; Smith *et al.*, 2001; Griffiths, 2002; Griffiths and Stokes, 2008; De Freitas, 2009). Despite the accuracy of field survey and mapping for engineering purposes, Price (2009) stated several important issues: i) it must never be forgotten to produce engineering maps that are of immediate use to the engineer; ii) maps must be 'user friendly', easily understood and easily read; iii) mapping for rock quarry engineering purposes requires large scale maps (detailed surveys: ranging 1:50 to 1:250; general framework: 1:1000 to 1:10000).

Geographic Information System (GIS) techniques have brought new insights to cartography, particularly to geosciences mapping. GIS techniques, supported by high-resolution Global Positioning Systems (GPS), permit large amounts of data from the field survey and rocks sample testing to be overlaid. GIS-based mapping is also useful in providing accurate thematic maps, spatial data analysis and data geovisualisation aiming, for example, at the assessment of discontinuous rock mass systems.

In this article GIS-based mapping was produced to highlight the importance of the geotechnical zoning map as an excellent tool to support rock mass quarrying investigations and development. The fractured hard-rock masses assessment was enhanced by this integrated approach and should contribute to sustainability management.

Selected site: coupling engineering geosciences mapping and mining geotechnics

The strength of jointed rock masses is influenced by the degree of interlocking between individual rock blocks separated by discontinuities such as faults and joints. Drilling is one of the operations involved in rock mass fragmentation by blasting. Dinis da Gama (1983) demonstrates that in full-scale bench blasts, less energy is required to fragment a discontinuous rock than a homogeneous rock.

Correctly performed rock blasting produces very clean faces with a minimum of over-break and disturbance. Rock drilling assumes an important role in technical and cost-effectiveness issues, as well as in the subsequent operations such as loading, handling, splitting and crushing (Singh, 2000). Rock mass blasting involves three groups of parameters (e.g., Dinis da Gama, 1983; Singh, 2000; Smith *et al.*, 2001; Dinis da Gama, 2013): i) petrophysical, geotechnical and geomechanical patterns of the rock fabric and intact rock; ii) top hammer and bench drilling tools; iii) blast design.

It is quite challenging to comprehend how structural geology, geotechnical and rock mechanics features and parameters interact among themselves. In addition, we must take into consideration all of the equipment, technologies, models and brands of drilling tools and different methodologies, as well as the overall cost-effectiveness of the processes involved. The aim for rock cut quarrying is to produce an aligned drilling that permits blasting with enhanced rock fragmentation, lower vibrations and optimisation of drilling and explosive quantity. The global costs of the main operations involved in the quarry industry are not equally distributed (***Fig. 4***). Treatment is the last operation of a global process related to exploitation of the rock georesources, which represents over 75% of the total costs. However, its effectiveness depends on the global quality of the earliest operations to reach high productivity of the entire process.

A comprehensive integrated study of georesources was carried out at a selected site in NW Portugal. The study coupled GIS-based mapping with assessments of structural geology, engineering geology and rock mechanics. Thematic maps were prepared from multi-source geodata, namely remote sensing, topographic, morphotectonic and geological mapping, as well as geotechnical field surveys. These maps were converted to GIS format and then integrated with the purpose of elaborating a geotechnical zoning map intended to support the georesource conceptual site model and further stages on blasting engineering. The basic techniques of mapping, engineering geosciences and rock mechanics (e.g., Griffiths, 2002; Price, 2009, and references therein) were applied at the study site ((***Fig. 5***).

In the first stage a field survey was conducted in order to define the main geological and morphotectonical constraints of the rock mass in the quarry site and nearby area. This assessment focussed on several features, such as: i) regional and local geology and morphostructure, ii) lithological description; iii) mapping of macro and mesostructures; iv) identification of the weathering areas and mapping of their thickness; v) location of the seepage and hydrological constraints. In the next stage, a detailed geotechnical description of the rock mass was made and in situ geomechanical testing was performed (particularly the Schmidt Hammer and Point Load Test). This integrative approach allowed the basic description of rock masses and established an engineering geosciences zoning map (following particularly the recommendations of several organisations: ISRM – International Society for Rock Mechanics, CFCFF – Committee on Fracture Characterization and Fluid Flow, GSE – Geological Society Engineering Group Working Party and IAEG – International Association for Engineering Geology and the Environment). The scanline sampling technique was applied to the study of free rock mass faces on different benches to characterise the rock mass discontinuities and to define the in situ block size. The structural geology data collected at the site were analysed with stereonets and rose diagrams. The scanline technique involves laying a tape along the length of an outcrop or exposure. This approach was also supported by: i) geo-referenced data using a high-precision GPS for the fieldwork survey, ii) the use of geo-calculator applications (particularly, *"GeoTech|CalcTools"* and *"MGC-RocDesign|Calc"*) to support the analysis, design and modelling, iii) GIS-based mapping and application tools.

Monte do Fojo rock quarry site (Paredes de Coura, NW Portugal)

The selected study site, Monte do Fojo granitic rock quarry (NW Portugal, Iberian Peninsula), is located in the vicinity of regional fault zones (e.g., the Vigo – Vila Nova de Cerveira – Régua fault zone). Monte do Fojo quarry is found NE of Ferreira and Vale parishes (the village of Paredes de Coura), (***Fig. 6***). The geology comprises crystalline fractured bedrock of a deformed Palaeozoic metasedimentary rocks and Variscan granites. There are some prevailing tectonic lineaments (NE-SW and NNE-SSW to N-S). The granitic basement is also crosscut by aplite-pegmatite veins and sills. Locally, the geomorphology is characterised by steep slopes and entrenched valleys.

The main activity in the Monte do Fojo quarry is the extraction, treatment and production of crushed rock aggregates for the civil engineering industry. The quarry area is over 7 ha, including also the strategic reserves and the equipment compounds. The extraction site occurs in an open pit, and the blasting is headed northwest, with 5-m-high benches.

The Monte do Fojo rock-mass comprises two-mica granite, which is medium to fine grained, and yellowish to grey colour.

The rocks exposed in the quarry face range from fresh to slightly weathered rock (W_{1-2}). Moderately (W_3) to highly weathered (W_4) outcrops are observed on surrounding upper slopes. The granitic rock mass is crossed by joint sets with NNE-SSW to NE-SE, NW-SE, ENE-WSW orientations. Discontinuity surface conditions can be summarised as the : i) fracture intercept (F) being mainly wide to moderate spacing (F_2 to F_3); ii) the aperture varies from open to closed, iii) the persistence is low to moderate; iv) there is the presence of soft clay and gouge infillings; v) surfaces are plane to undulating and with a low roughness; vi) rock uniaxial compressive strength is moderate to high (S_3 to S_2); vii) and the Geological Strength Index (GSI), based on rock structure versus discontinuity surface condition, ranges from 75-65 for the rock quarry area exposure (i.e., blocky to very blocky, interlocked partially disturbed rock mass consisting of cubical to multifaceted angular blocks, formed mainly by orthogonal discontinuity sets and random fractures; which is compatible with rock blasting techniques). The possibility of integrating these geo-databases into a dynamic GIS allowed the definition of different scenarios and approaches to be evaluated, which have culminated in the geotechnical zoning map of the Monte do

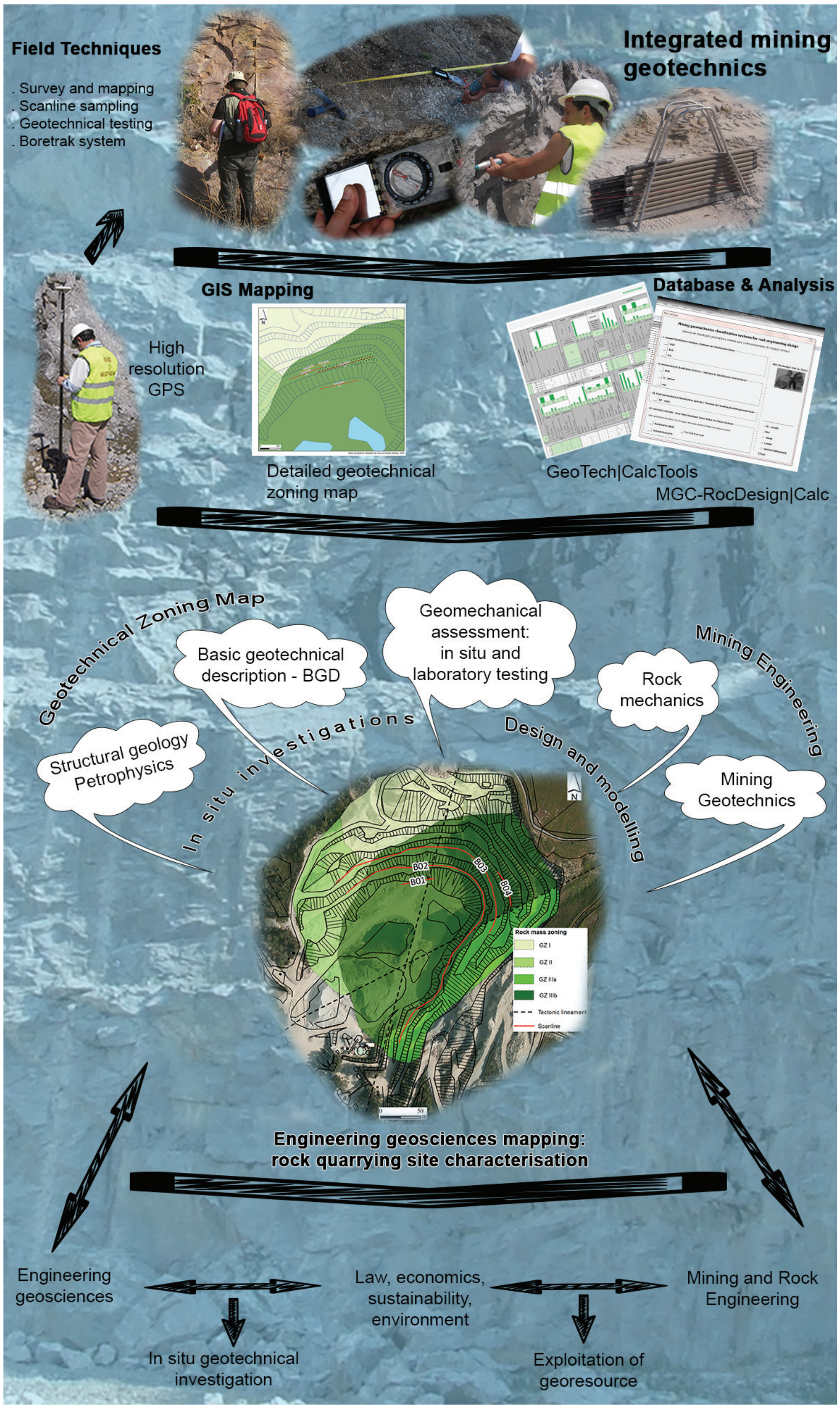


Figure 5: Engineering geosciences mapping on rock quarrying site activities: a general outlook on an integrated georesources exploitation framework ("GeoTech|CalcTools – Rock Mass Database"* by L. Ramos, L. Fonseca, A.C. Galiza and H.I. Chaminé; and* "MGC-RocDesign|Calc – Mining Geomechanics Classification systems for rock engineering design"*, by R. Pinheiro and H.I. Chaminé]).*

Fojo quarry site. Therefore, geotechnical units for the rock quarry site and surrounding area were defined as shown in ***Figure 6***. In short, integrative studies offer a reliable multi-scale approach for investigating the on-site mining geotechnics. Thus, this methodology has proven to be highly valuable for a better understanding of the overall georesources system.

Concluding remarks

Mapping has widespread applications, such as military operations, oil industry, mining engineering, geotechnical engineering, engineering geosciences, environment, and planning. This paper has focused on the importance of coupling engineering geosciences mapping and mining geotechnics to site characterisation for rock quarrying design and modelling. Quarrying activities are the key source for the extraction of aggregates for construction projects. Aggregates are used in concrete, asphalt, mortar, railway ballast, drainage courses and bulk fill. Blasting processes affect the productivity and efficiency of quarrying. Blasting design depends on many variables, especially on the rock mass properties. Blast performance is influenced by geologic structure, rock fabric and intact rock strength. In mining geotechnical practice it is recognised that rocks are normally heterogeneous. The geometry of the discontinuities, intact rock fabric and their geotechnical conditions (e.g., spacing, roughness, aperture, infilling, seepage, etc.) are some of the factors that have a major effect on blasting. The assessment of blast fragmentation required the consideration of some basic variables, i.e. rock mass properties, explosive properties, drilling pattern and bench geometry.

The integrative approach presented in this paper contributes to a better definition of rock quarrying design parameters, and these play a key role in economic excavation, the development of sustainable mineral production, and the supply of raw aggregates. Professor Ralph B. Peck summarised that perspective in an unusual way: *"if you can't reduce a difficult engineering problem to just one sheet of paper, you will probably never understand it"* (DiBiagio and Flaate, 2000: 28). This impressive quotation must be the motto for any geoengineering approach.

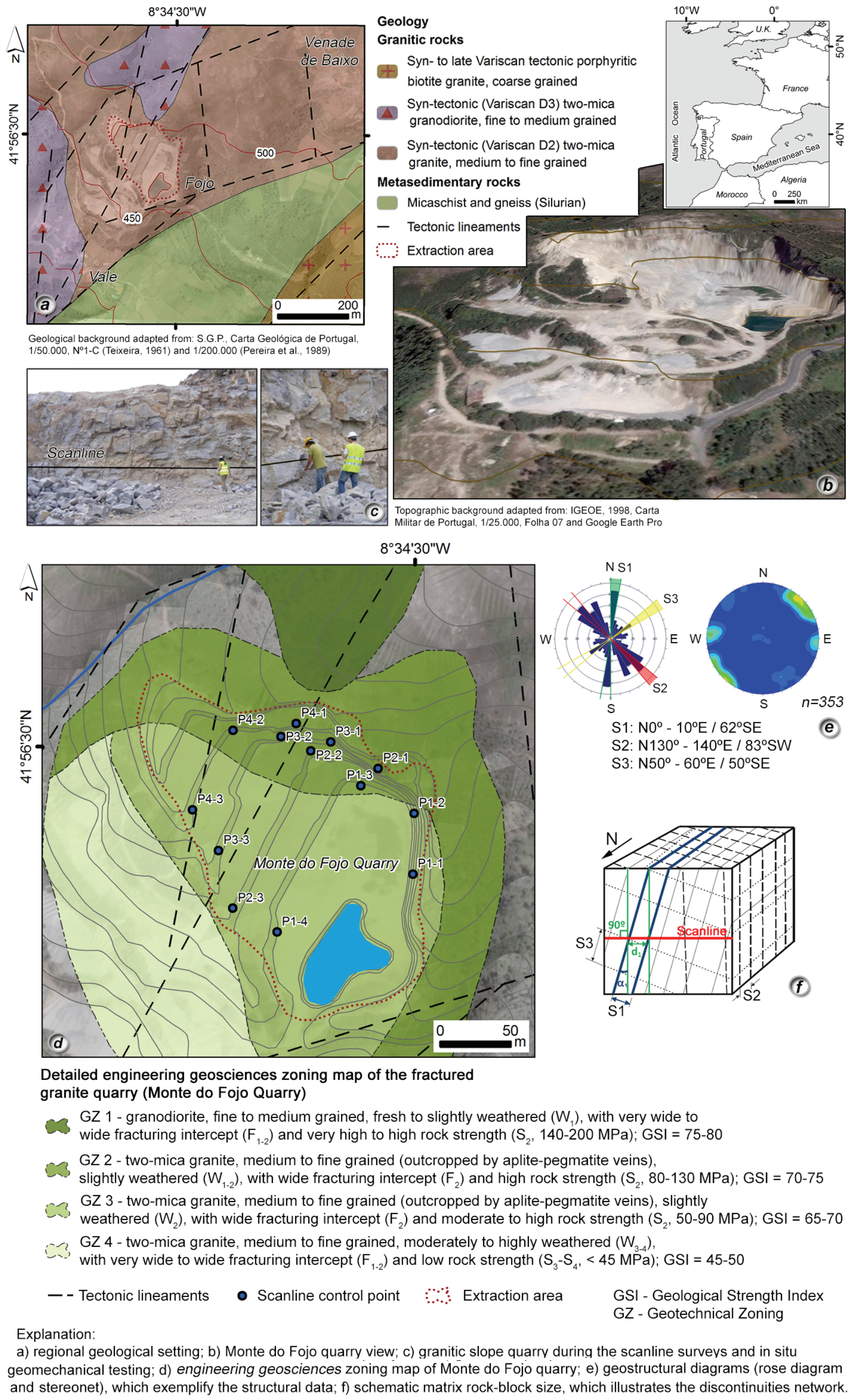


Figure 6: Monte do Fojo granitic quarry site (Paredes de Coura, NW Portugal) framework: an example of engineering geosciences site mapping.

Acknowledgements

This study was performed under the scope of the LABCARGA|ISEP re-equipment program (IPP-ISEP| PAD'2007/08) and Centre GeoBioTec|UA (PEst-C/CTE/UI4035). Special thanks are due to F. Convié and R. Fernández-Rubio for kindly reviewing the French and Spanish version of the abstract, respectively. We acknowledge MonteAdriano: Agregados SA (Elevo group) for all support. The authors would like to thank the reviewer for their helpful comments and inputs to improve the manuscript. The present paper is dedicated to leading Portuguese mining engineers Prof. F. Mello Mendes (UL), Prof. J.A. Simões Cortez (UP) and Prof. C. Dinis da Gama (UL), and structural geologists Prof. F. Sodré Borges (UP), Prof. A. Ribeiro (UL) and Prof. L.C. Gama Pereira (UC), who promote the accurate use of the geosciences in site investigations in rock engineering and structural geology practice.

References

Barton, N. 2012. From empiricism, through theory, to problem solving in rock engineering: a shortened version of the 6th Müller Lecture. *ISRM News Journal*, 14, pp. 60-66.

De Freitas, M.H. 2009. Geology: its principles, practice and potential for geotechnics. *Quarterly Journal of Engineering Geology and Hydrogeology*, 42. 397-441. DOI 10.1144/1470-9236/09-014

DiBiagio, E., Flaate, K. 2000. Ralph B. Peck: engineer, educator, a man of judgement. Pub. 207. Norwegian Geotechnical Institute: Oslo.

Dinis da Gama, C. 1983. Use of comminution theory to predict fragmentation of jointed rock mass subjected to blasting. In Holmberg, R., Rustan, A. (eds.), *Proceedings of the First International Symposium on Rock Fragmentation by Blasting.* Balkema, Luleå, Sweden, pp. 563-579.

Dinis da Gama, C. 2013. Easy profit maximization method for open-pit mining. *Journal of Rock Mechanics and Geotechnical Engineering*, 5(5). pp. 350-353. DOI org/10.1016/j.jrmge.2013.07.001

Dobereiner, L., De Freitas, M.H. 1986. Geotechnical properties of weak sandstones. *Géotechnique*, 36(1), pp. 79-94. DOI 10.1680/geot.1986.36.1.79

Smith, M.R., Collis L., Fookes, P.G., Lay, J., Sims, I., West, G. 2001. *Aggregates: Sand, Gravel and Crushed Rock Aggregates for Construction Purposes*. 3rd ed.. Engineering Geology Special Publications, Vol. 17. The Geological Society of London: London.

Griffiths, J.S. 2002. *Mapping in Engineering Geology.* Key Issues in Earth Sciences, Vol. 1. The Geological Society of London: London.

Griffiths, J.S., Stokes, M. 2008. Engineering geomorphological input to ground models: an approach based on earth systems. *Quarterly Journal of Engineering Geology and Hydrogeology*, 41. 73-91. DOI 10.1144/1470-9236/07-010

Hudson, J.A., Cosgrove, J.W. 1997. Integrated structural geology and engineering rock mechanics approach to site characterization. *International Journal of Rock Mechanics and Mining Sciences*, 34(3/4). pp. 136.1-136.15. DOI 10.1016/S1365-1609(97)00018-X

Keaton, J. 2013. Engineering geology: fundamental input or random variable? In Withiam, J.L., Phoon, K.-K., Hussein, M. (eds.), *Foundation Engineering in the Face of Uncertainty: Honoring Fred H. Kulhawy.* ASCE. GSP 229, pp. 232-253. DOI 10.1061/9780784412763.020

Kiersch, G.A. 1998. Engineering geosciences and military operations. *Engineering Geology*, 49(2). 123-176. DOI 10.1016/S0013-7952(97)00080-X

McHarg, I.L. 1992. *Design with Nature.* 25th anniversary edition, Wiley Series in Sustainable Design, John Wiley & Sons: New York.

Price, D.G. 2009. *Engineering Geology: Principles and Practice.* Springer Verlag: Berlin.

Singh, S.P. 2000. New trends in drilling and blasting technology. *International Journal of Surface Mining, Reclamation and Environment*, 14(4). 305-315. DOI 10.1080/13895260008953338

Terzaghi, R.D. 1965. Sources of errors in joint surveys. *Géotechnique*, 15(3). 287-304. DOI 10.1680/geot.1965.15.3.287

Zhang, L. 2005. *Engineering Properties of Rocks.* Elsevier Geo-Engineering Book Series, Vol. 4, Elsevier Science: Berlin.

N° 36 November 2013

European Geologist

Journal of the European Federation of Geologists

Industrial minerals - materials in our everyday life