Journal of Rock Mechanics and Geotechnical Engineering 9 (2017) 364–369

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Full Length Article

Applying rock mass classifications to carbonate rocks for engineering purposes with a new approach using the rock engineering system

Gioacchino Francesco Andriani*, Mario Parise

Dipartimento di Scienze della Terra e Geoambientali, Università degli Studi di Bari Aldo Moro, Via E. Orabona n. 4, Bari 70125, Italy

ARTICLE INFO

Article history:
Received 17 August 2016
Received in revised form
16 November 2016
Accepted 18 December 2016
Available online 19 January 2017

Keywords:
Rock mass classification
Carbonates
Karst
Rock engineering system (RES)

ABSTRACT

Classical rock mass classification systems are not applicable to carbonate rocks, especially when these are affected by karst processes. Their applications to such settings could therefore result in outcomes not representative of the real stress–strain behavior. In this study, we propose a new classification of carbonate rock masses for engineering purposes, by adapting the rock engineering system (RES) method by Hudson for fractured and karstified rock masses, in order to highlight the problems of implementation of geomechanical models to carbonate rocks. This new approach allows a less rigid classification for carbonate rock masses, taking into account the local properties of the outcrops, the site conditions and the type of engineering work as well.

1. Introduction

During the preliminary design stages of a project, information on rock masses, in terms of strength, deformability, in situ stress and hydrologic characteristics, is not greatly detailed, and the rock mass classification system is the most common approach used for solving rock engineering purposes. It is a common practice to use, for any rock engineering application with different boundary conditions and geometries, multi-parameter classification schemes, such as those proposed by Bieniawski (1973, 1974, 1989, 1993) and Barton et al. (1974), without due consideration of the original aims for which these systems were developed, and the engineering geological characteristics of the rock mass as well (Fookes, 1997; Jing, 2003; Andriani and Parise, 2015; Parise et al., 2015a). The majority of the available schemes use a defined number of parameters, to which ranges of value are assigned, based upon in situ surveys, or laboratory and field tests (for instance, attitude, discontinuity conditions, uniaxial compressive strength, and rock quality designation (RQD)). This approach is highly useful to solve many engineering geological problems, but, on the other hand, it is too rigid when dealing with particular situations (e.g. slope instability and foundations), especially when rock masses not exactly responding to the original criteria of the scheme are dealt with. This is certainly the case for carbonate rock masses, which are particularly sensitive to syn-depositional and post-depositional diagenesis, including dissolution and karstification processes, cementation, recrystallization, dolomitization and replacement by other minerals. Furthermore, as sedimentary rocks, carbonate rocks are typically stratified, laminated, folded, faulted and fractured. As a consequence, a carbonate rock mass is characterized by inherently anisotropic properties (physico-mechanical, hydraulic, dynamic, thermal). Anisotropy can be found at different scales in carbonate rocks ranging from intact specimens to the entire rocks. The strength and deformability of carbonate rock masses depend, therefore, on those of the intact blocks and on their freedom of movement which, in turn, are affected by the discontinuities, as well as by their pattern, orientation and infilling. For a complicated case, the development of karst features, showing irregular geometry, has to be added (De Waele and Parise, 2013). Eventually, the scale of the engineering problem determines the choice between a continuum model and a discontinuum model to represent the rock mass behavior at the stage of design analysis. Such a choice is of extreme importance, and should be derived from the knowledge acquired during the engineering geological characterization of the rock mass (Barla and Barla, 2000; Jing and Hudson, 2002; Andriani, 2015).

Due to the presence of karst features, either active or related to paleo-karst, implementation of the main classification schemes to carbonate rock masses has several problems (Fig. 1). Furthermore, other complications are related to the stratigraphic and structural settings, and to lack of a parameter in the classification schemes

* Corresponding author.
E-mail address: gioacchinofrancesco.andriani@uniba.it (G.F. Andriani).
Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

http://dx.doi.org/10.1016/j.jrmge.2016.12.001

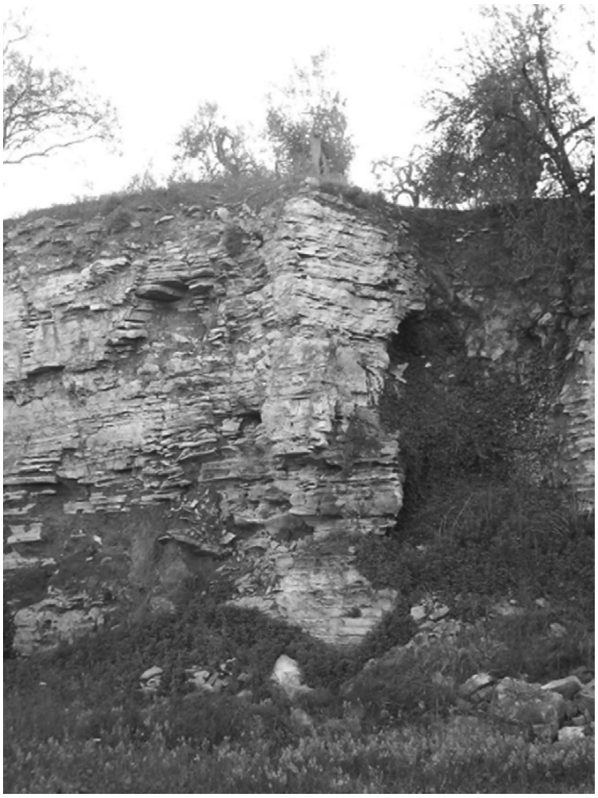

Fig. 1. Quarry wall in thinly bedded Cretaceous limestone, deeply karstified, with sub-horizontal conduits and caves.

which could account for the time effect on the strength and deformability properties of the rock masses (i.e. creep) (Scholtz, 1968; Dusseault and Fordham, 1993; Benardos and Kaliampakos, 2004). Experiences from underground calcarenite quarries have shown that the stability degree of pillars and vaults within the quarries decreases with time, as an effect of creep on the total strength of the rock mass (Bruno et al., 2007; Parise and Lollino, 2011; Lollino et al., 2013; Pepe et al., 2013). This effect is particularly significant in humid or wet sites, and for soft rock mass with high water content (Andriani and Walsh, 2002, 2007, 2010; Ciantia and Hueckel, 2013).

A further problem to be considered is overrating the proneness to instability by classical methods as the rock mass rating (RMR) by Bieniawski or the Q-system by Barton, as an effect of the correction factors of the discontinuity attitude. The same trend, even though less marked, characterizes the slope mass rating (Romana, 1985), derived from the original RMR. An interesting possibility, alternative to the classical methods, is the rock engineering system (RES) (Hudson, 1992). RES focuses upon the objective: this means that elements and interactions to consider may be adapted to the setting, the aim of the study, and the goal of the project. At the same time, the details needed to characterize the system, its elements and interactions, may change, too. RES so far has been successfully applied in several fields, including slope stability (Mazzoccola and Hudson, 1996; Calcaterra et al., 2004; de Luca Tupputi Schinosa, 2008; Andriani et al., 2009).

In this paper, we present an adaptation of RES to the classification of carbonate rock mass in karst environments. The approach aims at defining a practical model for simulating the behavior of karstified rock masses for engineering purposes, with particular regard to stability analyses of natural and man-made walls in carbonate rocks.

2. Methodology

The RES approach was first introduced by Hudson (1992) for the analysis of complex engineering problems in rock mechanics applications, including the stability of natural and artificial slopes, tunnels, underground quarries and caves (Mazzoccola and Hudson, 1996; Andrieux and Hadjigeorgiou, 2008; Budetta et al., 2008; Naghadhei et al., 2011; Palma et al., 2012a,b; Rafiee, 2014).

The approach is inspired to the general theory of the systems by von Bertalanffy (1950, 1968), according to which a system is defined as “a complex of elements in interaction”, and later by Hall and Fagen (1956), according to which a system is “a set of objects together with relations between the objects and their attributes”, where the objects are the components or parts of the system, the attributes are the properties of the objects, and the relationships “tie the systems together”.

The first application of the systematic model in geomorphology dates back to Strahler (1980). Hudson and Harrison (1992) considered that in rock mechanics modeling and rock engineering design for a specific project, it is necessary to consider not only the individual parameter of the system but also how these parameters all interact together. At this goal, identification of all the relevant parameters of the system, corresponding to the physical variables, and the linking mechanisms are important, and their combined operation has to be considered. In practice, a general understanding of a rock engineering problem includes not only the primary mechanisms and factors, but also the interactions between them.

Although the RES approach is general and widely applicable, in each location and for each specific purpose, the description of the rock mass is fitted to the physical reality and to the engineering problem.

The RES approach is a systematic method in which the interactions between the various parameters of the system are listed in a matrix. The principal parameters considered relevant to the problem are listed along the leading diagonal of a square matrix (top left to bottom right) and the interactions between pairs of principal factors form the off-diagonal terms. The interaction between the parameters is then analyzed with a clockwise influencing convention. Generally, the influence of a parameter on the other is different, which means that the matrix is, in general, asymmetrical. This asymmetry is associated with the fact that the interaction depends on the path. The assigned values to off-diagonals are called “coding the matrix”. Several methods have been developed for numerically coding the interaction matrix, such as the 0–1 binary, expert semi-quantitative (ESQ) method (Hudson, 1992) and the continuous quantitative coding (CQC) method (Lu and Latham, 1994). The most common coding method is the ESQ in which only one value is deterministically assigned to each interaction. Therefore, it is implicitly considered that there are no uncertainties when the influence of one parameter on the others is expressed in the matrix. Typically, the following coding values between 0 and 4 are employed with ESQ coding schemes: no, 0; weak, 2; medium, 3; strong, 4; and critical, 5. However, such coding values are not always constant and/or certain, depending on the type of problem. In other words, it is always possible that the coding value needs to be updated and/or modified under the specific conditions of a project, and, in many cases, it is also possible that an exact (and unique) digit-code cannot express the correct particular interaction. This could be due, for instance, to uncertainties in the assignment of values or even due to uncertainties on the physics of the problem (Naghadhei et al., 2011).

The main parameters (P_i) were listed along the leading diagonal of the matrix, as highlighted in Fig. 2. The row passing through P_i represents the influence of P_i on all the other parameters in the

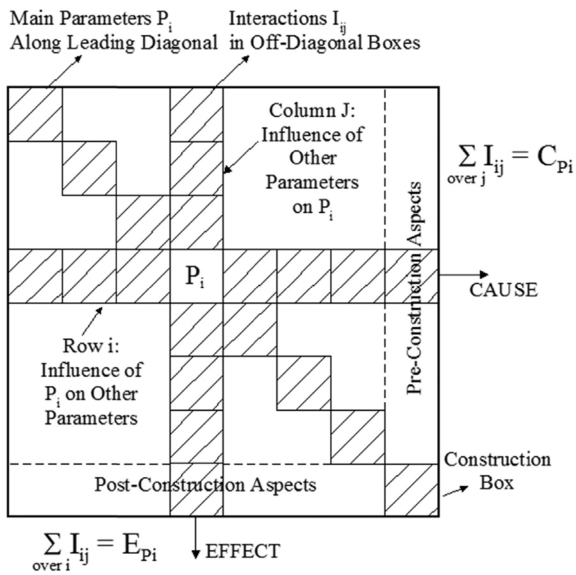

Fig. 2. Summation of coding values in the row and column through each parameter to establish the cause and effect coordinates (modified after Hudson, 1992).

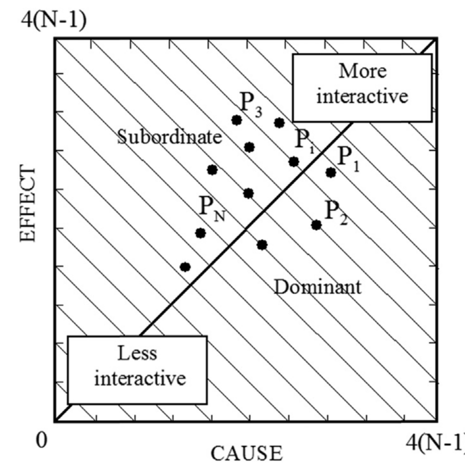

Fig. 3. Cause–effect plot for the leading diagonal parameters of a system.

system. Conversely, the column through P_i represents the influence of the other parameters, which is the rest of the system, on P_i. Once the matrix is coded approximately, the sum of each row and each column is found. The sum of the row values is the *cause* and that of the column is the *effect*, designated as coordinates (C, E). Thus, C represents the way in which P affects the system and E represents the effect that the system has on P.

The interactive intensity value of each parameter is denoted as the sum of the C and E values ($C + E$), and it is used as an indicator of the parameter significance in the system. The $C - E$ value (*dominance*) represents how dominant the parameter is within the system. A positive value of $C - E$ is representative of a *dominant* parameter, which means it affects the system to a greater extent than the system affects the parameter. A negative value represents a subordinate parameter, meaning that the system affects the parameter more than the parameter affects the system.

The percentage value of $C + E$ is used as the parameter weighting factor, as shown in the following equation:

$$a_i = \frac{C_i + E_i}{\sum_i C_i + \sum_i E_i} \times 100 \tag{1}$$

The coordinate values for each parameter can be plotted in cause and effect space, forming the so-called *cause–effect* plot or more simply C–E plot (Fig. 3). Conventionally, the causes are given on the x-axis and the effects on the y-axis. The length of both axes is limited to $4(N - 1)$, where 4 is the maximum value that the cause or the effect of a parameter may assume, and N is the number of parameters considered. The diagonal line with equation $C = E$ ($C = E$ line) represents the locus of points in which all the parameters have equal dominance/subordination; the dominant parameters, $C > E$, plot to the right of the $C = E$ line while the subordinate parameters, $C < E$, plot to the left of the $C = E$ line. With such a plot, it is therefore possible to recognize which parameter plays an important role in influencing the system.

In the second step, once the coding matrix has been built, it is necessary to assign a numerical value, or rating, indicated by "V", to all the considered parameters, on the basis of their weight on the instability of the system. The quantification of the parameters is very important, allowing to put both the quantitative and qualitative parameters at the same level of analysis, associating a numerical value with the latter. The assessment of the influence of the parameters on the instability of the system is based on the expert evaluation approach and is calibrated by morphological analysis, morpho-evolution models, geomechanical surveys and geotechnical laboratory results. Thus, for each parameter, 3 classes of rating are set: 0 for low contribution, 1 for medium contribution, and 2 for strong contribution.

In the final step, the rock mass instability index (RMII) is calculated for each slope or quarry wall, assuming that all parameters contribute to instability with different weights. Higher values of RMII indicate higher degrees of slope instability. RMII is calculated through the following equation (Mazzoccola, 1992; Mazzoccola and Hudson, 1996; Ali and Hasan, 2002):

$$RMII_j = \sum_{i=1}^{N} (a_i V_{ji}) \tag{2}$$

where i refers to parameters (from 1 to N), j refers to slopes or quarry walls (e.g. for an open pit quarry, the analysis can be carried out for each wall or for homogeneous sectors, in the case that the geological and environmental conditions are locally different), a_i refers to the interactive intensity for each parameter, and V_{ji} is the rating assigned to different classes of parameter values (it is different for each j slope or wall).

In each site, for the purpose of the verification of the methodology and results, the procedure has to be applied to both stable and unstable slopes. This allows to define the class-limits among stable, partially stable and unstable slopes, and to associate a correct approach with modeling carbonate rock masses, based upon the outcomes of the geostructural and geomechanical analyses, including the assessment of the potential failures and typologies of movement.

In many natural and artificial slopes in karst terrains, the stability analysis is very complex, due to difficulties in accessing data, because of logistic constraints, impossibility to carry out laboratory tests on representative specimens, and the high number of interacting factors. For such complexity, the sequence of the critical rock parameters could be determined first, by combining qualitative and quantitative data from in situ surveys and laboratory geotechnical tests, integrated with evaluation of natural (seismic, hydrological, presence of vegetation) and human-induced variables controlling slope instability; secondly, by applying a hierarchical screening procedure of the parameters, also based upon the ratings obtained from other rock classification systems (e.g. Bieniawski and Barton classification schemes). The high spatial variability of carbonate slopes might suggest to geologists the subdivision of the study area in sectors based above all on morphological and geological criteria, before performing the analysis of those parameters considered significant to the problem.

The relevant parameters in karst environment (indicated in italics in the following) can be grouped into the following categories:

(1) *Geology*: expresses the rock types (*lithology*), including the thickness ratio of the lithological units cropping out on the quarry walls or slopes (e.g. calcarenites, limestones, and dolostones), structural characters (*fractures and faults, folds, number of sets, orientation, parallelism, aperture, roughness, infilling, spacing, persistence and extent*) and hydraulic conditions, including the presence of water and the rock mass characteristics which control water flow (*degree of saturation, permeability, drainage paths*). As regards *parallelism* among joints and slope face, the presence of tension cracks at the wall-top edge is considered as the most hazardous condition.
(2) *Morphometry*: refers to quantitative evaluations of *slope inclination, height and width*. The presence of vertical or overhanging walls is considered as the most hazardous condition.
(3) *Intact rock properties*: refer to *unit weight, deformability, strength* and *durability* at the sample scale.
(4) *Rock mass properties*: include *unit weight, deformability* and *strength* based on overall continuum material assumption. If the rock mass is modeled as a discontinuous medium, *block sizes* (Palmstrom, 2005), *strength* and *deformability of discontinuities* have to be determined. For both the approaches (continuum and discontinuum), the degree of weathering and karstification and their influence on potential failure modes (*weathering and karst*) (Fookes and Hawkins, 1988; Parise, 2008, 2011; Gutierrez et al., 2014; Parise et al., 2015b) must be taken into account, as well as the *in situ stress*, including degree of tectonics and disturbance.
(5) *Stability index and failure mechanisms*: refer to the ratio between wall height and its critical height (*stability index*). The estimate of the critical height can be carried out with the lower bound theorem of limit analysis adopting the Mohr-Coulomb failure criterion (Andriani and Pellegrini, 2014). Identification of the more likely failure mechanisms in different sites may be based upon an expert evaluation approach, or/and on the analysis of polar stereographic projections (*failure mechanisms*).
(6) *Previous instabilities*: refer to evidence of *past instabilities*, useful to provide insights on the proneness to instability of the quarry walls or natural slopes.
(7) *Natural hazards*: include *seismicity*, *hydrological events* and presence of *spontaneous vegetation* (e.g. destabilizing effect of shrub and tree roots on the discontinuity network).
(8) *Human factors*: include adjacent blasting, nearby constructions or overloads close to the upper boundary of the quarry face (*human hazards*) and *reinforcement* such as wire meshes and bolts.

It has to be noted that not all the parameters have to be considered as leading diagonal terms within a case study. Therefore, a flexible implementation of the method derives, which should be adapted to the peculiar features of the carbonate rock mass, as a function of the local properties of the outcrops and the site condition for specific engineering geological problems.

3. Conclusions

Rock mass classifications represent undoubtedly a helpful tool for planning and design in engineering applications, but they should be carefully used, with due consideration of the limits and applicability in each geological setting, and in relation to different engineering geological problems. The classical schemes are often difficult to be applied, and might result in providing not useful outcomes, especially where the geological and stratigraphic features of the site are quite far from those for which the classification systems were developed.

It is not by chance that systematic approaches to assess the heterogeneity of rock masses and incorporation of the variability into the design process have yet to gain wide acceptance in the rock engineering community.

In the case of karstified carbonate rock masses, the high complexity makes not applicable the general classifications, due to impossibility to represent the effect of the karst features on the quality of the rock mass. In such settings, there is therefore the need to use more adaptable methods, able to provide a semi-quantitative analysis for the parameters that are considered to be significant, in function of the available data and, most important, of the specific peculiarities of each case study. Fragility of karst and high vulnerability of the natural resources therein contained represents peculiar characteristics that are worth to be faced by means of approaches specifically dedicated to karst, which have necessarily to take into account the presence of typical landforms (caves of variable size, conduits, swallow holes, etc.), and their variable functionality as well. In this contribution, we made a first attempt in pointing out such need and working in the above indicated direction, and aimed at contributing to creating methodologies and tools which could be effectively used in karst settings.

Conflict of interest

We wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Acknowledgments

Many thanks are due to the anonymous reviewers for useful comments and suggestions. This research was supported by MIUR (Italian Ministry of Education, University and Research Grant 15034/2007) under Grant 2010 ex MURST 60% “Modelli geologico-tecnici, idrogeologici e geofisici per la tutela e la valorizzazione delle risorse naturali, ambientali e culturali” (coordinator G.F. Andriani) and Grant 2013 ex MURST 60% “Ricerche stratigrafico-sedimentologiche di base ed applicate per il riconoscimento, la gestione e la tutela delle georisorse e dei beni storico/culturali e geoambientali” (coordinator M. Tropeano). Work carried out within the framework of the project Interreg III A-“WET SYS B” 200-2006 (responsible G.F. Andriani), with the financial contribution by the European Community.

References

Ali KM, Hasan K. Rock mass characterization to indicate slope instability at Bandarban, Bangladesh: a rock engineering systems approach. Environmental and Engineering Geoscience 2002;8(2):105–19.
Andriani GF, Bruno G, Calcaterra D, Cherubini C, De Luca Tupputi Schinosa F, Parise M, Vessia G, Walsh N. Applicabilità dei sistemi di classificazione geomeccanica agli ammassi rocciosi carbonatici. Rendiconti Online della Società Geologica Italiana 2009;6:13–4 (in Italian).
Andriani GF, Parise M. On the applicability of geomechanical models for carbonate rock masses interested by karst processes. Environmental Earth Sciences 2015;74(12):7813–21.

Andriani GF, Pellegrini V. Qualitative assessment of the cliff instability susceptibility at a given scale with a new multidirectional method. International Journal of Geology 2014;8:73–80.
Andriani GF, Walsh N. Petrophysical and mechanical properties of soft and porous building rocks used in Apulian monuments (south Italy). Geological Society of London, Special Publications 2010;333:129–41.
Andriani GF, Walsh N. Physical properties and textural parameters of calcarenitic rocks: qualitative and quantitative evaluations. Engineering Geology 2002;67(1–2):5–15.
Andriani GF, Walsh N. The effects of wetting and drying, and marine salt crystallization on calcarenite rocks used as building material in historic monuments. Geological Society of London, Special Publications 2007;271:179–88.
Andriani GF. Uso proprio e improprio dei criteri di resistenza degli ammassi rocciosi. Geologi e Territorio 2015;1:17–22 (in Italian).
Andrieux P, Hadjigeorgiou J. The destressability index methodology for the assessment of the likelihood of success of a large-scale confined destress blast in an underground mine pillar. International Journal of Rock Mechanics and Mining Sciences 2008;45(3):407–21.
Barla G, Barla M. Continuum and discontinuum modelling in tunnel engineering. Gallerie e Grandi Opere Sotterranee 2000;61:15–35.
Barton NR, Lien R, Lunde J. Engineering classification of rock masses for the design of tunnel support. Rock Mechanics 1974;6(4):189–239.
Benardos AG, Kaliampakos DC. A methodology for assessing geotechnical hazards for TBM tunneling-illustrated by the Athens Metro, Greece. International Journal of Rock Mechanics and Mining Sciences 2004;41(6):987–99.
Bieniawski ZT. Classification of rock masses for engineering: the RMR system and future trends. In: Hudson JA, editor. Comprehensive rock engineering: principles, practice and projects. Rock testing and site characterization, vol. 3. Oxford: Pergamon; 1993. p. 553–73.
Bieniawski ZT. Engineering classification of jointed rock masses. Civil Engineer in South Africa 1973;15(12):335–44.
Bieniawski ZT. Engineering rock mass classifications. New York: John Wiley and Sons; 1989.
Bieniawski ZT. Geomechanics classification of rock masses and its application in tunnelling. In: Proceedings of the 3rd International Congress on Rock Mechanics; 1974. p. 27–32.
Bruno G, Cherubini C, Vessia G. Affidabilità di pilastri in roccia tenera nelle cave in sotterraneo. In: Proceedings of the Sicurezza nei Sistemi Complessi Congress, Bari; 2007.
Budetta P, Santo A, Vivenzio F. Landslide hazard mapping along the coastline of the Cilento region (Italy) by means of a GIS-based parameter rating approach. Geomorphology 2008;94(3–4):340–52.
Calcaterra D, de Luca Tupputi Schinosa F, Fenelli GB. Rockfall hazard assessment at Mt. San Costanzo (Sorrento Peninsula, Italy). In: Proceedings of the 9th International Symposium on Landslides. Taylor and Francis; 2004. p. 265–71.
Ciantia MO, Hueckel T. Weathering of submerged stressed calcarenites: chemo-mechanical coupling mechanisms. Géotechnique 2013;63(9):768–85.
de Luca Tupputi Schinosa F. La valutazione della stabilità di versanti in roccia: aspetti metodologici ed applicazioni su aree campione del territorio campano [Ph.D. Thesis]. Napoli: University of Naples Federico II; 2008 (in Italian).
De Waele J, Parise M. Discussion on the article “Coastal and inland karst morphologies driven by sea level stands: a GIS based method for their evaluation” by Canora F, Fidelibus D, Spilotro G. Earth Surface Processes and Landforms 2013;38(8):902–7.
Dusseault MB, Fordham CJ. Time-dependent behaviour of rocks. In: Hudson JA, editor. Comprehensive rock engineering: principles, practice and projects. Rock testing and site characterization, vol. 3. Oxford: Pergamon; 1993. p. 119–49.
Fookes PG, Hawkins AB. Limestone weathering: its engineering significance and a proposed classification scheme. Quarterly Journal of Engineering Geology and Hydrogeology 1988;21:7–31.
Fookes PG. Geology for engineers: the geological model, prediction and performance. Quarterly Journal of Engineering Geology and Hydrogeology 1997;30: 293–424.
Gutierrez F, Parise M, De Waele J, Jourde H. A review on natural and human-induced geohazards and impacts in karst. Earth Science Reviews 2014;138:61–88.
Hall AD, Fagen RE. Definition of system. General System 1956;1:18–28.
Hudson JA, Harrison JP. A new approach to studying complete rock engineering problems. Quarterly Journal of Engineering Geology 1992;25:93–105.
Hudson JA. Rock engineering systems: theory and practice. New York: Ellis Horwood; 1992.
Jing L, Hudson JA. Numerical methods in rock mechanics. International Journal of Rock Mechanics and Mining Sciences 2002;39(4):409–27.
Jing L. A review of techniques, advances and outstanding issues in numerical modeling for rock mechanics and rock engineering. International Journal of Rock Mechanics and Mining Sciences 2003;40(3):283–353.
Lollino P, Martimucci V, Parise M. Geological survey and numerical modeling of the potential failure mechanisms of underground caves. Geosystem Engineering 2013;16(1):100–12.
Lu P, Latham JP. A continuous quantitative coding approach to the interaction matrix in rock engineering systems using grey systems theory. In: Proceedings of the 7th International Congress of the International Association of Engineering Geology. A.A. Balkema; 1994. p. 4761–70.
Mazzoccola D, Hudson JA. A comprehensive method of rock mass characterization for indicating natural slope instability. Quarterly Journal of Engineering Geology and Hydrogeology 1996;29:37–56.
Mazzoccola D. Una nuova metodologia classificativa dell'ammasso roccioso per una valutazione preliminare dell'instabilità di versante a grande scala. Geologica Romana 1992;30:185–96 (in Italian).
Naghadhei MZ, Jimenez R, KhaloKakaie R, Jalali SME. A probabilistic systems methodology to analyze the importance of factors affecting the stability of rock slopes. Engineering Geology 2011;118(3–4):82–92.
Palma B, Parise M, Reichenbach P, Guzzetti F. Rock-fall hazard assessment along a road in the Sorrento Peninsula, Campania, southern Italy. Natural Hazards 2012a;61(1):187–201.
Palma B, Ruocco A, Lollino P, Parise M. Analysis of the behaviour of a carbonate rock mass due to tunneling in a karst setting. In: Han KC, Park C, Kim JD, Jeon S, Song JJ, editors. The present and future of rock engineering. Proceedings of the 7th Asian Rock Mechanics Symposium; 2012. p. 772–81.
Palmstrom A. Measurements of and correlations between block size and rock quality designation (RQD). Tunnelling and Underground Space Technology 2005;20(4):362–77.
Parise M, Closson D, Gutierrez F, Stevanovic Z. Anticipating and managing engineering problems in the complex karst environment. Environmental Earth Sciences 2015a;74(12):7823–35.
Parise M, Lollino P. A preliminary analysis of failure mechanisms in karst and man-made underground caves in southern Italy. Geomorphology 2011;134(1–2): 132–43.
Parise M, Ravbar N, Živanovic V, Mikszewski A, Kresic N, Mádl-Szőnyi J, Kukuric N. Hazards in karst and managing water resources quality. In: Karst aquifers – characterization and engineering. Springer; 2015b. p. 601–87.
Parise M. Rock failures in karst. In: Cheng Z, Zhang J, Li Z, Wu F, Ho K, editors. Landslides and engineered slopes; 2008. p. 275–80.
Parise M. Surface and subsurface karst geomorphology in the Murge (Apulia, southern Italy). Acta Carsologica 2011;40(1):79–93.
Pepe P, Pentimone N, Garziano G, Martimucci V, Parise M. Lessons learned from occurrence of sinkholes related to man-made cavities in a town of southern Italy. In: Land L, Doctor DH, Stephenson B, editors. Proceedings of the 13th Multidisciplinary Conference on Sinkholes and the Engineering and Environmental Impacts of Karst. Carlsbad: National Cave and Karst Research Institute; 2013. p. 393–401.
Rafiee R. Development of rock behavior index around underground space using a rock engineering system. Journal of Geology and Mining Research 2014;6(4): 46–56.
Romana M. New adjustment rating for application of the Bieniawski classification to slopes. In: Proceedings of International Symposium on Rock Mechanics for Mining and Civil Works. International Society for Rock Mechanics; 1985. p. 59–63.
Scholtz CH. Mechanism of creep in brittle rock. Journal of Geophysical Research 1968;73(10):3295–302.
Strahler AN. Systems theory in physical geography. Physical Geography 1980;1:1–27.
von Bertalanffy L. An outline of general system theory. British Journal for the Philosophy of Science 1950;1:114–29.
von Bertalanffy L. General system theory: foundations, development, applications. New York, USA: G. Braziller Publisher; 1968.

Gioacchino Francesco Andriani is a researcher in engineering geology at the Department of Earth and Environmental Sciences, University of Bari “Aldo Moro”, Italy. He is adjunct professor of rock and soil mechanics at the University of Bari, and since 2010, he is scientific responsible of the geotechnical laboratory. He taught in master, doctoral and executive programs in engineering geology, physico-mechanical characterization of stones, deterioration and conservation of soft-rock buildings and monuments, stability of rocky coasts, and hydraulic properties of calcarenite. He is a reviewer for several international journals in the fields of geomechanics, geotechnics, earth sciences and environment, engineering geology and geomorphology. He is the author or co-author of more than 40 scientific papers and 20 oral and poster contributions to national and international conferences, some of which have been published in peer review proceedings. He was convener and chairperson at national and international conferences. Since 2006, he has participated, also as coordinator, in several research activities on conservation and valorization of cultural heritage and areas of special geological interest, with the financial contribution of MIUR (Italian Ministry of Education, University and Research), EU (European Union) and private entities.

Mario Parise is professor in engineering geology at the Department of Earth and Environmental Sciences, University of Bari "Aldo Moro", Italy. From 1999 to December 2016, he was first researcher at the Research Institute for Geo-Hydrological Protection of the National Research Council, Bari, Italy, covering the fields of geological and geomorphological analysis of slope movements, study of the influence of weathering in the predisposition of landslides, debris flows and erosional processes in areas recently affected by wildfires, support to civil protection actions for monitoring of natural and man-made hazards and for disaster risk management, evaluation of natural and anthropogenic hazards in karst, analysis of sinkholes and of their effect on the human environment. He was scientific responsible of several projects, both at the national and international levels, dealing with karst and sinkhole analysis and assessment, and of several projects with the National Department of Civil Protection, following geo-hydrological disasters in southern Italy. He is the co-editor of two books published by the Geological Society of London, about "Natural and anthropogenic hazards in karst" and "Weathering and slope movements", respectively. He has been organizer of several international congresses and sessions about karst hazards, weathering and slope movements, sinkholes, and speleology in artificial cavities. He is author or co-author of about 100 papers on peer reviewed journals.