**ON THE APPLICABILITY OF GEOMECHANICAL MODELS FOR CARBONATE ROCK MASSES INTERESTED BY KARST PROCESSES**

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**Abstract**

Rock mass classification and geomechanical models have a particular importance for carbonate rocks, due to their peculiar fabric, variability of the main features, and scarce availability of experimental data. Carbonates are particularly sensitive to syn-depositional and post-depositional diagenesis, including dissolution and karstification processes, cementation, recrystallisation, dolomitisation and replacement by other minerals. At the same time, as most of sedimentary rocks, they are typically stratified, laminated, folded, faulted and fractured. The strength and deformability of carbonate rock masses are, therefore, significantly affected by the discontinuities, as well as by their pattern and orientation with respect to the in situ stresses. Further, discontinuities generally cause a distribution of stresses in the rock mass remarkably different from those determined by the classical elastic or elasto-plastic theories for homogeneous continua.

Goal of this work is the description of the difficulties in elaborating geomechanical models to depict the stress-strain behavior of karstified carbonate rock masses. Due to such difficulties, a high degree of uncertainty is also present in the selection of the most proper approach, the discontinuum one or the equivalent continuum, and in the numerical model to be used within a specific engineering application. The high uncertainty might cause wrong assessments as concerns the geological hazards, the design costs, and the most proper remediation works.

Even though recent developments in the application of numerical modeling methods allow to simulate quite well several types of jointed rock masses, as concerns carbonate rock masses many problems in representing their complex geometry in the simulation models still remain, due to peculiarity of the structural elements, and the presence of karst features.

In the common practice, the improper use of the geomechanical models comes from a superficial geological study, or from the lack of reliable geological and structural data that, as a consequence, bring to erroneous evaluations of the influence of the geological-structural features on the in situ stress state and the stress-strain rock mass behavior.

KEY WORDS: carbonate rocks, karst, modeling, discontinuities, geomechanical model

**INTRODUCTION**

The use of geotechnical models is today considered as a powerful tool in the characterisation of a site for civil, mining and environmental engineering design (Fookes 1997; Miroshnikova 1999; García-Jerez et al. 2007; Stavropoulou et al. 2007; Andriani and Tropeano 2009; Royse et al. 2009; Palma et al. 2012a; Lisjak and Grasselli 2014; Andriani et al., 2015).

The geotechnical model of a site consists of a two- or three-dimensional schematic representation of the geometrical relationship and spatial distribution of the soil and rock types, which are subdivided into distinctive units of reasonable homogeneity in terms of lithological and technical characters, and water pressure regime, within the so-considered representative volume. In detail, it includes the prevailing geomorphologic aspects of the natural landscape, the geo-structural and hydrogeological features, and the physical and mechanical properties of the different units, providing a rational basis for the prediction of the geomaterials behavior and the interaction between ground and man-made structures as well. Actually, such a model is definitely necessary in the selection of the most proper computational method, which should be suitable to face and solve all the problems related to engineering applications. In other words, the geotechnical model should ideally summarize any likely evidence of potential instability, in terms of kinematics and instability actions, and the mechanisms of resistance of the involved materials, able to counteract to the loss of static equilibrium. The computational method, on the other hand, requires the adoption of a constitutive law and a strength criterion, able to properly characterize the particular behavior of the material in the range of a specific interval of stresses, within the framework of the considered engineering application.

It is not always easy to create an exhaustive and correct geotechnical model when sampled data are patchy and insufficient, and this is especially true in the case of very complex geological settings, and/or with uncertain spatial relationships among the litho-technical units (Qiang and Hua 2004; Pellegrino et al. 2008; Nengxiong and Hong 2009). In these cases, the model is largely based upon subjective interpretation using a combination of empirical and mathematical techniques. When the uncertainty increases, it may lead to an erroneous assessment of the geological hazards, with heavy consequences on the design costs, and the choice of the most appropriate intervention strategies as well.

In comparison with soils, rock masses are notoriously more anisotropic and discontinuous, due to the presence of discontinuity families of different origin, including joints, faults, bedding planes etc. As a consequence, a greater complexity of the simulation models derives. Further, the limited

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**ha eliminato:** Use of geotechnical models is today considered a powerful tool in the validity in time due to landscape changes by both natural processes and anthropogenic activities has to be added. This may produce sensible variations in the rock mass properties and performances, for which the time-dependent behaviour of geomaterials has to be considered.

As concerns carbonate rock masses, the complexity is even greater, being also related to the high variability of the structures characterizing them. The strength and deformability of carbonate rock masses are, as a matter of fact, significantly affected by different type of discontinuities and by their pattern and orientation with respect to the in situ stresses. Besides, discontinuities, for the most part, cause a distribution of stresses and displacements in the rock mass remarkably different from those determined by the classical elastic or elasto-plastic theories for homogeneous continua. To all of these, the peculiarity of carbonate rocks, and of the processes affecting them, must be added. Karst processes consist of the solution of soluble rocks (carbonate mainly, but also other types of rocks could be affected: evaporites, and even quartzites), and in the formation of complex networks of conduits, as well as passages of variable size, up to development of caves enterable by man (Ford and Williams 2007; Palmer 1991, 2007). Karst networks strongly change the behaviour of the rock mass, since they represent often the larger discontinuity families (both in terms of size, frequency, and pervasiveness), and control the flow of water, especially when the highest amount of water is available, on the occasion of the most intense rainstorms.

As well, discontinuities are a serious obstacle to the definition of a reliable model which might be of practical use to predict the performances of rock masses. 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.

At the preliminary design stage, the practical way to characterise rock masses and estimate their strength and deformability is to apply a rock mass classification system. Starting from Terzaghi's rock load theory (1946), which represented the first successful attempt to classify rock masses for engineering purposes, over the years many other classification systems have been developed. Amongst them, the most widely known are the RMR system by Bieniawski (1973, 1974, 1993), the Q system by Barton, Lien and Lunde (1974, 1975), and the GSI system and later applications (Hoek 1994; Hoek et al. 1995; Hoek and Brown 1997; Hoek et al. 1998; Marinos and Hoek 2001).

Despite the widespread and quite successful use of the above classifications, as regards rock support system design for tunnels, dams and other rock works, doubts and/or practical difficulties of application still remain for soluble rock masses interested by karst processes, especially as regards different rock engineering problems, such as the stability of rock slopes and caves.

## APPROACHES FOR MODELING CARBONATE ROCK MASSES

Correctly approaching the modeling of a carbonate rock mass is a crucial step of the design analysis, besides representing the result of the knowledge acquired during the geological and geotechnical characterization (Barla and Barla, 2000). According to the fracturing degree of the rock mass, and the scale problem, different models can be taken into account in rock mechanics, from continuous media, to equivalent continuous and discontinuous media (Figs. 1 and 2). In the continuous model, the rock mass is considered homogeneous and isotropous, mainly without any discontinuity; this geomechanical model is typically adopted for the intact rock, without any structural anisotropy. In the equivalent continuous model, the discontinuous medium is assimilated to a continuous medium where the effect of the discontinuities controls the behaviour of the whole rock volume. The density and orientation of discontinuities are such that no preferential paths of stress-strain responses are present. In the discontinuous model, particular attention is dedicated to the discontinuities which, being a crucial part of the geometrical model, should be characterized and taken into account in the analysis for which geological structures control the anisotropy in terms of strength and deformability of the rock masses (Fig. 3).

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The main question is: When do we have to adopt, for carbonate rock masses, the continuum, the discontinuum, or the equivalent continuum model? Actually, hypothesis of isotropy and homogeneity are present only at the sample of massive rock masses, including both soft and porous calcarenites, and hard-brittle limestones and dolomites, when these do not show meso-structures that confer to the rock mass "directional" properties. The study of the influence of anisotropic characters at the scale of the sample upon deformability and strength of the rocks has been already dealt with in the past, from both the theoretical and experimental standpoints. Anisotropy of deformability was treated within the linear elasticity theory, in reference to two particular and simplified situations of elastic symmetry: 1) the orthotropic symmetry; and 2) the transversely isotropic symmetry (Crea et al. 1981; Barla et al. 1989; Levin and Markov 2005). The anisotropy of strength was analyzed in most of the studies through hypothesis of transversely isotropic symmetry (Donath 1961, 1963; Jaeger and Cook 1979; McLamore and Gray 1967; Nova 1980). For carbonate rock masses of Apulia (southern Italy), evidence for transversely isotropic symmetry are actually produced by the presence of thin layers (locally known as *"chiancarelle"*), or of stylolites and stromatolites at different levels within the overall succession.

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Carbonate rock masses for which it is possible to adopt an equivalent continuum approach are those highly degraded, crushed and strongly tectonized, where hypothesis of homogeneity and isotropy in terms of strength and deformability properties could be invoked.

Discontinuous carbonate rock masses consist of blocks and joints where the latter can be considered clean cut fractures with different apertures. The stress-strain behavior of a discontinuous rock mass should be defined by examining separately the blocks and the discontinuities. If the response of the rock mass is mostly governed by discontinuities, deformation of the single blocks can be considered as negligible. Failures are evident by sliding along the joint planes only (Fig. 4). In this case, behavior of the discontinuities describes the behavior of the rock mass, since the blocks could be considered as rigid. However, joints are often not completely persistent in the carbonate rock masses, and their apertures might change, decreasing toward the inner part of the rock mass (Fig. 5). The presence of rock bridges makes the simulation model even more complex, because of the prior failure of the intact bridges, and the successive shear along joint planes at larger strains. In this case, the strength and deformability features of the intact rock, that is of the rock bridges, can be taken into account. In practice, the discontinuum approach for carbonate rock masses should have an effective correspondence to physical reality in the case of a rock mass consisting of intact blocks separated by a moderate number of discontinuities, in the forms of pseudo-planar joints.

In the real world, particularly for the high complexity of karst environments, this situation is quite improbable due to the presence of cavities, of residual deposits, and of re-deposited calcite that partly or totally fill the discontinuities, including both the karst caves and conduits (Fig. 6), and those of tectonic origin such as faults and fractures.

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Therefore, what is the approach to be used? In karst, it is very frequent to encounter these types of problems. What are the numerical methods most respondent to the physical reality?

Over the past few decades different computer-based numerical methods in geomechanics have been proposed that can be ranked under the groups of continuous methods and discontinuous methods (Jing and Hudson 2002; Jing 2003; Bock 2014). Among the first group, we can list the Finite Difference Method (FDM), the Finite Element Method (FEM), and the Boundary Element Method (BEM). Discontinuous methods include the Discrete Element Method (DEM), the Discrete Fracture Network (DFN) method and the Hybrid continuous/discontinuous models. The continuous methods practically describe the rock mass as a discretized dominium composed of "elementary units" with geometrically simple form (triangles, quadrilaterals, tetrahedrons, etc.) which, even when deforming, remain constantly in contact through the relative surfaces of separation. In the discontinuous methods the rock mass is represented as an assembly of discrete blocks which interact through contact forces; blocks can be rigid or deformable. Whilst in the continuous methods the contacts among "elementary units" do not change, independently from the response of the model, the discontinuous ones are updated after each iteration, based upon the position and the

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relative movement of the single elements. Therefore, complex mechanisms involving rotation or breakout of blocks cannot be modeled by the continuous approaches.

Even though the isotropic continuum models have the drawback not to represent the stress-strain behavior to failure of the medium (since they do not allow the reciprocal separation among the elements of the system, and therefore the detachment of individual blocks), nevertheless they are very useful for determining the onset of instability (collapse mechanisms) or large movements that cause block detachments (Hammah et al. 2008). In carbonate rock masses, implementation of numerical continuum approach analyses may provide especially accurate results for stability analyses of massive or slightly damaged rock masses, as well as when the block size is significant if compared to geometry of the engineering design, or, even, when the rock mass is strongly fractured or crushed. In the latter case, the problem is to obtain samples that could be considered as representative of the whole rock mass (Fig. 7).

In general, the appropriate numerical method for elastic and elasto-plastic analyses of closely jointed rock masses is the Distinct Element Method (Brady 1992). As aforementioned, however, in karst this simple scheme is not respected, due to presence of cavities and conduits with a geometry that is very difficult to be reproduced by numerical solutions techniques (Fig. 8).

Karst processes strongly work in modifying the porosity and permeability of carbonate rocks in all the diagenetic stages of the rock itself. For instance, karst may determine, with time, a porosity on the order of 40-50 %, considered as the simple ratio void vs. rock (Focus Group on Karst Hydrology 2008). Therefore, there is an extremely high variability in the behavior of carbonate rock masses, as concerns their hydrogeology, which is strongly dependent upon the different orders of porosity (Palmer 1999; Worthington 1999), and a distinction among the porosity related to tectonics, from that due to bedding planes is necessary. Further, bedding planes are very often filled, partly or totally, by residual deposits and terre rosse (Mongelli et al. 2014), which, in turn, may have a strong influence on the modality of groundwater circulation. Porosity of karst aquifers is, for all the above reasons, typically divided into three types: intragranular porosity of the matrix, porosity of the joints, and porosity of the conduits. Analysis of the so-called triple porosity aquifers is definitely not easy (Worthington 1999; Worthington et al. 2001).

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Cave pattern, and the formation of phreatic passages and conduits in the rock mass due to solution, control the groundwater flow and, in turn, the development of weathering processes that induce a decrease in the physical properties of the soluble rock mass (Ford and Ewers 1978; Fookes and Hawkins 1988; De Waele and Parise 2013). Later, these karst forms may be linked through successive collapses, mostly controlled by tectonic discontinuities (Kastning 1999; Sasowsky 1999; Sebela et al. 1999; Harrison et al. 2002; Gueguen et al. 2012; Pepe and Parise 2014), thus creating more complex networks of voids in the rock mass, including also vadose and mixed features (Fig. 9). The integrated work of karst processes, weathering, and tectonically-controlled failures determines the occurrence of single and/or complex detachments of rocks and blocks, up to developments of slope instability, and of collapses or sinkholes at the ground (Culshaw and Waltham 1987; Klimchouk and Andrejchuk 2002; Waltham 2002; Parise 2008; Iovine et al. 2010; De Waele et al. 2011; Palma et al. 2012b; Gutierrez et al. 2014).

Computer codes able to develop sophisticated methods of analysis are not well suited for solving constraint problems involving complicated geometry. The realistic modeling of the mechanical behavior of a carbonate rock mass is a prerequisite for the successful numerical modeling of discontinuous medium. The risk is that the actual complexity of the rock mass is not really described by the model, and the real critical structural features are not taken into account by the analysis (Hart 1993; Lollino et al. 2013). Further, the role played by the residual deposits, partly or totally filling the cavities, cannot be disregarded, since they strongly influence the geomechanical behavior. As a matter of fact, these deposits may show very different geotechnical properties, depending upon the type of deposit and the chemical-mineralogical composition, and the relative thickness and distribution as well (Grassi et al. 1975; Moresi and Mongelli, 1988). The main feature of a karstified rock mass appears therefore to be the strong anisotropy, both in the horizontal and vertical sense, which is very difficult to be simply reproduced in a scheme (Parise and Lollino 2011; Andriani et al. 2015).

## CONCLUSIONS

Modeling of rock mass behavior in engineering design presents many difficulties and uncertainties, especially as regards discontinuous media. This is mainly due to the lack of detailed geological and geotechnical data and to the impossibility to represent through simplified schemes the discontinuities that characterize a rock mass.

A practical model for simulating the behavior of discontinuous rock masses for engineering purposes should be able to represent the system geometry (including the discontinuity system related to geometry in the design process), the boundary and initial conditions, the in situ and induced stresses, and the constitutive laws for both the rock matrix and discontinuities, including the scale-time effects. Additionally, the interaction between the rock mass and the engineering application should be included in the modeling procedure, aimed at predicting the manner in which the failure could occur.

Carbonate karstified rock masses are the most typical example of discontinuous, anisotropic, inhomogeneous and not-elastic medium, due to both the presence and role played by features originated by karst, and later evolved through tectonic and/or gravity-related control, that act as the main ways followed by water to move through the rock mass, further causing additional weathering and inducing minor resistance in the overall rock mass.

The combination of geo-structural characters, complex in situ conditions of stresses and fluid pressures make karstified rock masses a medium in which it is very difficult to identify the failure mechanisms and the constitutive laws with the associated variables and parameters. It follows that geomechanical model and numerical simulation remain generally highly questionable.

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The special nature of karstified rock masses and the consequential difficulties when attempting to model their behavior confer a greater importance to the collection and elaboration of field data, and to the results of geotechnical laboratory tests, together with the experience in interpreting the results. Due to the high difficulties in obtaining samples that could effectively be representative of the rock mass, choice of the input geotechnical parameters may be a crucial step in the final reliability of the outcomes. The use of sophisticated mathematical models makes sense only when the input parameters and the geomechanical model of reference are effectively representative of the physical reality, and when there is a capability in the critical assessment of the input and output data.

Analyses methods and solutions mostly derived from other field of engineering or mechanics, in primis statics and dynamics, may provide in some cases significant insights on the stress-strain behavior of karstified rock masses and the likely failure mechanisms, especially when supported by a well-thought and deep analysis of the involved parameters.

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FIGURE CAPTIONS

Fig. 1 – Continuous and discontinuous rock masses (after Eldebro 2003, modified).

Fig. 2 – Scale design analysis influence on the modeling approach for rock masses (after Eldebro 2003, modified).

Fig. 3 – Models of elasto-plastic behavior of rock masses.

Fig. 4 – Carbonate outcrop clearly showing sets of joints with different attitudes, possibly controlling the development of failures. Local presence of terra rossa filling paleo-cavities can also be noted.

Fig. 5 – Joints filled with terra rossa in the first meters of a carbonate succession. Note the progressive closure of the joints toward the bottom.

Fig. 6 – Paleo-karst cave filled by residual deposits (terra rossa) and calcite speleothems.

Fig. 7 – Crushed carbonate rock mass: in this case it is not possible to obtain representative samples for laboratory geotechnical tests.

Fig. 8 – Quarry walls in carbonate rock masses: a) presence of karst caves, mainly developed along sub-vertical joints partly filled with residual deposits; b) evidence of large karst caves within a sub-horizontally thinly bedded succession.

Fig. 9 – Karst features along the walls of a collapse sinkhole (Pulo di Molfetta, southern Italy): phreatic caves, produced by equilateral water pressure in the forms of circular passages, are present on more levels; they have been later connected through vertical joints, that partly canceled the original shapes.