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# Rock Mass Rating spatial estimation by geostatistical analysis

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ABSTRACT

This work aims to estimate the Rock Mass Rating of 200 km$^2$ area of the Italian Central Alps, along San Giacomo Valley (province of Sondrio). The regional geological setting is related to the Pennidic Nappe arrangement, which is characterized by the emplacement of sub-horizontal gneissic bodies, separated by meta-sedimentary cover units. The resulting RMR map can be a useful tool to forecast the quality of outcropping rock masses as well as to derive their geomechanical behaviour. Almost 100 geomechanical field surveys have been carried out in the research area, in order to characterize the outcropping rock masses; afterwards rock mass quality indexes have been evaluated in each surveyed site. In order to estimate the Rock Mass Rating values in un-sampled locations, different geostatistical techniques (kriging and simulations) have been applied, using both bi-dimensional and almost three-dimensional approaches. The validation process shows that kriging tends to produce smoothened distributions, while conditional simulations allow respecting local extreme values. Although geostatistical analysis reveals that geomechanical properties show spatial correlations, it is to remind that rock mass quality is strongly related to its geological and structural history.



## 1. Introduction

The knowledge of rock mass quality indexes in an extended area is an important prerequisite in design of civil engineering and mining activities; the Rock Mass Rating [1] (RMR) is a widely used index to evaluate geomechanical features and stability conditions in areas of interes for the planning and construction of large-scale engineering works, or affected by rock slope stability problems. The RMR classification has found wide applications in various types of engineering projects (such as tunnels, foundations and mines), as well as in geological risk management. The accuracy degree in predicting, evaluating and interpreting the quality of rock masses, for instance a tunnel alignment, is a key for the successful execution of the project. Actually, the RMR is one of the rock mass classification systems which, as well as the Q-system [2], can be used as a guideline for the selection of the appropriate excavation technique, the kind of rock reinforcements and permanent support in tunnels, for the prevision of stand-up time, and for deriving the deformability parameters of the rock mass. At the same time, the RMR can also be used to evaluate the landslide susceptibility of rock slopes, allowing one to identify the more critical portions of rock masses that could be prone to failure. For instance, rockfall analysis needs an accurate study of the cliff and the localization of the source areas of blocks. In addition, the rock mass quality affects the choice of the conceptual model used in numerical modelling and analysis: a highly fractured rock mass, with respect to the geological and engineering problem, can be modelled as an equivalent continuum media, while a massive rock mass, with few discontinuities, must be approached with a discrete model.

In preliminary studies, it is a common practice to execute direct geomechanical surveys in few representative areas, where the logistic difficulties can be bypassed, reducing time and costs. In both applications (civil works and slope stability), the common measurement techniques of rock mass properties provide point-wise values, referred to a specific sampling location. Therefore the reproduction of the spatial variability of geomechanical quality in the whole area can be a very useful tool, especially during the pre-feasibility and feasibility planning phases, particularly to individuate critical points.

This paper focuses on the estimation of the RMR values in the shallow rock masses of San Giacomo Valley (Italian Central Alps), far from the measurement locations. This valley is characterized by high sub-vertical rock cliffs, incumbent on infrastructures and villages; in this valley, slope instability problems are quite frequent. The last one, involving a rock volume of 20,000 m$^3$, occurred in September 2012, and obstructed the main road, isolating the villages of the upper San Giacomo Valley for few days. It follows that the safeguard of the territory, the protection of elements at risk, together with the necessity of touristic and commercial development, rend necessary the implementation of the transportation network, with roads hewn out of the rock face,

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halfway up the hill, as well as in underground. The availability of a continuous map of RMR values can therefore be used in land use planning, prevention, mitigation and management of risks, but also in the prevision of the behaviour of rock masses.

The number and distribution of outcrops often constrains the quantitative description of rock mass properties, therefore indirect techniques, such as geostatistical methods, have been suggested to estimate rock mass characteristics in the whole area [3–5], so that the study of variations of rock mass features, in relation with the distance between survey points, can reveal spatial correlation structures. The theory of regionalized variables [6], afterwards shortened by the mining engineering community to the term "geostatistics", is able to incorporate these structures, which mean spatial dependence of regionalized variable at different locations in space.

Several authors have applied the geostatistical approach to analyze rock mass fracture-distribution [7–15] or rock mass specific properties [16–23]. The RMR index has been estimated using geostatistical analysis since 2004 [24–31], especially for tunnel projects; the kriging method has usually been applied to borehole data, sometimes integrated by geophysical surveys, with a secondary and only qualitative role. RMR values have always been considered as a single regionalized variable, and not as the sum of more variables.

Another very popular index of rock mass quality is the Q-system, which was developed for depth rock mass classification and tunnel applications. The Q-index has been successfully estimated, as a single variable, by geostatistical techniques, studying also its effects on the Tunnel Boring Machine related parameters [29].

In the San Giacomo Valley, considering the main demand in land use planning and the lack of data regarding depth rock masses, only the RMR has been considered; in this paper only field superficial measurements have been used as input to estimate the RMR values. The main innovation consists of RMR estimation in a wider area than those of the previously cited works; in fact, this research has been carried out at regional scale. The results obtained by applying two different approaches (2D and almost 3D one) and techniques (kriging and simulations) have been validated, compared and discussed.

## 2. Geological setting

The study area is located in the Italian Central Alps (Fig. 1a); it is aligned along the San Giacomo Valley (province of Sondrio), which is situated between Lake Como and the Splügen Pass, which connects Italy to Switzerland. San Giacomo Valley has an extent of about 200 km$^2$ and its morphology results from its structural and glacial evolution.

The Central Northern Alps are a fold and thrust system, belonging to the Alpine nappe pile, which was created in a subduction zone environment during the closure of Piemontais and Valaisan oceans. The major thrust sheets developed during the Alpine compressional phase and imbricated from South to North, forming, in the region of interest, the Pennidic Nappe arrangement. The Penninic units were emplaced by thrusting, towards NW, in the early Tertiary [32]. In particular, the research area pertains to the upper Penninic units which have been considered to be an orogenic wedge, consisting of underplated basement and sedimentary slices related to the Valaisan subduction [33]. After the onset of continental collision, E-W extension took place along major ductile displacement zones; late folding overprinted and steepened the previous structures. The latest structures are brittle normal faults cross-cutting all the previous structures (e.g. the Forcola fault), and may be coeval with displacements along the Engadine line and the Iorio–Tonale line, which corresponds to the late stage of the Insubric line [34].

In brief, the regional geological setting of the San Giacomo Valley is characterized by the emplacement of sub-horizontal gneissic bodies ("Tambò" and "Suretta" units), emplaced towards East, and separated by a metasedimentary cover unit, called "Spluga Syncline". The tectonic contact between the two main nappes gently dips towards NE. The Tambò and Suretta nappes form thin crystalline slivers, each about 3.5 km thick, essentially composed of polycyclic and poly-metamorphic basement of paragneiss; thin layers of amphibolite and orthogneiss are intercalated within the paragneiss. The lithological features of basements are almost similar. The basement of both nappes is unconformably overlain by a Permo-Mesozoic sedimentary cover, which shows a typical stratigraphy of internal Brianconnais sediments [35]. The Permo–Mesozoic cover, from older to younger sediments, is constituted of: conglomerates with quartz pebbles and albite-bearing quartzites, which probably formed from Permian volcano-detritic sediments [36]. The Mesozoic cover consists of pure quartzites in the Suretta nappe and impure quartzites in the Tambò nappe, dolomitic marbles, marbles and schists. The Tambò cover unit, called Spluga Syncline, shows important deformation and thickness variations: from a few metres up to several hundred metres in thickness. The Alpine metamorphic grade increases from the top of the Suretta nappe to the bottom of the Tambò nappe and from the North to the South of nappes from greenschist facies to amphibolite facies [37].

In the San Giacomo Valley main structural alignments show the following directions: WNW–ESE, NW–SE, NE–SW and NS. The first system seems to be related to the regional orientation of the Insubric Line, whilst the second one has the features of the Forcola Line. The NE–SW system is related to the Engadine Line and is characterized by shear component of movements, which are frequently underlined by movement streaks. The last system, parallel to the valley, is not directly connected to any tectonic line of regional significance, but it is represented by a bundle of persistent fractures, including both fractures formed in the post-glacial age, and shear joints, probably attributable to pre-existing tectonic lines, along which the pre-glacial valley developed. In the study area, beyond the main mentioned systems, many other local discontinuities sometimes occur; they have been locally described during the geomechanical surveys.

## 3. Local rock mass properties

In the San Giacomo Valley, geomechanical surveys have been carried out, during several field campaigns, in 97 different sites, mainly located on the left side of the Liro Stream; 78 sampling points involve the Tambò basement, 7 the Spluga Syncline, and 12 the Suretta basement. As shown in Fig. 1b, the measurement points are very scattered, because they are strongly affected by the position and accessibility of the outcropping rock masses.

Detailed geomechanical field surveys have been performed according to the International Society of Rock Mechanics (ISRM) suggested methods [38], allowing the characterization of each investigated rock mass, its intact rock and discontinuities, in terms of: number of main joint sets, their representative orientation, vertical and horizontal intercepts, average set spacing, persistence, aperture, degree of weathering, moisture conditions, roughness and joint wall compression strength coefficients, presence and nature of infill. From the collected data, rock mass quality indexes, such as the RMR and the Geological Strength Index [39], have been evaluated.

The RMR defines the geomechanical quality of a rock mass as the sum of five rates referred to the following rock and rock mass