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THE IMPACT OF NEW TECHNOLOGIES IN THE ENGINEERING CLASSIFICATION OF ROCK MASSES

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EXTENDED ABSTRACT

La caratterizzazione degli ammassi rocciosi rappresenta il primo step nell'analisi ingegneristica dei versanti rocciosi e dei tagli stradali. Le classificazioni RMR (*Rock Mass Rating*), SMR (*Slope Mass Rating*), Q-*System* e la più recente Q-*Slope*, sono le più utilizzate nella geologia applicata e nell'ingegneria. Tra queste, SMR e *Q-Slope* rappresentano in generale la scelta più idonea nell'analisi dei versanti naturali e nei tagli stradali. I dati necessari all'utilizzo di tali metodologie di classificazione vengono solitamente ricavati tramite rilievi geomeccanici in sito. I rilievi convenzionali sono però condizionati dall'assetto del versante in studio. Infatti, nel caso in cui il versante sia di elevata altezza o nel caso non sia raggiungibile in condizioni di sicurezza, l'utilizzo di tali tecniche di rilievo risulta difficile e spesso i dati ottenuti non sono rappresentativi dell'intero affioramento.

Negli ultimi anni, l'avvento di nuove tecnologie per il rilievo e l'analisi dei versanti ha notevolmente cambiato l'approccio allo studio della qualità e stabilità degli ammassi rocciosi. In particolare, tecniche di rilievo da remoto, come la fotogrammetria terrestre ed il laser scanning, rappresentano oggigiorno metodologie comunemente usate in questo tipo di analisi. Se da un lato l'utilizzo del laser scanner è, nel mondo professionale, meno utilizzato a causa dei costi elevati, la fotogrammetria rappresenta una tecnica di rilievo affidabile ed economica. In particolare, la tecnica "*Structure from Motion*" ha reso la creazione dei modelli fotogrammetrici tridimensionali più semplice e speditiva. Nonostante ciò, anche nel caso della fotogrammetria, per creare modelli georeferenziati e scalati è necessario avvalersi di punti di appoggio a terra, generalmente acquisiti tramite stazione totale o GPS. L'utilizzo di tali strumenti incrementa i costi associati a questa tecnica.

In questo studio, gli autori evidenziano il ruolo delle nuove tecnologie nelle classificazioni geomeccaniche. Saranno proposti due tipi di approccio, applicati nei versanti sovrastanti la strada provinciale SP52, nell'area della Montagna dei Fiori (Appennino Centrale), la quale attraversa diverse formazioni della successione Umbro-Marchigiana. Il primo approccio, speditivo ed economico, è basato sull'utilizzo di rilievi convenzionali e permette, tramite l'impiego di applicazioni per smartphones, di calcolare il *Q-Slope* e l'angolo di sicurezza limite del versante direttamente sul campo. Nel secondo approccio, di dettaglio e approfondito, si combinano in maniera integrata rilievi convenzionali, fotogrammetrici e Sistemi Informativi Geografici (GIS). In particolare, viene presentato un nuovo metodo per l'utilizzo della fotogrammetria che permette di ottenere modelli 3D georeferenziati senza l'ausilio della stazione totale e del GPS, abbassando notevolmente i costi associati a tale tecnica. I dati raccolti tramite fotogrammetria sono integrati con i dati provenienti da rilievi geomeccanici classici allo scopo di creare un database di informazioni completo e rappresentativo dell'area di studio. Tale database verrà organizzato tramite GIS con lo scopo di incrementare l'interpretazione dei dati e, tramite l'utilizzo di carte tematiche, facilitare il calcolo di parametri geomeccanici anche in aree dove non sono stati effettuati rilievi diretti. Utilizzando tale approccio sarà possibile calcolare il *Q-Slope*, l'angolo di sicurezza limite e lo SMR. In ambito di valutazione delle condizioni di stabilità di versanti stradali, l'utilizzo combinato delle classificazioni *Q-Slope* e SMR risulta essere di notevole importanza in quanto grazie al *Q-Slope* è possibile ottenere l'angolo di sicurezza limite del versante sovrastante la strada, mentre con lo SMR si può definire la qualità dell'ammasso roccioso e, in relazione a ciò, suggerire le più idonee opere di messa in sicurezza o contenimento. Ne consegue che queste informazioni permettono di effettuare una indagine geologica-tecnica in grado di definire, in base ai costi ed alle esigenze, la possibilità di adottare nella progettazione l'angolo di sicurezza ottenuto dal *Q-Slope* o, se questo non fosse possibile o economicamente non vantaggioso, di suggerire le opere di sostegno da attuare nel caso di tagli stradali con angoli più elevati rispetto a quello di sicurezza.

ABSTRACT

The engineering classification of rock masses represents the first stage in the analysis and characterization of rock slopes and road cuts. Among the existing classification methods, four systems are mainly used for mining, tunneling and slope design: the RMR, the Q-system/Q-Slope, the GSI and the SMR. Software has been recently developed for using these classification systems and some, such as Q-system/Q-slope, are also available as smartphone applications, to be directly used on the field. Rock mass parameters necessary for such classification systems are usually obtained through engineering geological analyses along scanlines. Nowadays, the advent of new technologies has led to step-change increase in the quality of data available for the study of rock slopes. These include new remote sensing sensors, platforms, new techniques and software for engineering rock mass analyses. Data obtained from these techniques, integrated with field geomechanical measurements, can improve the quality of engineering rock mass classifications. Furthermore, Geographic Information Systems provide a useful tool for managing such data and performing regional rock mass analyses, suitable in the study of rock slopes and road cut design. In this context, this research aims to analyze: i) the importance of using remote sensing and GIS techniques in engineering rock mass classifications; ii) the advantages of combining different engineering classification systems and iii) the possible use of low-cost technique for engineering design.

KEYWORDS: *rock mass classification, new technologies, smartphone applications, photogrammetry, GIS*

INTRODUCTION

Engineering rock mass classifications represent an important aspect of engineering geological analyses, especially during the feasibility study for roads and/or tunnels and for understanding the rock mass quality of natural and engineered rock slopes (GHIROTTI *et alii*, 2011; SALVINI *et alii*, 2013; SCIARRA *et alii*, 2015; SPREAFICO *et alii*, 2017). The Rock Mass Rating, RMR (BIENIAWSKI, 1989), the Q-system (BARTON *et alii*, 1974) and Q-Slope (BAR & BARTON, 2017), the Geological Strength Index, GSI (HOEK & BROWN, 1997) and the Slope Mass Rating, SMR (ROMANA, 1993; ROMANA *et alii*, 2015) are the most commonly used rock mass classification systems. The RMR and the Q systems were initially developed for tunnel engineering. The RMR was subsequently adapted for slopes and foundations (BIENIAWSKI, 1989) but its use in this type of studies is still challenging. For this reason, when dealing with natural slopes or road cuts, the RMR is integrated by the SMR. The recent Q-Slope represents a modification of the Q-system and has been intended for the study of reinforcement-free road or railway cuts or open pit mines. GSI is based on the geological description of homogeneous and heterogeneous rock masses (HOEK & BROWN, 1997). This method is simple and useful, especially when numerical simulations are needed, but it was not developed to provide preliminary information for engineered slope, open pit mines and road cut design. In this context, the more suitable classification systems are the SMR and the Q-Slope. In this research, we present the combined use of these classification methods in the Montagna dei Fiori area, Italian Central Apennines (Figure 1).

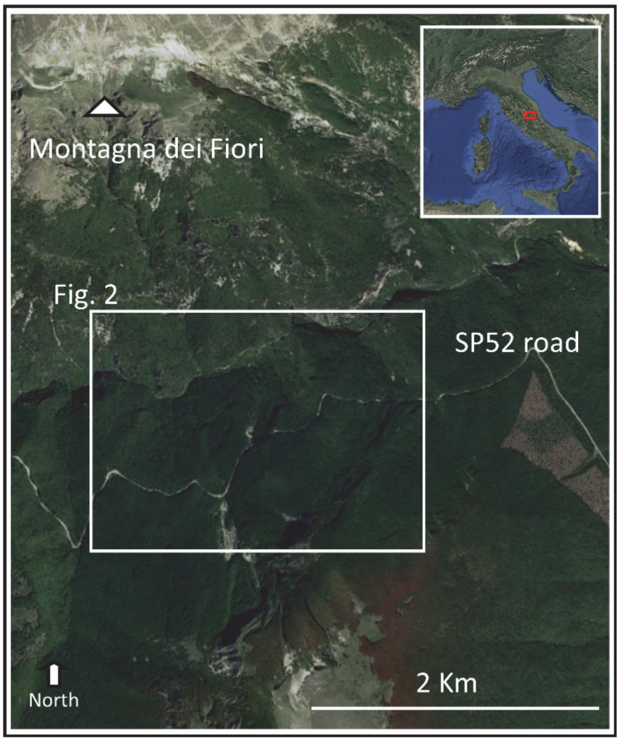

Fig. 1- Montagna dei Fiori area and SP52 road

The Montagna dei Fiori is an overturned anticline with an NNW-SSE axial trend, which developed during the Lower Pliocene and involves the Umbria Marche carbonate succession (Jurassic–Miocene) and the Messinian foredeep siliciclastic deposits (MATTEI 1987; SCISCIANI *et alii*, 2002).

The SP52 road crosses the study area, running in an E-W direction. Along the road, from west to east, the following formations of the Umbria Marche succession outcrop: Marne con Cerrogna (MCERR, Miocene), Corniola (COI, Early Jurassic, overlaying the older Early Jurassic Calcare Massiccio, CM), Rosso Ammonitico (RAM, Early Jurassic), Formazione del Salinello and Calcari Diasprigni (CDU, Late/Middle Jurassic), Maiolica (MAI, Early Cretaceous), Marne a Fucoidi (FUC, Early Cretaceous), and the Scaglia Rosata and Scaglia Cinerea (SR, Late Cretaceous–Oligocene). Figure 2 shows the geological map, the stratigraphic column (after MATTEI, 1987;

FRANCIONI *et alii*, 2018a) and the photographs of the four geological formations, COI, RAM, CDU and MAI, characterizing the section of the SP52 road studied in this research.

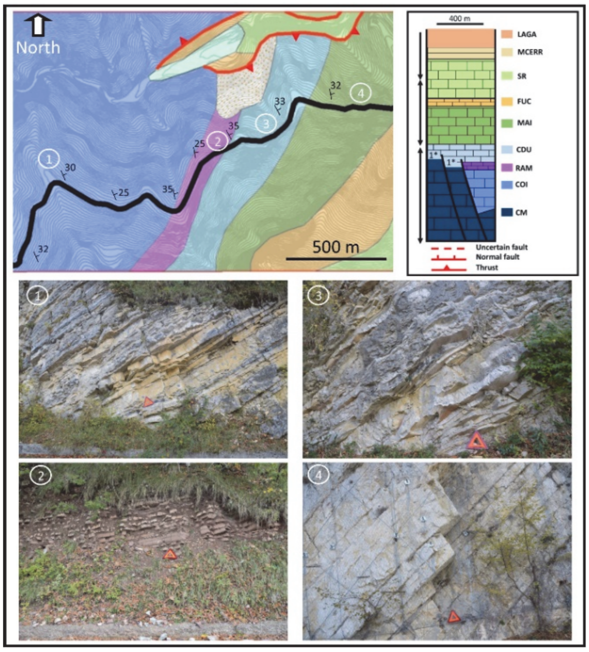

Fig. 2 - Geological map of the area highlighted in Figure 1 by the white rectangle with the stratigraphic column (after Mattei, 1987) and photographs of the four geological formations characterizing the section of the SP52 road studied in this research. Photographs are taken looking toward South. Red triangle with 0.425 cm length side as scale

The study of natural and engineered rock slopes can often be challenging due to the inaccessibility of the slopes and the risk for the surveyors. In this context, remote sensing techniques can be useful in both improving the amount and quality of data and decreasing the time and risk of the survey (FRANCIONI *et alii*, 2018b). In this research, a low-cost Digital Photogrammetry (DP) method for creating georeferenced 3D model of slopes without the need for total station/GPS is presented. Furthermore, the use of commercial smartphone for DP is introduced. Data obtained from DP surveys and conventional geomechanical scanlines are integrated and analyzed through GIS to improve the understanding about slope failures and rock mass quality (FRANCIONI *et alii*, 2018c). The Q-Slope and SMR classifications have been used/combined for the engineering study of the rock outcrops along the SP52 road.

METHODS

Conventional geomechanical and DP surveys have been carried out along the SP52 road, in the Montagna dei Fiori area (Figure 1). Two types of approach have been used:

Approach 1 - rapid rock mass classification of rock slopes, performed directly in the field using conventional geomechanical surveys and a smartphone application;

Approach 2 - in depth analysis of the outcrops integrating conventional geomechanical surveys, DP and GIS.

Approach 1 has been adopted for rock mass characterization through the Q-Slope smartphone application (Gecko Geotechnics, http://www.geckogeotech.com/q-slope/). Data necessary for the use of the smartphone application is: slope height, slope angle, slope stability, RQD-Rock Quality Designation, joint set number, joint roughness and alteration, orientation factor, Jwice (environmental and geological conditions) and Strength Reduction Factor. The smartphone application allows to select these parameters among a list of pre-definite values, making the use of the Q-slope classification easy and quick. With regard to the Approach 2, an easy method for creating georeferenced DP 3D model of slopes without the need for total station and GPS is presented. This is based on the use of an object of known geometry that is located on the slope under study and that provides references during the creation of the 3D model. In this case, we have used an emergency warning car triangle. The dip and dip direction of the surface of the triangle and the angle between its base and the horizontal have been measured through a geological compass. These measurements are used in 3D CAD software for reconstructing the 3D geometry of the object (3D roto-translation) and to extract the coordinates of its vertices, which will be used as ground control points during the creation of the 3D photogrammetric model by the "Structure from Motion" technique (RONCELLA *et alii*, 2005; ASSALI *et alii*, 2004; VASUKI *et alii*, 2004).

The CAD 3D roto-translation, carried out using the geological compass measurements, allow to obtain North-oriented ground control points and, consequently, North-oriented 3D DP models. These can therefore be used for measuring the geometry and orientation of geological features (FRANCIONI *et alii*, 2019). The DP survey has been performed using a reflex digital camera and commercial smartphones. This methodology has been validated comparing the 3D DP model of a travertine slope outcropping in Civitella del Tronto (Central Italy) with a Laser Scanning (LS) model. The 3D models of the slopes obtained using this approach has a centimetric accuracy suitable to extract data useful for the characterization of the slope under study such as discontinuity sets, discontinuity spacing and trace length. This information, manually extracted from the 3D models using CloudCompare software and integrated with field data such as aperture, infilling material, etc., was then utilized to classify the rock mass through the SMR and Q-slope systems. These classifications are strongly affected by the geometrical relationship between slope and discontinuity attitudes. Due to this, the results of such classification can vary within the same geological formation in case of slope attitude variations. In this context, we have used GIS to create the slope and aspect thematic maps, representing the slope angle and the slope attitude, respectively. Combining the geomechanical/geological data with the information contained in these maps, it was possible to extrapolate the SMR also in inaccessible areas.

RESULTS

Conventional geomechanical surveys have been integrated with DP analyses. The data obtained are listed on Table 1 and 2. These data have been used in the Q-Slope and SMR classification systems for the calculation of the Q-slope value, the steepest slope angle (*β*) and the SMR value.

Formation	Joint set	Dip°/Dip Dir°	n. poles
MAI	S0	39/077	45
	J1	86/163	67
	J2	59/243	44
CDU	S0	36/066	45
	J1	54/264	59
	J2	74/336	48
RAM	S0	22/088	48
	J1	78/324	42
	J2	66/249	40
COI	S0	31/077	58
	J1	77/339	47
	J2	69/256	59

Tab. 1. Discontinuity sets

	MAI	CDU	RAM	COI
UCS (MPa)	75	74	59	85
RQD%	75	57	29	81
Spacing (m)	0.23	0.11	0.1	0.3
Length (m)	15	20	15	10
Aperture (mm)	2-30	1-100	1-7	1-100
Roughness	Smooth	Rough	Rough	Rough
Infilling	Soft	Soft	Soft	Soft
Weathering	Moderate	Moderate	High	High
Jv	8.9	17.9	23.5	6.7

Tab. 2. - Geomechanical characteristics of the formations (discontinuity properties refer to the most critical joint sets in each geological formation)

The calculation of Q-slope value and steepest slope angle can be performed directly in the field through the smartphone application developed at this purpose (Approach 1). An example of results obtained using this approach is showed in Table 3, which highlights the Q-slope and *β* values for the four geological formations surveyed.

Geological formation and slope dip /dip direction	Q Slope	β
MAI (75/162)	0.61	61
CDU (84/319	0.69	62
RAM (75/340)	0.27	53
COI (83/318)	0.8	63

Tab. 3 - Q-slope and β values calculated using the Approach 1

When using DP, we can create a 3D model of outcrops, which can be studied/analyzed in post-processing. DP allows to extract a lot of geomechanical information representative of the entire slope. In this research, we were able to extract from the DP models the slope attitude, the discontinuity dip and dip directions, spacing and persistence. These information have been integrated with field geomechanical data. Figure 3 shows an example of the 3D models of the outcrops obtained using DP.

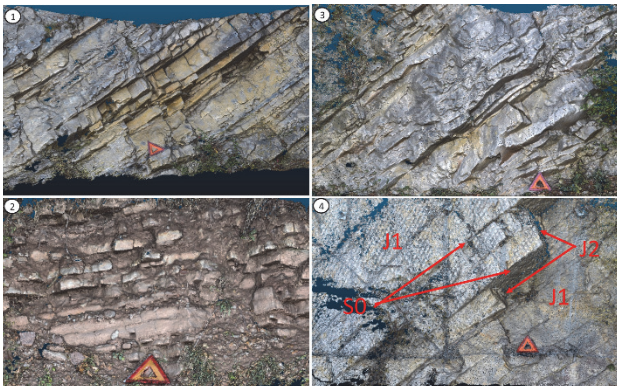

Fig. 3 - 3D models of: 1) COI; 2) RAM; 3) CDU; 4) MAI. In the MAI formation, the discontinuity sets are highlighted in red. Red triangle with 0.425 cm length side as scale

The proposed DP method has been validated comparing the 3D DP model in a travertine slope outcropping in Civitella del Tronto, Central Italy (Figure 4A) against a LS model. The comparison showed the good agreement between DP and LS data. The differences between DP and LS increase with the distance from the object of known geometry, up to 5 cm at 15 m of distance (red areas in Figure 4B). The DP methodology has been also tested using smartphone cameras. In this case, the errors increase up to 8-10 cm at 15 meters of distance from the ground control points, but in general the DP model is still in good agreement with LS model (Figure 4C).

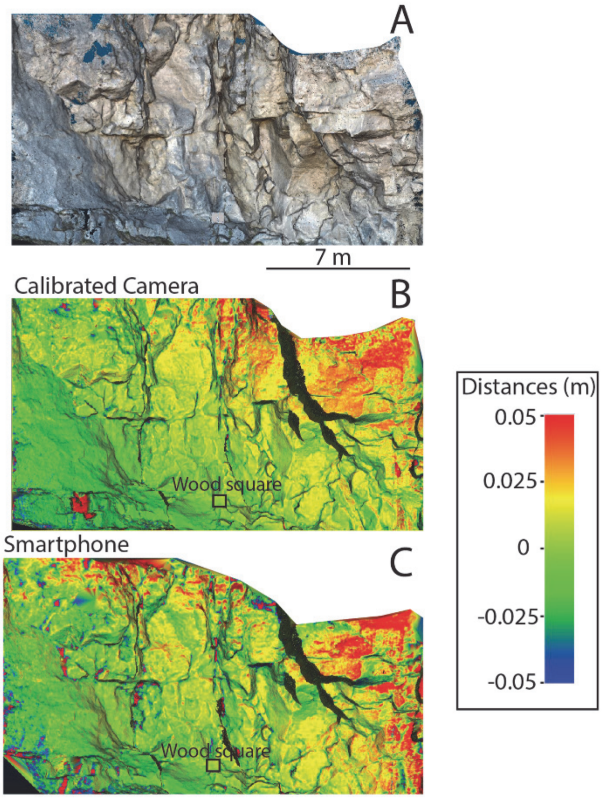

Fig. 4. 3D validation of the proposed DP methodology in a travertine slope at Civitella del Tronto, Central Italy. A) Photogrammetric 3D model obtained using reflex digital camera. B) Comparison between DP model obtained through reflex digital camera and LS. C) Comparison between DP model obtained through reflex digital camera and LS. View of models toward East

To further verify the quality of the DP models, we have compared measurements of the same discontinuity surfaces taken with the compass and the DP and LS models. Table 4 shows the results of such comparison in relation to the four surfaces shown in Figure 4A, highlighting the good agreement between the manual and DP/LS measurements.

Method	*Surface 1*	*Surface 2*	*Surface 3*	*Surface 4*
Compass	86/247	72/114	82/298	74/276
Reflex	87/248	71/113	88/295	77/271
Smartphone	89/248	72/114	88/297	79/277
LS	89/250	67/112	87/297	79/275

Tab. 4 - Dip and Dip direction of the 4 surface highlighted in Figure 4A acquired with compass, DP and LS

As aforementioned, the Q-slope and steepest slope angle values, as well as the SMR, change in relation to the slope attitude, even within the same geological formation. For this reason, GIS can be very useful for managing the information obtained from geological, geomechanical and DP surveys. Slope and Aspect GIS thematic maps (Figure 5 A-B) are used to identify the variation of slope dip and dip direction.

This information, integrated with the geological map (Figure 2) and data collected for each geological formation using geomechanical survey and DP (Table 2 and 3), allows the semi-automatic calculation of Q-slope values, steepest slope angles and SMR in each section of the study area, included inaccessible ones. Figure 6A-D shows the results of this process highlighting the Q-slope (Figure 6B), steepest slope angle (Figure 6C) and SMR values (Figure 6D) for every section of the SP52 road.

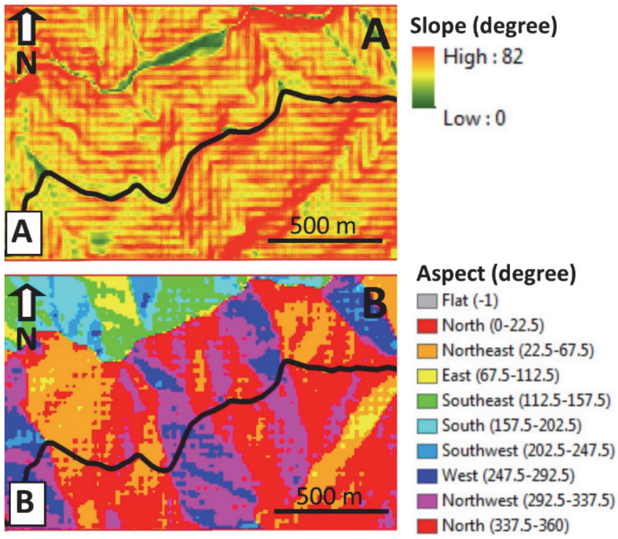

Fig. 5 - Thematic Slope (A) and Aspect (B) maps

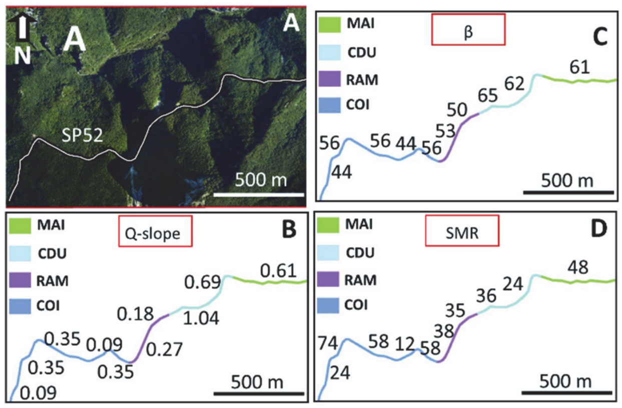

Fig. 6 - A) White line indicates the SP52 road in the orthophoto of the study area. B) Semi-automatic calculation of Q-slope values: C) Steepest slope angles: C) SMR (after Francioni et alii, 2018a)

DISCUSSION AND CONCLUSIONS

Geological engineering characterization of rock masses represents the first step in road cuts engineering design. When dealing with such interventions it is important to consider both the costs and the risks associated with the engineering solution to be adopted.

The cost of engineering classification of rock masses depends on the approach decided to be use. A rapid approach, such as the described Approach 1, has very low-cost mainly associated with the time necessary for the geomechanical analyses. The advent of dedicated smartphone applications, such as the Q-slope one, makes this approach easier and even more attractive. However, the results of this classification is connected to the amount of measurements taken in the field and, often, representative of the section of the outcrop that has been surveyed. When using DP, costs can increase, especially if total station or GPS are necessary. Using the DP method proposed in Approach 2, it is possible to avoid the use of GPS/total station and therefore decrease the cost of DP. The use of smartphone, as tested in this research, furtherly decreases the costs (which becomes comparable with the costs associated with Approach 1) but the precision of the model slightly decreases. In this case, it is suggested to validate the model in respect of field measurements. DP allows to improve the quality and the amount of data, making the analysis more consistent. Data become representative of the entire slope and it will be possible to perform more reliable kinematic slope analyses. The use of GIS permits to furtherly improve the data managing and to define the slope dip and dip direction also in inaccessible areas. This information can be combined with the geomechanical characteristics of the geological formation to understand the geometrical relationship between slope and discontinuity sets. Through this approach, engineering rock classification values can be extrapolated also to inaccessible areas (if the geology is known).

Finally, it is important to note how the use of remote sensing techniques allows to decrease the time of the field survey and the risk for the surveyor. The combined use of Q-slope and SMR is important because the SMR defines the possible kinematic problems and, in relation to the SMR class, Romana (1993) suggests engineering solutions for stabilizing the slopes. Q-slope allows the definition of the steepest slope angles. Therefore, the proposed methodology permits to estimate the slope angle to be adopted without reinforcements and, at the same time, the possible solutions in case the slope could not be designed with such angle. Figure 7 shows an example of geomechanical map, highlighting SMR and β, achievable using the proposed approach. The best cost-effective solution during engineering road design can be decided accordingly, decreasing the cost and the risk during the design of road cuts.

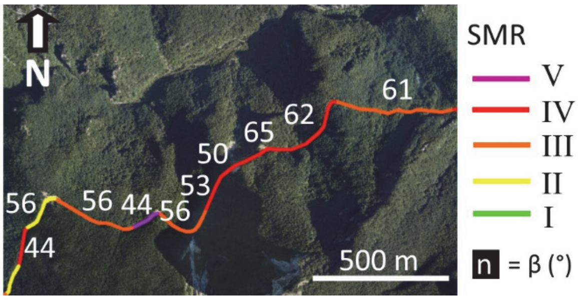

Fig. 7 - SMR classes and steepest slope angle (β).

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