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THE EVOLUTION OF METHODS FOR THE SURVEY AND ANALYSIS OF ROCK SLOPES: A REVIEW

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EXTENDED ABSTRACT

Le frane di crollo nei versanti in roccia rappresentano uno dei maggiori rischi nelle geo-scienze, specialmente quando essi avvengono o possono avvenire in prossimità di strutture ed infrastrutture quali edifici, strade, ferrovie, etc.

Risulta quindi evidente che lo studio di questi fenomeni è molto importante e richiede molta attenzione. In generale si può dire che lo studio dei versanti in roccia è caratterizzato da tre principali *steps* che sono: i) il rilievo e la caratterizzazione dell'affioramento (o degli affioramenti) che identificano l'ammasso roccioso, ii) la determinazione dell'assetto strutturale e cinematico dell'ammasso e la sua classificazione geomeccanica, iii) l'analisi di stabilità e delle potenziali traiettorie di caduta dei massi instabili.

Il rilievo e la caratterizzazione degli affioramenti (i) si base sull'analisi approfondita dell'ammasso roccioso, definito come l'insieme del materiale roccioso e delle discontinuità che lo caratterizzano. Questa prima fase può essere fatta tramite tradizionali *scanline* geomeccaniche o tramite l'ausilio di tecniche remote sensing (fotogrammetria digitale e laser scanning) che permettono di ricostruire tridimensionalmente l'ammasso roccioso e di poter effettuare molteplici analisi in post-elaborazione. Una volta effettuato il rilievo e la caratterizzazione dell'ammasso sarà possibile effettuare le prime valutazioni sulla qualità stessa dell'ammasso (tramite le classificazioni geomeccaniche) e delle preliminari analisi cinematiche volte ad analizzare le relazioni tra la geometria delle discontinuità e del versante, al fine di valutare la possibilità di cedimenti (ii). L'ultimo *step* è infine rappresentato dalle analisi di stabilità e/o delle traiettorie di caduta dei massi (iii). In questa fase, a seconda dello scopo finale del lavoro, si andrà a definire la probabilità di cedimento dei versanti (o di singoli blocchi) e le aree potenzialmente interessate da questi ultimi.

Come facilmente intuibile, duranti le fasi di studio appena descritte è possibile scegliere tra una moltitudine di tipi di rilievi ed analisi e la loro scelta può giocare un ruolo fondamentale in termini di tempi e difficoltà di elaborazione dei dati, costi e qualità del dato finale. In tale contesto, questa ricerca ha lo scopo di presentare un *toolbox* da utilizzare durante le fasi di rilievo che sarà possibile interpellare durante le analisi necessarie alla valutazione di pericolosità di cedimento di versanti rocciosi. Questo *toolbox* andrà infatti a valutare le esistenti tecniche di rilievo e analisi, evidenziando vantaggi e limitazioni di tali tecniche durante le diverse fasi dello studio. Saranno inoltre introdotte innovative tecniche di rilievo ed analisi, sviluppate allo scopo di rendere le fasi rilievo più semplici ed accessibili, e di migliorare alcuni *steps* durante l'analisi dei versanti.

In particolare, le tecniche di rilievo che saranno descritte ed analizzate in questo lavoro sono: a) analisi geomeccanica convenzionale tramite *scanline*, b) fotogrammetria digitale terrestre tramite l'ausilio di camere reflex, c) fotogrammetria digitale terrestre tramite l'utilizzo di *smartphones* e d) fotogrammetria digitale tramite drone (*Unmanned aerial vehicle* - UAV).Tali tecniche saranno discusse andando ad evidenziare i vantaggi e le limitazioni di ognuna di esse e, in relazione ai dati ottenibili, saranno fatte valutazioni riguardanti qualità e costi associati ad ogni tecnica.

Una volta valutate le tecniche di rilievo si andranno ad esaminare i metodi di analisi di stabilità e delle traiettorie dei blocchi.

Il *toolbox* finale sarà quindi basato sull'analisi e valutazione critica delle tecniche di rilievo ed analisi che vengono generalmente utilizzate durante la valutazione di pericolosità dei versanti rocciosi. In relazione a tali indicazioni ed all'entità/importanza del progetto in esame, sarà possibile fare delle valutazioni specifiche su ogni tecnica da utilizzare ed andare a decidere le tecniche di rilievo ed analisi più idonee o più convenienti.

ABSTRACT

Rockfalls are a major hazard for human activities, especially in proximity of infrastructures. The steps in the analysis of rockfalls may include: i) the survey and characterization of rock outcrops, ii) the kinematic assessment and engineering classification of rock masses, ii) stability analysis and rockfall simulations.

This research aims to present a toolbox for rockfall hazard studies and risk mitigation. The toolbox has been created combining the existing methods of survey and analysis and new and innovative techniques developed during this project.

In particular, the survey techniques that have been analyzed are: i) conventional geomechanical survey, ii) reflex camera-based terrestrial photogrammetry, iii) recently developed Smartphone-based terrestrial photogrammetry and iv) UAV-based photogrammetry. Once evaluated such methods of survey, we discuss the use of gathered data for engineering rock mass classifications and rockfall analyses.

The toolbox can represent an innovative and important step in engineering rock slope analyses, allowing to understand advantages and limitations of each survey/analysis technique, not only related to the quality of data and results, but also considering other important aspects, such as the cost, the time of survey and post-processing and the complexity of survey and data management.

***Keywords**: rockfall, engineering rock mass characterization, remote sensing, smartphone application, cost-benefit analysis*

INTRODUCTION

Rockfalls and rock avalanches are a major hazard for human activities, especially in proximity of infrastructures such as roads, railways and housing. The study of such events is complex and has been related to several factors including the geology and structural setting of the area, rainfall, earthquakes, vegetation etc. In the last few decades researchers have proposed different methods for the analysis of such catastrophic events which affect both mountainous and coastal areas. The steps in the analysis of rockfalls and rock avalanches usually include the survey and characterization of rock outcrops, the kinematic assessment and engineering classification of rock masses and, where necessary, stability and rockfall simulations.

The survey and characterization of rock outcrops allow acquisition of information about the geometrical and physical characteristics of rock masses, such as rock strength, slope and discontinuity attitude, discontinuity spacing, persistence, roughness etc. Such parameters are usually collected through conventional engineering geological (geomechanical) surveys, sometimes combined with more innovative remote sensing technique. The advent of new technologies for the survey of geological features has led to step-change increases in the quality of data available for slope/geomechanical studies. Laser Scanning (LS) and Digital Photogrammetry (DP) have been the most widely used remote sensing techniques for landslide studies and characterization. Selected examples of the use of LS and DP for slope characterization can be found in Lato *et alii* (2009), Sturzenegger & Stead (2009a), Spreafico *et alii* (2017), Kromer *et alii* (2017) and Mazzanti *et alii* (2018). Lato *et alii* (2009) showed how to improve the use of LS data for the automated structural evaluation of discontinuities in rock slopes while Sturzenegger & Stead, (2009a) highlighted the possible uses of close-range LS for discontinuity characterization on road cuts. A critical overview of some of the limitations of terrestrial DP and LS when dealing with high steep rock slopes was presented by Sturzenegger & Stead (2009b). Many of the limitations discussed by Sturzenegger & Stead (2009b) have now largely been overcome by the increasing use of aerial platforms such as Unmanned Aerial Vehicles (UAV). The introduction of such platforms has dramatically improved the application of these systems, making DP and TS even more attractive for investigation of natural hazards. Francioni *et alii* (2020) showed the use of DP with UAV for improved rockfall simulations and Donati *et alii* (2017) illustrated their use in the analysis of the Hope Slide (Canada). Francioni *et alii* (2018) reviewed the use of remote sensing techniques for slope stability purposes, providing guidance and on how and when the data obtained from these techniques can be used as input for stability analyses.

Although remotely sensed data improves the quality of engineering rock mass analysis and classifications, it should be emphasized that the cost associated with the techniques and the increasing complexity of data management should be considered (Francioni *et alii*, 2018). Therefore, it is important to decide the most appropriate technique of survey in relation to the objectives of the work and the geometry of the slope.

The data gathered during geomechanical surveys allow the engineering classification/characterization of rock masses. The most commonly used rock mass classification systems are the Rock Mass Rating, RMR (Bieniawski, 1989), the Geological Strength Index, GSI (Hoek & Brown, 1997);the Slope Mass Rating (Romana, 2003) and the NGI Q-system and Q-Slope (Barton & Grimstad, 2014; Bar & Barton, 2017).

Classification systems represent very powerful tools for geotechnical engineering during slope analysis, road cut and/or pit excavation. It is important to select the most appropriate classification system in relation to research/work project that is intended to be performed. When dealing with natural and engineering slopes and road cuts, the most used systems are the SMR and the Q-Slope, with the Q-Slope providing potential adjustments to slope angles (the reinforcement-free steepest slope angle) and the SMR, the rock mass quality and the most appropriate mitigation works.

During the analysis of rockslide and rockfall hazards, engineering rock mass classification may be integrated with stability analysis techniques (limit equilibrium and numerical analyses) and rockfall simulations. These types of analyses allow to better understand slope behavior and verify the trajectory of potential failing rock blocks and the most suitable characteristics of protection works (e.g. dissipation energy of rock blocks). Different types of slope analyses and rockfall simulations can be undertaken in relation to software and data available. In general, the quality of the results achieved from these analyses is related to the input parameters. In particular, the geometry of the slope, discontinuities and potential failing blocks and coefficient of restitutions play a key role in the final results (Robiati *et alii*, 2019; Kusák *et alii*, 2019; De Stefano *et alii*, 2021).

In light of what discussed, it is clear that the study behind the analysis rock slope is a complex process which requires multiple steps. The choice of the type of survey, rock mass classification system, rock slope analysis and rockfall simulation has important implications in terms of quality of the results obtained, time and costs. In this context, this research aims to review the existing methods of survey and analysis and to develop/propose a toolbox for rockfall/rock avalanche hazard studies and risk mitigation.

SURVEY AND CHARACTERIZATION OF ROCK OUTCROPS

During this research, conventional engineering geological (geomechanical) survey and Digital Photogrammetry (DP) are combined to characterize rock slopes impacting roads and infrastructure. During geomechanical surveys it is possible to determine the physical properties of rock masses and other important parameters such as discontinuity attitude, spacing, aperture and infill materialiiThe methodology to perform such type of survey, based on the acquisition of joint characteristics along a scanline, is well known and deeply described in literature (Priest & Hudson, 1981). Scanline survey has the advantage to be a low-cost technique and to guarantee the possibility to investigate in depth every joint along the scanline. Limitation are related to the time necessary to acquire all the information on the field (several scanlines are often necessary to avoid biases in the results). Furthermore, it will only be possible to acquire data in the accessible parts of the slope (e.g. Fig.1), and the surveyors will be exposed to potential rockfall risks.

Nowadays, to overcome these issues, scanline method is integrated with remote sensing techniques. Three different types of DP techniques have been evaluated in this research: reflex camera-based DP, recently developed Smartphone-based DP (Francioni *et alii*, 2019a) and rotary wing UAV-based DP.

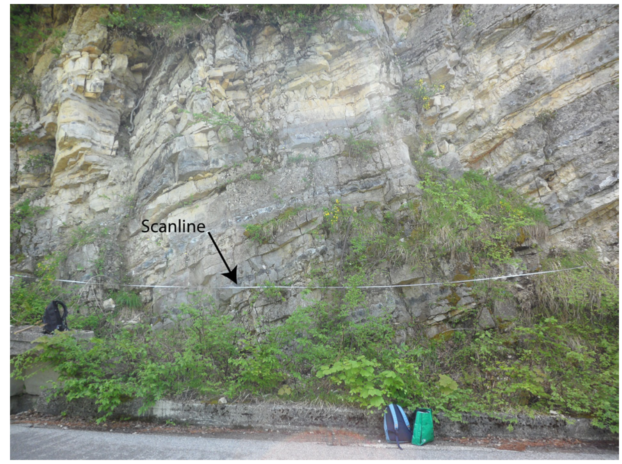

Fig. 1 - Example of Scanline method. Measurements will be taken along the tape set up at the slope toe

Reflex camera-based DP is one of the most used technique for the survey of accessible slope. When using this method, the camera can be hand-held or it is possible to use a tripod. A simple way to perform the survey is the use of image fan method (Birch, 2006) (Fig. 2), where the photographs are captured from specific camera locations (which are not independent). This easily defines, for every photogrammetric station, the area acquired by each photograph and guarantees the correct overlap.

The advantages of this technique are: i) it is possible to have full control of the camera and photographs can be acquired

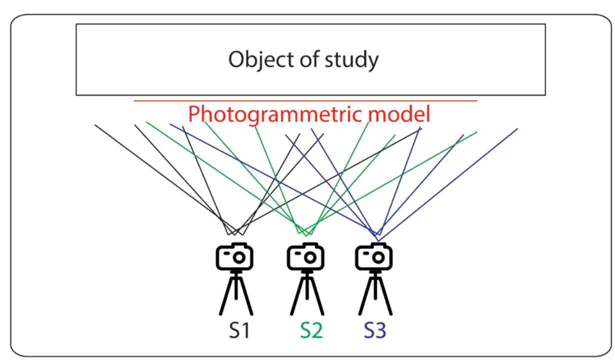

Fig. 2 - Image fan method.Photographs of the object of study are captured from specific camera locations

with great precision; ii) high portability of the instrumentation, (especially when using the orientation method proposed by Francioni *et alii*, 2019a, which allows to avoid the use of total station or GPS); iii) limits the cost incurred to the use of a digital camera; iv) reduces the time of the survey and therefore decreases the risk to the surveyor; v) data extracted can be used for engineering geological interpretation and post processing. Among the limitations, the most important is related to the presence of occlusions in the case of very high slopes.

Smartphone-based terrestrial photogrammetry has been demonstrated by Francioni *et alii* (2019a) and introduce the use of smartphone in engineering geological applications. The procedure for the use of this technique is the same illustrated for reflex cameras (Fig. 2). An example of photograph acquisition and 3D models for both reflex camera-based and smartphone based DP is shown in Fig. 3A-B.

The advantages of this technique are: i) it is possible to have a semi-total control of smartphone camera setup (in relation to the type of smartphone) and, with the new generation of smartphones, it is possible to acquired photographs with great quality; ii) very high portability of the instrumentation; iii) it is cost-free; iv) reduces the time of the survey and therefore decreases the risk to the surveyor; v) data extracted can be used for engineering geological interpretation and post processing. As for the reflex camera-based DP, the most important limitation is related to the presence of occlusions in the case of very high slopes. Furthermore, quality and precision of photographs (and related 3D models) are associated to the quality of the smartphone (Francioni *et alii*, 2019).

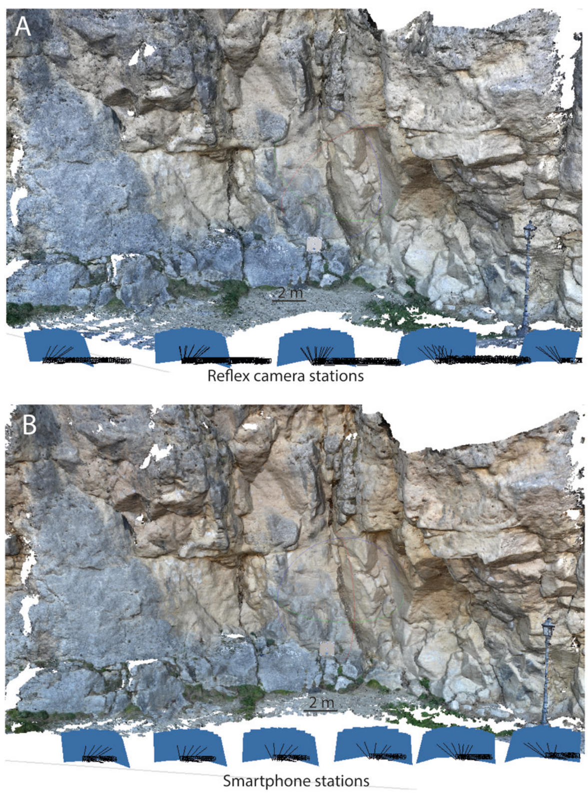

Fig. 3 - Photographs acquisition and camera stations during reflex-based (A) and smartphone-based DP (B)

Regarding the UAV-based DP, this become fundamental in case of very high and steep slopes and in case of inaccessible areas. In this case the acquisition of photographs can be carried out manually during the UAV flight or can be controlled through flight planning software. An example of photographs acquisition in vertical slopes is shown in Fig. 4. The advantages of this technique can be summarized as following: i) it is possible to reach and survey areas not accessible with any other survey technique; ii) the survey is relatively quick, and it is possible to acquire very large areas; iii) it is possible to have a semi-total control of UAV camera setup (this is related to the type of drone and camera) and to acquire photographs with great quality; iv) data extracted can be used for engineering geological interpretation and post processing. Among the limitation we can mention: i) the need of topographic instrumentation (GPS and/or total station) for the orientation of 3D model (not necessary in the other proposed DP techniques when using the method proposed by Francioni *et alii*, 2019a); ii) the survey is more complex if compared with the other DP techniques; iii) cost associated with the use of UAV and eventual topographic instrumentations remarkably increase.

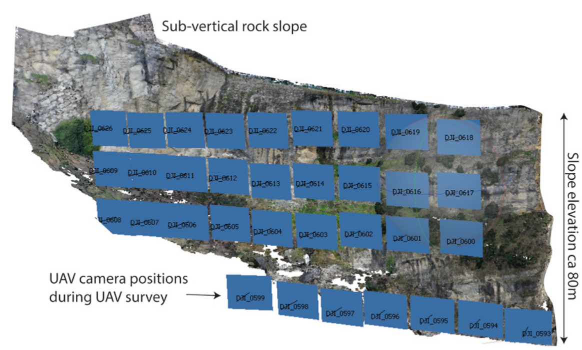

Fig. 4 - Photographs acquisition during UAV survey

THE KINEMATIC ASSESSMENT AND ENGINEERING CLASSIFICATION OF ROCK MASSES

Once the slope under study has been surveyed, the collected data are used for preliminary kinematic study and engineering rock mass classifications. Since this study is focused on the analysis of natural and engineered rock slopes, the Q-Slope and SMR are discussed.

Regarding the kinematic analysis, this is usually the first step in the analysis of rock slopes. Such analysis is based on the relationship between the geometry of joints and slope and its results are related to the quality of input data. It often happens that the geometry of slopes or joints vary over different areas. It is therefore important to have data representative of the entire study area. The integration of data collected with conventional scanline survey and remote sensing technique can play a key role in these studies. An example of this is showed in Fig. 5, where it is possible to observe the two stereonets extracted from scanline and DP survey sand the gathered DP 3D model with highlighted the joint set J1 (same case example of Fig. 1). The joint set J1has sub-vertical inclination and dip direction varying from NW to SE. Such variation is visible only through the DP survey, which allowed to create the 3D model of the entire slope.

Considering that the slope is dipping toward NNW, the results of kinematic analysis remarkably change in the two

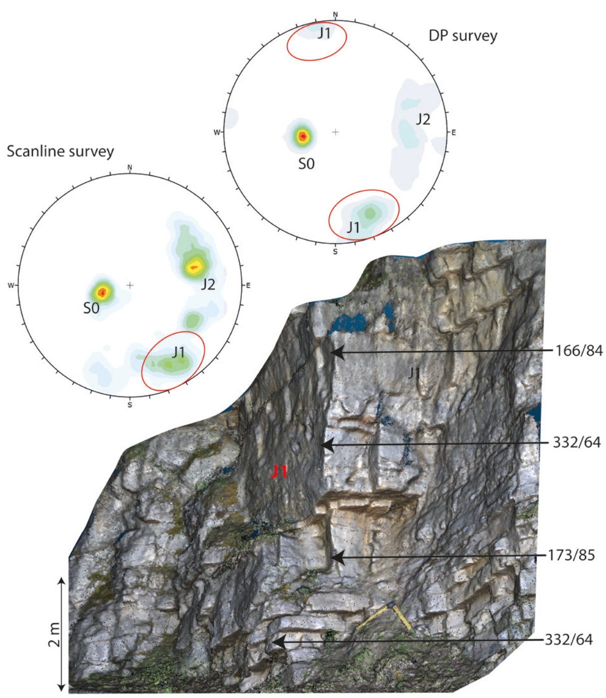

Fig. 5 - Stereonets obtained from scanline and DP surveys and the DP 3D model with highlighted the variation of joint set J1

stereonets.The stereonet from DP highlights the possibility of both planar and toppling failures along J1 while the stereonet from scanline survey shows only the potential planar failure along J1.

Furthermore, recent developments in available commercial software allow for including all the measured discontinuities in the kinematic slope analysis (instead of just considering the mean joint set orientations), making the use remote sensing data and kinematic analysis even more attractive.

The SMR (Formula 1 - Romana, 1993; Romana *et alii*, 2003) and Q-Slope (Formula 2 - Bar & Barton, 2017) are based on the integration of physical properties of rock mass and relationship between the geometry of the slope and joint sets.

Formula 1:

$$SMR = RMR_b + (F1 \times F \times F3) + F4$$

Where RMR_b is the Rock Mass Rating (without considering the parameter A6, adjustment rating for joints). F1, F2 and F3 represent the relationship between the slope and joint sets geometry. F4 is the adjustment factor for the method of excavation.

Formula 2:

$$Q_{slope} = (RQD/J_n) \times (J_r/J_a)_o \times (J_{wice}/SRF_{slope})$$

Where the symbols represent:

RQD: Rock quality designation; J_n Joint sets number

J_r: Joint roughness number

J_a: Joint alteration number

J_{wice}: Environmental and geological condition number

SRF_{slope}: Three strength reduction factors a, b, and c

O-factor: Orientation factor for the ratio J_r/J_a

In the SMR and Q-Slope, the geometrical relationship between slope and joint sets is controlled by the F1, F2 and F3 factors and the O-factor, respectively.

The physical properties are collected during the engineering geological (scanline) survey. The geometry of the slope and joint set can be gathered from both conventional and remote sensing surveys. Using the same example of Fig. 1 and Fig. 5, we have determined the SMR value and the Q-Slope using data from scanline and DP surveys. Considering what previously discussed about the set J1, the SMR and Q-Slope have been calculated taking into account the variability of such joint set. The results in terms of SMR values are reported in Tab. 1. It is possible to see that the most critical value is reported for the SW dipping joints of the set J1 (average dip direction of 159/77).

	Class	SMR
S0	Favourable	59
J1 (339\77)	Fair	54
J1 (159\77)	Unfavourable	41
J2	Fair	55
Wedge S0\J1	Favourable	100
Wedge S0\J2	Fair	100
Wedge J1\J2	Fair	51

Tab. 1 - Results of SMR classification for the caser study shon in Fig. 5

A similar result has been obtained from the Q-Slope, where the most critical joints, highlighted with a very unfavorable O-factor, are the SW dipping joints associated to J1, with a Q-Slope value of 0.2. Taking into account that through the conventional scanline survey the SW dipping joints associated to J1 were not measured (due to the slope elevation, Fig. 5), it is clear that, as for the kinematic analysis, the use of remote sensing survey can remarkably improve the reliability ofrock mass classification results.

STABILITY ANALYSIS AND ROCKFALL SIMULATIONS

The kinematic analysis and rock mass classification provide information about the quality of the rock masses and the kinematic/structural setting of slope and joints. When the stability of the slope needs to be investigated more in depth, limit equilibrium methods and/or numerical simulation can be undertaken.

Limit equilibrium methods are routinely used to identify the slope hazard occurring along a distinct failure surface(s). Analyses are performed to calculate either a Factor of Safety (FoS) or, through back analysis, a range of shear strength parameters at failure. The results of this type of analysis is based on the geometry of slope, material properties, forces involved, and discontinuity mechanical properties. In this context the use of remote sensing techniques can remarkably improve the results of the analysis, especially in the definition of the discrete location of the discontinuities that form the failure surface(s) and rear release (tension crack) of unstable blocks, the shape of the potentially unstable block and thereby the true potential failure volume (Fig. 6 – after Francioni *et alii*, 2018).

Although limit equilibrium methods are the simplest and most widely used slope analysis technique their use should, in general, be limited to uncomplicated case studies. More sophisticated numerical methods are better suited for the study of more complex case example and, also in such cases, these techniques of analysis can benefit significantly from remote sensing data, especially where 3D variations in the slope geometry and structure are important in the slope behaviour (Havaej *et alii* 2015; Francioni *et ali*i2014; Spreafico *et alii* 2016; Francioni *et alii*, 2018).

The volume and locations of blocks can also be used for rockfall simulations, which are based on the study of the slope geometry and the characteristics of potential falling blocks. Through rockfall simulation it is possible to determine the kinetic energy, velocity, "bounce height", end points and lateral dispersion of potential falling blocks. The possibility to gather a good representation of the slope morphology, potential unstable block geometry and land cover through remote sensing techniques is crucial for this type of simulation. Recently, Francioni *et alii* (2020) proposed a new method to use UAV data in advanced rockfall simulations. This is based on the study of fracture intensity and the development of 3D discrete fracture models from high resolution UAV imagery (Fig. 7, after Francioni *et alii*, 2020). The proposed method allows to statistically calculate the range of block volumes characterizing the studied slope and, therefore, to perform more realistic rockfall simulations.

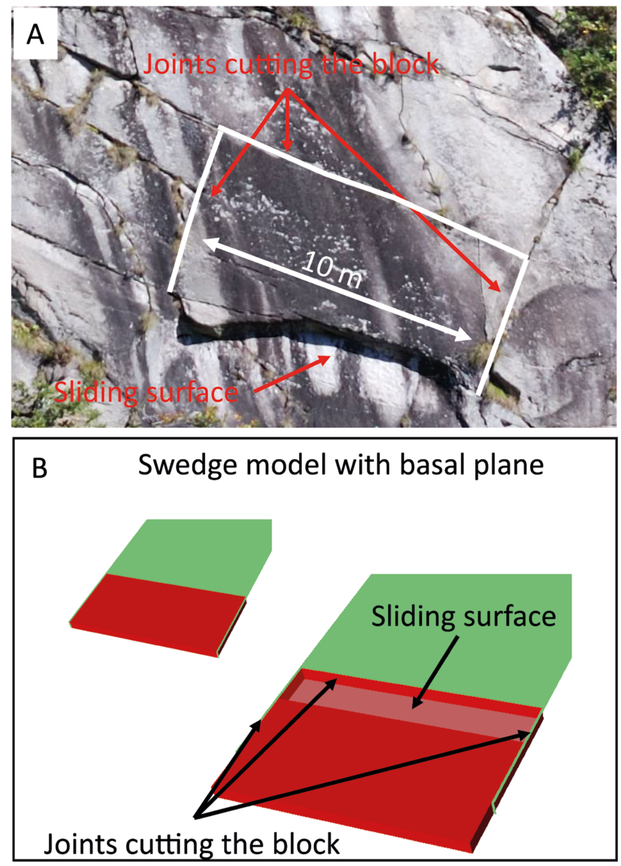

Fig. 6 - Photograph of potential instable block acquired through DP survey (A) and limit equilibrium model reconstructed from the DP model (B)

RESULTING DISCUSSIONS

The steps in the analysis of rockfalls are: i) the survey and characterization of rock outcrops, ii) the kinematic assessment and engineering classification of rock masses, ii) stability and rockfall simulations.

We have seen in the previous sections that remote sensing data can improve the quality of results during both surveys and analysis steps. Nevertheless, it should be emphasized that the cost associated with these techniques and the increasing complexity of data management should be considered (Francioni *et alii*, 2018). Therefore, it is important to decide the most appropriate technique of survey in relation to the geological risk and the geometry of the slope.

It is clear that the quality of the survey and analysis should increase when the slope morphology is complex and the risk for infrastructure and/or human life high. On the other hand, when the slope geometry is very simple and the risk low, the analysis can be performed so that to decrease time of post-processing and costs.

In this context, in relation to the case study and the associate risk, we can suggest the following guidelines.

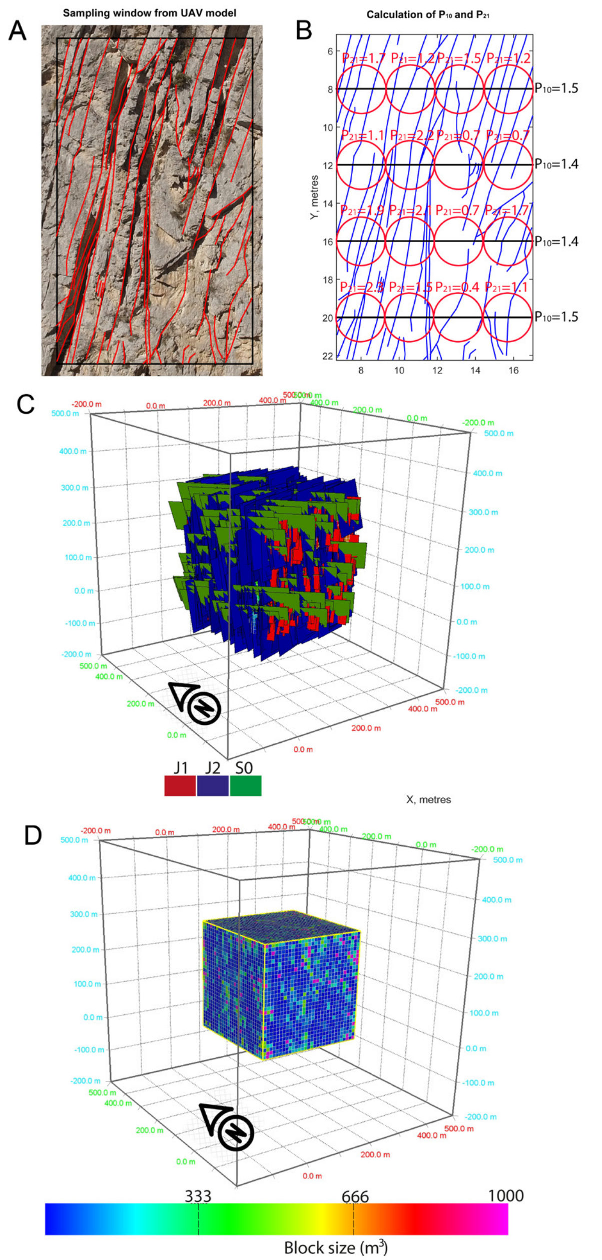

Fig. 7 - *A) Analysis of fracture intensity from high resolution UAV imagery. B) 3D discrete fracture model validated using P21 fracture intensity values. C)Statistic calculation of the range of block volumes characterizing the studied slope*

Methods for the survey and characterization of rock outcrops

We have analyzed four different type of survey which are: scanline methods, reflex camera-based DP, smartphone camera-based DP and UAV-based DP. Figure 8 summarize all the considerations made about the above mentioned techniques.

Through the methodology proposed by Francioni *et alii* (2019), it is possible to remarkably decrease the cost of DP surveys (cost-free in case of smartphone-based DP), maintaining a good quality of the resulting 3D models (for slope up to 10 m high).

We can therefore consider that the scanlines method and the smartphone-based DP are the less expensive techniques, followed by reflex-based DP (slightly higher) and UAV-based DP. Regarding the time of survey, reflex camera-based and smartphone-based are the fastest methods available, followed by UAV survey. The scanline is more time consuming. It has however to be highlighted that, when possible, the use of DP should be always considered additional to conventional scanline surveys (useful to determine physical properties of rock masses). When the scanline is integrated with DP survey, the scanline survey can be focused in the definition of physical characteristics

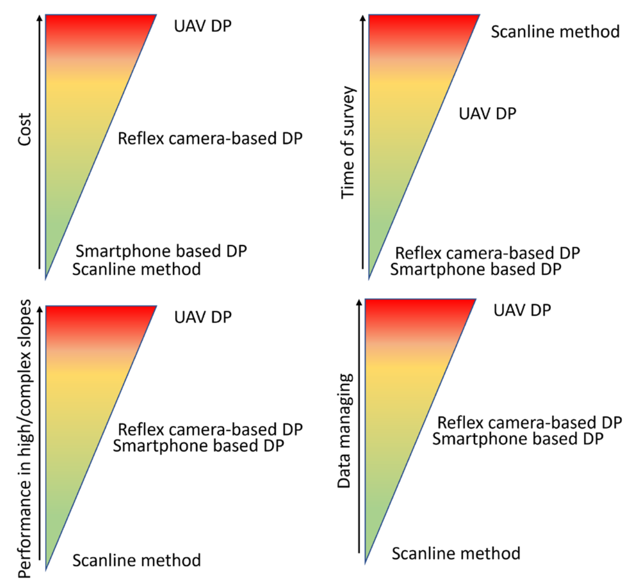

Fig. 8 - *Evaluation of DP techniques in relation to costs, time necessary for the survey, performance when dealing with high/steep slopes and data managing*

of joint sets and performed more rapidly.

In case of high and/or complex slope geometry, the use of UAV remarkably improves the quality and amount of data available. Smartphone and reflex-based DP can be considered a good solution for slopes up to 10-15 m while the data gathered from conventional scanline method (at the toe of the slope) should be used carefully. In case of slopes up to 2 meters with simple kinematic asset the scanline methods can be used without the integration of DP data. When the slope is between 2 to 10 m, the scanline method should be always integrated with terrestrial (smartphone or reflex-based) DP surveys. Over 10 m of elevation the use of UAV is suggested. In case of very complex slope geometry, terrestrial and UAV surveys can be combined.

Finally, with regard to the resulting data managing, it has to be considered that during the DP survey of high and wide slope, a large amount of photographs are acquired and the post processing of such data is more complex and require the use of high performance machine.

Slope analyses

Kinematic analysis is usually the first step in the analysis of rock slopes. As previously demonstrated, the result of this analysis is strictly connected with the quality of data available, which should be always representative of the entire slope. With regard to the rock mass classifications, the most used methods for rock slopes are the SMR and Q-Slope. Also in this case, we have demonstrated that the use of data representative of the entire slope allows to achieve more reliable results. It is also important to note that, as documented by Francioni *et alii* (2019b), the combined use of these two classification methods and GIS techniques makes the study of the slopes more exhaustive, allowing to gather the quality of rock mass and potential mitigation works (Romana, 2003) and the steepest reinforcement-free slope angle (Bar & Barton, 2015).When the slope geometry or the kinematic setting is very complex and the slope needs to be investigated more in depth, kinematic analysis and rock mass classifications should be integrated with limit equilibrium methods and/or numerical simulations and/or rockfall simulations (which allow to understand the potential trajectories of falling blocks and gather hazard and risk maps).

The cost, time, complexity and performance of the study that we want to carry out vary in relation to the type(s) of analysis that we decide to perform (Fig. 9). The kinematic analysis and rock mass classification represent the low cost solutions, but in case of complex slope geometry/kinematic asset, these could not be fully representative of the slope behavior. In such cases, slope analysis such as limit equilibrium or numerical simulation should be preferred. Numerical simulations represent the most sophisticate type of calculation and allows to simulate complex slope model. However, it has to be taken into account that the calibration and validation of numerical models is a complex process and, when not correctly done, can lead to incorrect results. Furthermore, the use of complex geometry increases the simulation time significantly and it is important to understand when this approach is necessary and when it can and should be avoided. Regarding rockfall analysis, these become very important when we need to understand the potential trajectory of rock blocks. Also in this case, the calibration of the runout model is very important but the time and complexity of the analysis is lower if compared with numerical simulations.

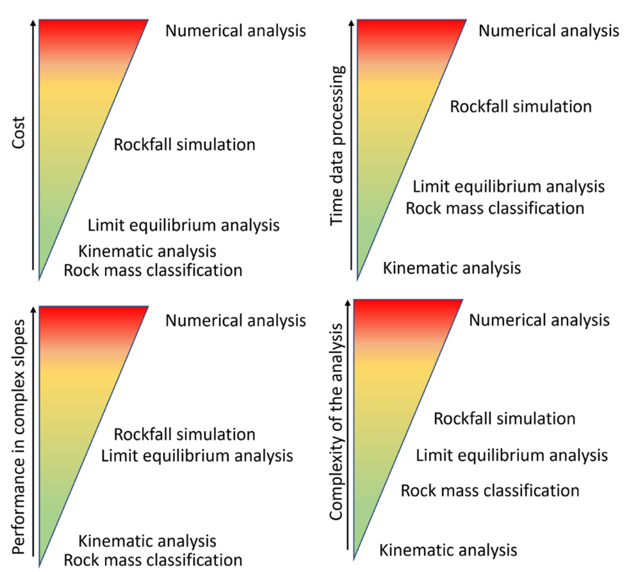

Fig. 9 - Evaluation of slope analyses in relation to costs, time of data processing, performance when dealing with complex slope geometries and complexity of the analysis

CONCLUSION

In this study we have analyzed and reviewed the existing and most used methods of survey and analysis of rock slopes. In particular, with regard to the survey techniques, we have taken into account the conventional scanline survey and three types of DP surveys. When the slope is less than 10 meters high, terrestrial DP survey can be a good solution, fast, low cost and with good quality resulting data. When the slope is more that 10-15 m high, the use of UAV system is recommended, although the cost and time of survey and data processing will increase.

Based on the case study presented and analyzed in this research, we have demonstrated the combined use of conventional scanline methods with DP techniques improve the results of all the examined slope analysis (rock mass classification, kinematic, limit equilibrium and numerical analyses). Furthermore, thanks to the methodology recently presented by these authors, the integration of DP and conventional survey remarkably improve the quality of data without increasing the cost and time of the survey.

Kinematic analysis and rock mass classification represent the first stage of rock slope studies. These are able to provide important preliminary information which can be used for engineering decisions. In particular, when the results of SMR and Q-Slope are combined, it is possible to obtain the quality of rock mass and suggest potential mitigation works and/or the steepest reinforcement-free slope angle.

When the slope geometry is more complex, limit equilibrium and numerical analyses should be preferred. These allow to better understand slope behavior and stability issues. The cost and time of analysis improve (especially in the case of numerical simulation) but, when the model is well calibrated, this can simulate complex slope behaviors.

It has however to be highlighted that the calibration and validation of numerical models is a complex and time-consuming process and, if now correctly performed, can lead to incorrect results and model behaviors.

Rockfall simulations are very important for the creation of hazard and risk maps. Also in this case the model calibration has to be carefully done but the results of such simulations are fundamental when the trajectories of potential falling blocks are unknow and falling blocks can reach infrastructures. The recent development of new methods, that combine fracture analysis and rockfall simulation (allowing to include in the analysis realistic ranges of block volumes) makes their use even more reliable and attractive.

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