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OPTIMIZATION OF GEOSTRUCTURAL SURVEYS IN ROCK MASS STABILITY ANALYSES USING REMOTE SENSING TECHNIQUES

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EXTENDED ABSTRACT

Gli ammassi rocciosi carbonatici sono frequentemente interessati da processi di instabilità associati al distacco di blocchi discreti individuati da discontinuità quali giunti di strato, fratture e faglie. Tali eventi potrebbero verificarsi sotto forma di scivolamenti, ribaltamenti o crolli; in corrispondenza di cavità naturali o antropiche, si possono inoltre sviluppare *sinkholes*. Ne consegue che, per la tutela del territorio, del patrimonio naturale, urbano e talvolta archeologico, risulta indispensabile definire la suscettibilità da frana e/o da dissesto idrogeologico, individuando le aree suscettibili a fenomeni gravitativi. Attualmente, le più sofisticate analisi di stabilità sono condotte tramite metodi numerici in grado di considerare l'evoluzione dei processi geomorfologici nel tempo. Tali tecniche richiedono una serie di dati sugli oggetti di studio che, nella pratica comune, sono raccolti tramite complesse attività di campagna. La presenza di discontinuità influisce sul comportamento meccanico degli ammassi rocciosi, per cui i rilievi geomeccanici e geostrutturali sono mirati alla raccolta di dati sulle discontinuità e sulle relative orientazione, spaziatura, persistenza, apertura, rugosità, resistenza delle pareti, alterazione e condizioni idrauliche. Il fine dei rilievi consiste nell'individuare le caratteristiche geometriche dell'ammasso, in modo da determinare la presenza di blocchi potenzialmente instabili, la loro forma, dimensione ed i cinematismi possibili. Nella pratica queste attività risultano particolarmente difficili e talvolta pericolose in aree ripide e poco accessibili, per cui è necessario ricorrere all'ausilio di geologi rocciatori esperti. Di conseguenza, si corre il rischio di commettere errori di campionamento e spesso i dati raccolti non sono sufficienti per una caratterizzazione geostrutturale e geomeccanica completa degli affioramenti. Recentemente si è cercato di rimediare a questi limiti avvalendosi di tecniche di telerilevamento nell'ambito della modellazione dei versanti, tramite le tecnologie di fotogrammetria digitale, *Terrestrial Laser Scanning* (TLS), LiDAR (*Light Detection and Ranging*) e, negli ultimi anni, di *Unmanned Aerial Vehicles* (UAV). L'acquisizione dei dati tramite fotocamere digitali, laser scanner e sistemi aeromobili a pilotaggio remoto, consente di rappresentare gli ammassi rocciosi tramite nuvole di punti geo-referenziate ad alta risoluzione. Nell'ambito della caratterizzazione geomeccanica, sono stati introdotti metodi per l'analisi di discontinuità da nuvole di punti, sebbene non sia stata sinora elaborata una procedura standard. L'attività di ricerca presentata mira a sperimentare, su casi di studio scelti in modo opportuno, le differenti tecniche disponibili in letteratura per l'estrazione e l'analisi di discontinuità dalle nuvole di punti e dei principali set, tramite procedure automatiche (mediante l'utilizzo di algoritmi) e semi-automatiche (con controllo manuale). I risultati saranno confrontati, al fine di comprendere i vantaggi ed i limiti dei metodi proposti, definire il più accurato e speditivo tra questi, ed elaborare una procedura per l'integrazione di rilievi tradizionali e di telerilevamento. I risultati saranno utilizzati per rappresentare le superfici planari su proiezioni stereografiche ed individuare i potenziali cinematismi, sulla base delle relazioni geometriche, tramite analisi cinematiche. Successivamente, i modelli geomeccanici saranno ottimizzati tramite la caratterizzazione fisica e meccanica dei materiali presenti in sito. In conclusione, i potenziali fenomeni di instabilità dei casi di studio saranno individuati tramite metodi numerici, con l'ausilio di software scelti accuratamente in relazione ai modelli ottenuti. Come risultato finale, ci si aspetta l'elaborazione di una procedura standard per una completa caratterizzazione geomeccanica di ammassi rocciosi, che può essere utilizzata per l'elaborazione di carte della pericolosità da frana in ambienti carbonatici.

ABSTRACT

Most instability processes in carbonate rock masses, such as slides, falls and topples are related to the mobilization of discrete blocks delimited by discontinuities (i.e. bedding planes or joints) and, eventually, to the presence of caves of both natural and man-made origin. Currently, the most sophisticated methods for evaluating potential or on-going gravitational instability mechanisms are based on advanced numerical software, that are also able to consider their evolution over time. In this context, accurate geomechanical characterizations, that include quantitative descriptions of the rock masses and of on-site materials, are fundamental for an appropriate stability analysis. Field geomechanical and geostructural surveys are carried out with the aim of detecting discontinuity orientation, spacing, persistence, roughness, wall strength, aperture, filling, seepage, number of discontinuity sets, block sizes and shapes. In practice, this approach is expensive and time-consuming, with many drawbacks such as lack of significant data in areas inaccessible or with difficult logistics. The aim of this research activity is to improve the methods for the characterization of rock masses by integrating traditional field surveys with remote sensing techniques, such as Terrestrial Laser Scanning (TLS), Light Detection and Ranging (LiDAR) and, eventually, Unmanned Aerial Vehicles (UAV), in order to carry out practical and realistic discontinuous modelling. Adequate case studies will be investigated by means of traditional scanline/window mapping methods and remote sensing techniques, supported by Terrestrial Laser Scanning and, at places, high-resolution UAV (Unmanned Aerial Vehicle) data. The acquired point clouds will be processed and tested for automatic (through algorithms) and semi-automatic (through algorithms and manual control) extraction of the discontinuities and related properties, both on raw data and on *meshes*, with the aim of establishing the most reliable method. The comparison of the results will allow to evaluate the advantages and limits of each technique and properly combine them, in order to create accurate 3D models of the case studies. Potential instability processes and geometrically possible motion of rock blocks will be detected through kinematic analyses with the help of stereographic projections, on the basis of the geometrical relations between the slope and the discontinuities. Successively, the results will be used for numerical stability solutions, thus identifying the propensity of the case studies to gravitational processes. The choice of the most suitable software will strongly be influenced by the calibrated geomechanical model and physical-mechanical behaviour of rock materials.

KEYWORDS: *stability, rock mass, point clouds, geomechanical classification*

INTRODUCTION

The identification of unstable areas in rock masses is fundamental for the protection of the environment, of human lives and of the cultural heritage at sites of particular archaeological interest. Natural disasters such as landslides can be prevented and mitigated through the construction of hazard maps which are based on the assessment of landslide susceptibility, defined as the probability of occurrence of a landslide in an area on the basis of the local terrain conditions (BRABB, 1984). Carbonate rock masses are frequently affected by failures as slides, falls and topples, related to the mobilization of discrete blocks delimited by discontinuities (i.e. bedding planes or joints); in addition, the presence of caves of both natural and man-made origin could lead to the formation of sinkholes (GUTIERREZ *et alii*, 2014). Since the geomechanical behaviour of rock masses is strongly influenced by the presence of discontinuities and of their properties (BIENIAWSKI, 1973, 1989), an accurate rock mass characterization requires a quantitative description of the discontinuity parameters. ISRM (1978) suggested to define, for each surface, a variety of parameters, including orientation, spacing, persistence, roughness, wall strength, aperture, filling, seepage, number of sets and block size. These data are traditionally collected from on-site surveys, through scanline and window mapping techniques (PRIEST, 1993; MAULDON *et alii*, 2001; KULATILAKE *et alii*, 2003) that consist in describing each discontinuity intersecting the scanline or located into the selected window by following the ISRM procedure (1978). In most cases traditional geomechanical and geostructural surveys can be dangerous, prone to instrument and human errors, such as sampling difficulties and choice of sampling methods (BARTON *et alii*, 1974; ISRM, 1978; FRANKLIN *et alii*, 1988; SLOB *et alii*, 2005; POROPAT & ELMOUTTIE, 2006). As a result, this approach is expensive and time-consuming, with many drawbacks such as lack of significant data in areas inaccessible or with difficult logistics, which do not allow to elaborate a complete reconstruction of the case study. In the last twenty years remote sensing techniques have been introduced in rock mass characterization with the aim of overcoming the disadvantages of traditional surveys, through the acquisition of high-resolution georeferenced 3D point clouds by non-contact measurements. In this perspective, FENG *et alii* (2001) proposed the use of total stations, but nowadays the most advanced techniques for discontinuity analysis are based on photogrammetry, Airborne Light Detection and Ranging (LiDAR), Terrestrial Laser Scanning (TLS) and Unmanned Aerial Vehicle (UAV). Once the outcrop data have been acquired with the help of digital cameras and laser scanners, the point clouds are processed in order to identify the planar surfaces and their related properties. Currently, the extraction of discontinuities can be achieved through semi-automatic and automatic methods. Semi-automatic procedures (GARCÍA-SELLÉS *et alii*, 2011; GIGLI & CASAGLI, 2011; RIQUELME *et alii*, 2014, 2015; MATASCI *et alii*, 2017; PALMA *et alii*, 2017) extract discontinuity sets and orientation directly from raw point clouds, by using advanced algorithms and software with manual control. The automatic procedures, proposed by SLOB & HACK (2004), SLOB *et alii* (2002, 2005), FERRERO *et alii* (2009), LATO *et alii* (2009), CHEN *et alii* (2016), WANG *et alii* (2016) and ZHANG *et alii* (2018) transform the point clouds in continuous 3D meshed surfaces by means of interpolation techniques (triangulation) before identifying the discontinuities. Furthermore, rock mass characterization can be completed through the identification of spacing (OPPIKOFER *et alii*, 2009; SLOB, 2010), persistence (STURZENEGGER & STEAD, 2009; RIQUELME *et alii*, 2018) and roughness (OPPIKOFER *et alii*, 2011) from point clouds.

The current research activity aims to compare the different remote sensing acquisition and processing methods available in the literature, after choosing appropriate case studies, to evaluate their advantages and limits. Once the most suitable technique is selected or a new one is developed, a method for integrating traditional geomechanical and geostructural surveys with new technologies, eventually including Unmanned Aerial Vehicles (UAV), will be defined. The 3D models of the studied outcrops will be tested into sophisticated software for numerical stability solutions that will be chosen after the identification of calibrated geomechanical models and physical-mechanical behaviour of rock materials.

RESEARCH ACTIVITY

The proposed research activity will be structured according to the flow chart shown in Fig. 1. Adequate case studies will be chosen considering accessibility and logistics, in order to carry out both traditional and remote sensing surveys. Each site will be subjected to data acquisition and data processing; then the resulting 3D models will be used to carry out structural analyses and to identify the potential and on-going failure mechanisms.

Data acquisition

Traditional geostructural and geomechanical surveys will be performed on representative areas of each case study. Scanline and window mapping technique (PRIEST, 1993; MAULDON *et alii*, 2001; KULATILAKE *et alii*, 2003) will be adopted, in order to collect discontinuity data according to ISRM suggestions (1988), including orientation, spacing, persistence, roughness, wall strength, aperture, filling, seepage, number of sets and block size. In addition, representative rock samples will be taken for laboratory investigations. Point clouds of the study areas will be acquired by means of high-resolution panoramic photographs, TLS and, at places, UAV techniques.

Data processing

The point clouds obtained from different scan positions will be translated, rotated and referenced in a unique coordinate system, through a registration process. The final point cloud will be filtered by removing non-geological objects and colored with RGB data acquired from the ground-based laser scanner. Next, a copy of the point cloud will be converted into a continuous surface (mesh) made up of triangles or facets, by means of triangulation or approximation. A realistic texturized 3D model will be obtained by overlapping the high-resolution photographs on the mesh model.

Structural analysis

The data collected during traditional field surveys will be reported on stereographic diagrams by tracing the planes on equatorial stereonets (Schmidt nets) with the aim of identifying the geometrical parameters of the outcrops and the main joint sets. The 3D models obtained from remote sensing techniques will be treated with statistical procedures. In particular, planar surfaces will be extracted both from the raw point clouds and from the mesh models, respectively by means of semi-automatic and automatic methods. Afterwards, the main joint sets and their mean orientation will be projected in stereographic diagrams, as illustrated in Fig. 2, and set spacing, persistence and roughness will be determined. The different algorithms described in the cited literature will be tested and the results will be compared one to the other, and with the results of the traditional surveys as well, in order to identify the most reliable technique. The final models will be obtained through the combination of data derived from the different acquisition methods.

Analysis of failure mechanisms

Kinematic analyses will be carried out by means of GOODMAN & SHI's (1985) graphical approach for detecting geometrically possible planar, wedge and toppling failures. Figure 3 shows an example of kinematic analysis carried out on a hypothetical rock mass with dip/dip direction 70/90 characterized by the presence of 4 discontinuity sets, with the following mean dip/dip directions: 65/91, 49/150, 88/180, and 5/84. Kinematic analyses identify only the geometrically possible motion of rock blocks, without considering the properties of the rock materials. Since the on-site materials strongly influence the mechanical behavior of rock masses, the samples collected during the field work will be investigated. For each identified facies, the physical and mechanical properties will be determined, together with qualitative fabric observations in petrographic thin sections, by means of a transmitted light polarizing optical microscope. After characterizing the intact rock, the rock masses of the case studies will be classified according to the geomechanical classification systems (BIENIAWSKI, 1973, 1989, 1993; BARTON, 2002; HOEK *et alii*, 1995, 2002; MARINOS, 2018). Finally, the prediction and assessment of the instability potential and failure types of the study areas will be determined by using appropriate numerical stability solutions. The choice of the most suitable software will strongly be influenced by the calibrated geomechanical model and physical-mechanical behaviour of rock materials.

CONCLUSIONS AND EXPECTED RESULTS

This paper briefly highlights the limits of geo-mechanical and geo-structural surveys for stability analysis in carbonate rock masses and illustrates the recent advances through remote sensing techniques. The proposed research activity aims to compare the different methods for rock mass recognition from digital dataset of appropriate case studies, in order to select and eventually revise the most reliable ones. The final 3D models will be improved with the properties of the rock materials and tested in numerical stability solutions. The expected result is the introduction of a standard procedure for a complete rock mass characterization, which could be used for the elaboration of landslide or sinkhole susceptibility maps in carbonate environments.

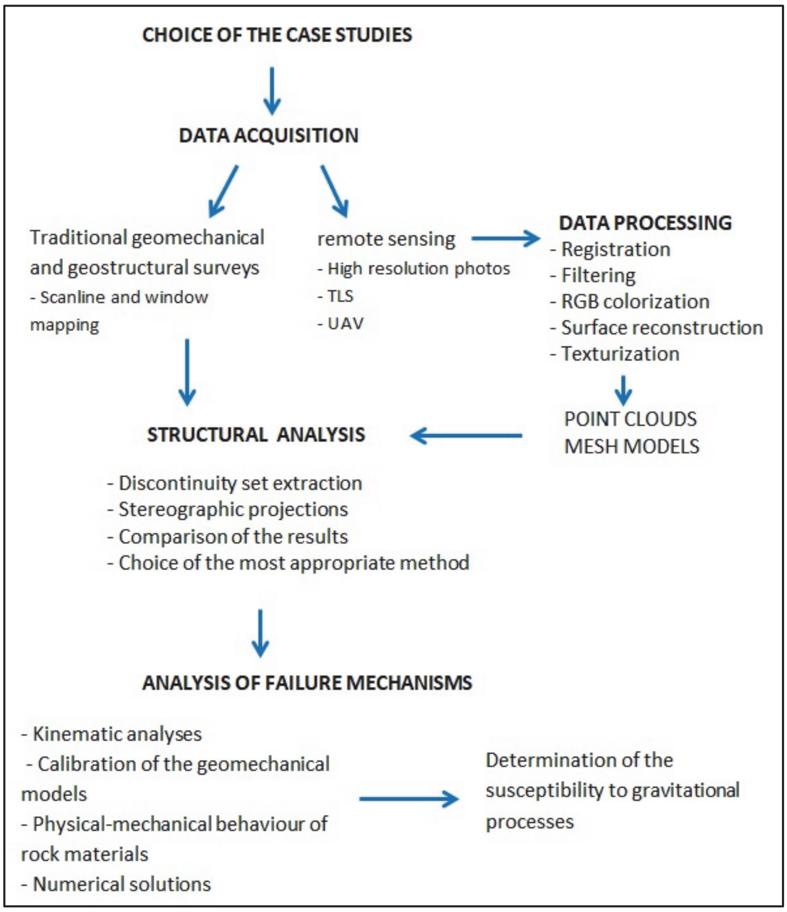

Fig. 1 - Flow chart representing the organization of the research activity

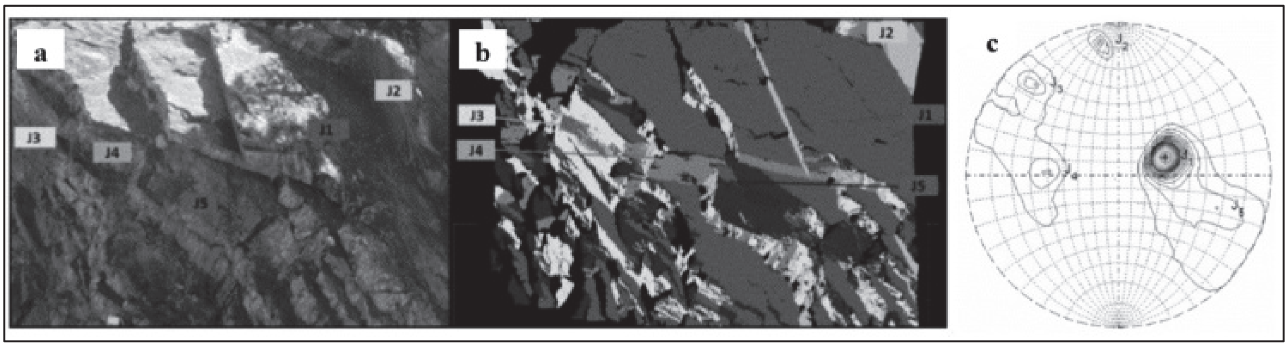

Fig. 2 - Example of semi-automatic discontinuity extraction from a rock mass point cloud (after RIQUELME et alii, 2014): a) photo of the tested road cut slope; b) assignment of the discontinuity sets (J1-J4) identified in the point cloud; c) representation of the main discontinuity sets in stereographic projections

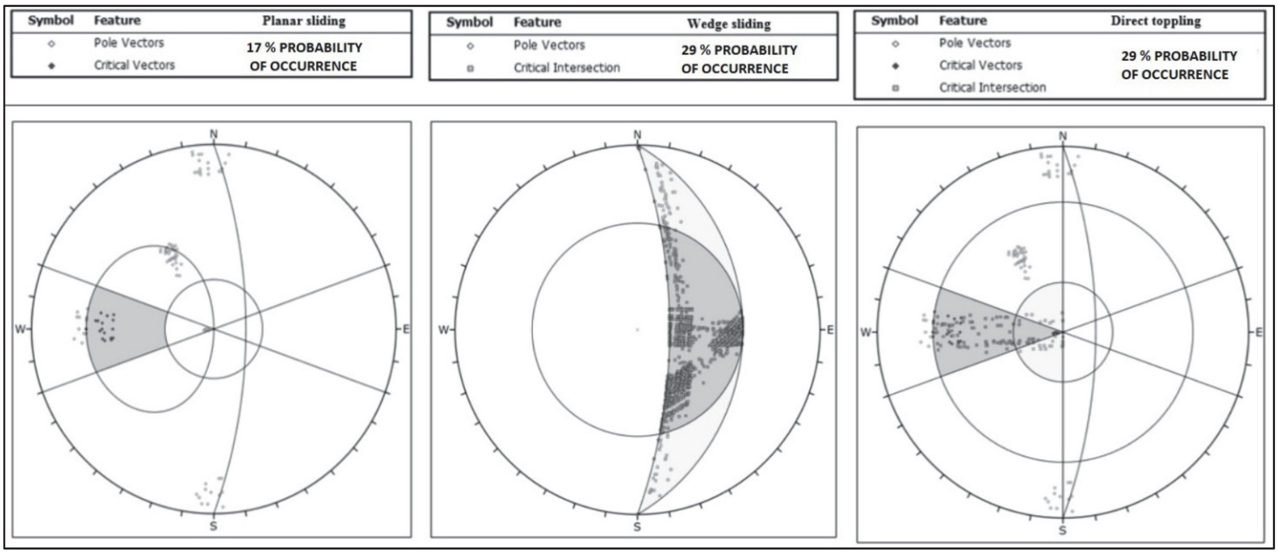

Fig 3 - Simulation of kinematic analysis carried out on a hypothetical rock mass characterized by the presence of 4 discontinuity sets: a) planar sliding test; b) wedge sliding test; c) direct toppling test. The poles and the intersections of the discontinuities located in the highlighted sectors of the stereonets represent critical states, with a probability of occurrence of 17 % for planar sliding, 29 % for wedge sliding and 29 % for direct toppling

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