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Classification of natural and engineered rock slopes using UAV photogrammetry for assessing stability

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Abstract. Ground failure on natural and engineered rock slopes is a geological hazard with potentially fatal consequences to the public or personnel in the mining industry. Aerial reconnaissance with the use of unmanned aerial vehicles (UAV) is rapidly becoming standard practice for geotechnical and engineering geological site investigations, enabling faster and safer data collection on slopes, which are often difficult to access on foot. Data obtained from aerial reconnaissance alongside conventional field investigations assist in the development of an engineering geological model that can form the basis of various stability analyses including kinematic, limit equilibrium and finite element analyses, and even rock fall simulations. This paper presents two case studies in which remote reconnaissance is used as an initial method of site investigation to classify natural and engineered rock slopes. The case studies from San Leo in Italy and an open pit mine in the Caribbean are used to demonstrate the effectiveness of these techniques for developing a preliminary engineering geological model from which stability analyses can be derived to predict future ground behaviour to assist in managing risks associated with the geological hazard.

Introduction

Rock mass characterization represents the first stage in definition of the quality and stability of rock masses. These are based on the engineering characterization of rock outcrops, which is usually carried out through traditional engineering geological surveys. When dealing with high and/or inaccessible slopes, both of natural and man-made origin, rock mass characterization become challenging. With the goal of overcoming such issue, since 2009 [1] suggested to couple traditional field measurements with data from remote sensing techniques, so that to improve the quality and amount of data available for rock mass analyses. Indeed, techniques such as terrestrial laser scanning (TLS) and digital terrestrial photogrammetry (DTP) for rock mass characterisation are increasingly being used in the last decades.

TLS and DTP allow accurate representation of rock outcrops by means of 3D textured point clouds and interpolated models. A limitation of ground-based remote sensing is related to the survey of high slopes and complex morphologies where the site of acquisition, generally at the bottom of the slopes, results in occlusion zones and shadows in the output data [2]. Such limitation can however be overcome using unmanned aerial vehicles (UAV), from which high-detail images can be acquired also in the case of high and steep slopes. UAV-photogrammetry allows to produce 3D data and orthophotos that can be

used to define the geometry of slopes and some characteristics of discontinuities. Although the use of UAV data in rock slope analyses have been discussed by many authors [3, 4, 5, 6, 7]; however, their use as tool for incorporation in empirical rock mass classification methods, such as the Geological Strength Index (GSI) [8] and Q-slope [9], has not been discussed in depth.

In this paper, two case studies, represented by the San Leo (natural) slope in Italy and individual benches in an open pit mine in the Caribbean are shown (figure 1), with the goal of demonstrating how output from UAV photogrammetry can be adopted for applying the Q-slope method in rock slope engineering for natural and excavated slopes which are otherwise not safely accessible on foot.

Figure 1. The case studies: (a) the scarp of the 2014 San Leo rock fall; (b) unreachable benches of an open pit mine in the Caribbean.

1. Q-slope

The Q-slope method for rock slope engineering [9] assesses the stability of excavated rock slopes. It provides a simple correlation between Q-slope and long-term stable slope angles based on several case studies in Asia, Australia, the Americas, and Europe.

Q-slope has been developed by supplementing the Q-system with parameters, RQD, joint set number (J_n), joint roughness number (J_r), joint alteration number (J_a) remaining unchanged. The joint water reduction factor is now termed J_{wice} and considers long-term exposure to various climatic and environmental conditions such as intense erosive rainfall and ice-wedging effects. Orientation weightings (O-factors) are applied to both sides of potential wedges, and slope-relevant SRF (strength reduction factor) categories for physical slope conditions, stress-strength ratios, and major discontinuities has been incorporated.

$$Q_{slope} = \left(\frac{RQD}{J_n}\right) \times \left(\frac{J_r}{J_a}\right)_O \times \left(\frac{J_{wice}}{SRF_{slope}}\right) \qquad (1)$$

With reference to the two case studies, Q-slope method has been evaluated using a combination of field-based and remote sensing datasets.

2. UAV Methodology

Photogrammetric surveys have been carried out using UAV technology to obtain high-resolution digital outputs (digital surface models - DSMs and orthophotos) for use in the classification of rock masses. An unmanned quadcopter equipped with a digital camera has been used. It consists of four electric rotors, a remote-control system and dedicated software for flight plan management. The UAV is equipped with a GPS and an inertial navigation system that can records 3D spatial coordinates and the orientation of the camera. Four vertical flights with overlap and sidelap ensured coverage of the entire areas. The pictures have been taken from an average distance of 30-50 m from the slope surface, yielding an

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estimated Ground Sample Distance of about 1 cm. CloudCompare and ShapeMetriX UAV software have been used to georeference and manage the point clouds and to extract geo-structural features in inaccessible areas.

3. Case studies

3.1. San Leo plateau (Italy)

San Leo is one of the most famous towns and castles of the historical region of Montefeltro (Northern Apennines, Italy). For centuries, it was renowned as an impregnable military fortress due to its elevated geographical position and massive fortifications. The town rises at the top of a rocky slab, bordered by subvertical and overhanging cliffs up to 100 m high, overlying gentle slopes (figure 1a). The fortress underwent significant restoration works during the course of centuries, mainly because of the effects of a number of landslides, most of which are well documented by chronicles, paintings and other historical documents. Even recently, in 2006 and 2014, large rockfalls (50,000 and 300,000 m^3 respectively) affected the northern and eastern cliffs of the plateau [10]. The plateau comprises calcarenite units overlaying clays along a tectonic contact. The entire rock slab is affected by lateral spreading which is evident through the presence of crack opening at top of the slab, differential movements, bulging and squeezing of clayey material at the base. Moreover, the clays undergo periodic swelling and are subjected to rapid erosion and unloading phenomena. Landslide processes such as earth slides-flows concentrate both at the foot of the cliff and in the surrounding badlands. As a result, the cliff itself is progressively undermined and the stability of the rock slab is affected by rock falls. Periodic and expensive maintenance and consolidation works are completed to minimize damage to the heritage site.
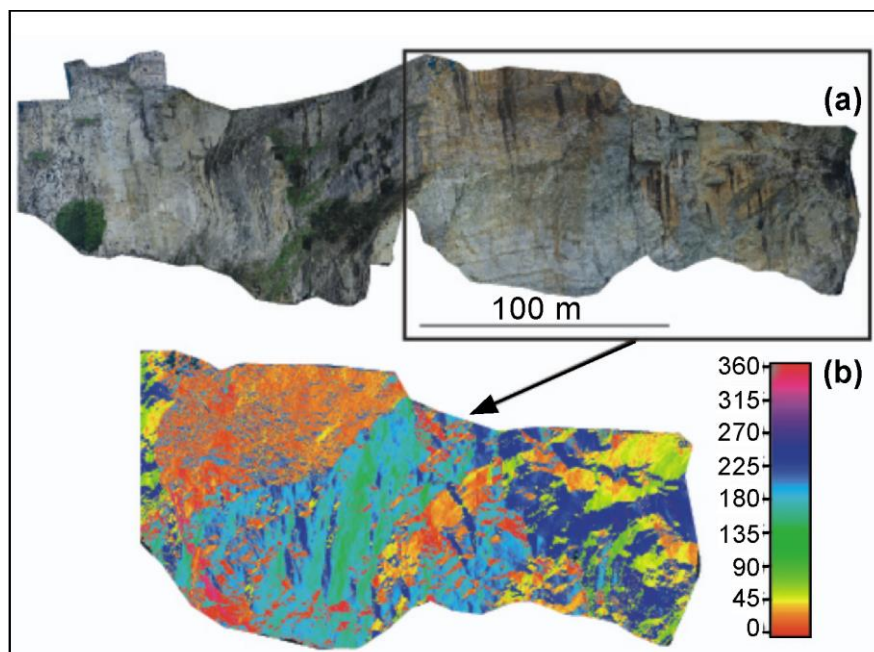

Figure 2. San Leo slope: (a) 3D point cloud extracted from UAV survey; (b) CloudCompare output; color scale represents slope face dip directions.

3.2. Benches in Open Pit Mine (Caribbean)

An open pit mine in the Caribbean archipelago is located at 300 to 500 m above sea level. It receives approximately 2,000 mm of annual rainfall, which occurs all year round, although the wet seasons receives almost twice the rainfall compared to the dry.

The open pit slopes (figure 3) are hosted in carbonaceous sediments comprising mudstones and sandstones, interbedded with various tuffs. The strata is generally sub-horizontal although it has been

faulted and domed upward with and andesitic intrusions. The stability of individual benches is typically dictated by the location, orientation, and persistence of weak joints and shears. Typically, these comprise sandy particles from disintegrated rock or silt and clay infilling.
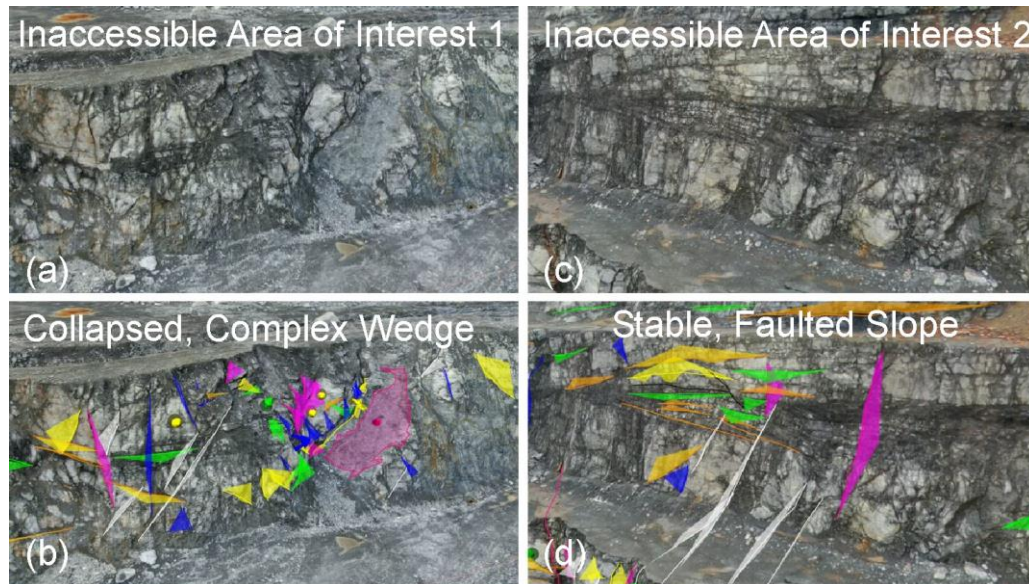

Figure 3. Open pit mine benches in the Caribbean. (a) & (b): Area 1 showing a local, complex wedge failure controlled by 3 discontinuity sets; (c) & (d): Area 2 showing stable slope with 2 discontinuity sets and random joints.

4. Results

The results presented incorporate the use of UAV photogrammetry for rock mass classification using Q-slope. Due to safety risks associated with rock fall and limited physical access to the physical, UAV surveys have been carried to improve the amount and quality of data available for the analysis. The post processing of UAV photographs allowed for the creation of 3D photogrammetric models representing the slopes under study. Figures 2 and 3 show the 3D models of the San Leo slope and benches in the open pit mine, respectively.

Regarding the San Leo case study, the natural slope, about 80 m high, is sub-vertical and characterized by a large slope (planar) failure that in 2014 lead to a subsequent rock fall. The structural/geomechanical analysis highlighted the presence of three discontinuity sets (Fig. 4, which excludes bedding). The other parameters useful for the estimation of Q-slope can be summarized as it follows. The RQD is equal to 100%, testify a good quality of the rock mass. The main discontinuity set involved in the instability of the slope (Set A, Table 1) is characterized by a clean, irregular, undulating surface (joint roughness - J_r of 3). The environmental and geological conditions are typical of a wet environment with a J_{wice} of 0.7. Considering the very unfavourable orientation of Set A (causing failure if unsupported), with an orientation factor of 0.25, the calculated Q-slope is equal to 5.83.
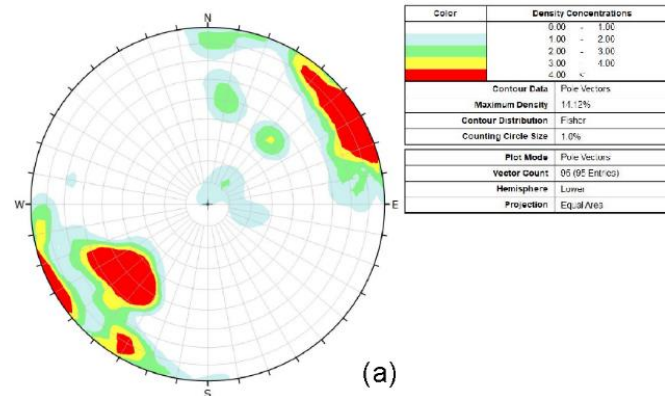
Figure 4. Stereonet representing the discontinuity sets in San Leo (note: bedding not shown for clarity).

Area 1 in the open pit mine is a failed slope (localized wedge), with a height of 10 m and a pre-failure slope angle of 56 degrees. Area 2 is a stable slope, 11 m high with a slope angle of 57 degrees. Mapping of geological structures using UAV photogrammetry models highlighted the presence of three main joint sets for Area 1 and two main joint sets (plus random joints) for Area 2 (figure 5 and Table 1). The parameters for estimating Q-slope (Table 1) were obtained from logging nearby boreholes. RQD was estimated to be 70% on average in both the slopes. This was confirmed with UAV photogrammetry focusing on open fractures in the slope.

Area 1 is characterized by a complex wedge failure where the joint sets (Set A and B, Table 1) are characterized by a smooth, undulating joint surfaces. The Set B has clayey infilling, while infill in Set A comprises sandy particles and rock fragments. Area 2 is stable and has similar joint characteristics to Set A in Area 1. O-factors have been described based on the orientation of the discontinuity sets relative to the slope.

The environmental and geological condition of the open pit mine are typical of a wet environment. A J_{wice} of 0.7 was adopted since the rock is generally competent and with stable structure.

The physical conditions of the open pit slopes are described as slightly loosening due to surface location, defining their maximum SRF to 2.5.
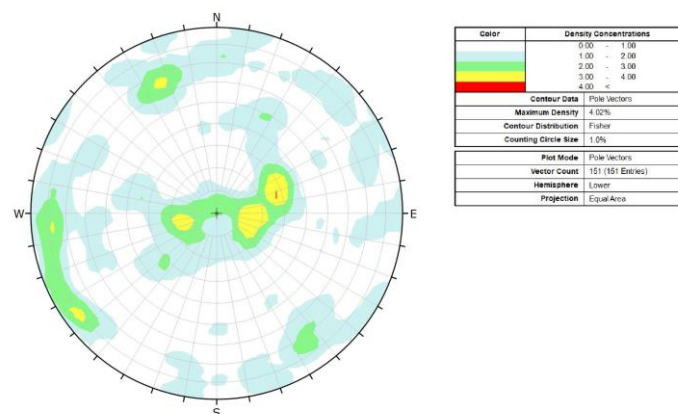

Figure 5. Stereonet representing the discontinuity sets in the open pit mine, inclusive of Area 1 and 2.

Table 1. Evaluation of Q-slope for the analysed slopes.

Q-slope parameters	San Leo landslide		Open pit mine (Area 1)		Open pit mine (Area 2)	
Status	Failed		Failed		Stable	
Excavated Slope Angle	89 degrees		65 degrees		67 degrees	
Slope Height	80 m		10 m		11 m	
RQD	100%		70%		70%	
J_n	3 sets		3 sets		2 sets + random	
Set	A	B	A	B	A	B
J_r	3	-	2	2	2	-
J_a	1	-	4	6	6	-
O-factor	0.25	-	0.75	1	1	-
J_{wice}	0.70		0.70		0.70	
SRF_a	1		2.5		2.5	
SRF_b			1		1	
SRF_c			1		1	
Q-slope	5.833		0.272		1.088	

5. Discussion and conclusions

UAV photogrammetry and Q-slope were applied to natural and engineered slopes for the case studies in hazardous areas in Italy and in the Caribbean. The results shown in figure 6 are in agreement with previous Q-slope assessments that were completed, on foot, in the field.

The benefit of combining UAV photogrammetry and Q-slope in these case studies is the ability to rapidly create an accurate topographical survey and to derive geological structure information in areas that are not safely accessible by people.

Limitations of UAV photogrammetry in these case studies are mainly associated with limited ability to estimate joint roughness and alteration properties. Similarly, intact rock strength could not be estimated at the exact locations. Supplementary information from historic boreholes had to be used to estimate Q-slope effectively.

Q-slope was developed for use by geotechnical engineers and engineering geologists in the field, to enable decision making and adjustments to slope designs during construction. In both case studies, the combined use of UAV photogrammetry and Q-slope are used as a retrospective analysis tool. The process required considerable additional time than conventional, in-field, Q-slope assessments.
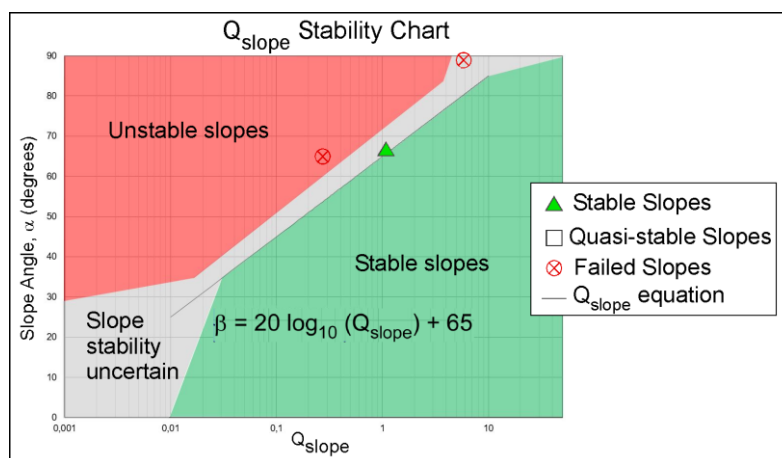

Figure 6. Q-slope stability chart with Italian and Caribbean case studies using UAV photogrammetry

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