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Use of Digital Terrestrial Photogrammetry in rocky slope stability analysis by Distinct Elements Numerical Methods

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ABSTRACT

Current approaches to rocky slope stability analysis require knowledge of the geometrical–structural setting, as well as the physical–mechanical properties of the intact material and its discontinuities. The physical–mechanical properties are derived from in situ and laboratory tests, whereas the geometrical characteristics come from field attitude measurements. Frequently, the inaccessibility of walls does not allow direct measurement of discontinuity surfaces by traditional geological methods. In such cases, data can only be obtained by statistical methods. Although this approach is significant and provides spatial meaning, it is ineffective for deterministic analysis.

This paper provides a solution to this problem by applying digital terrestrial photogrammetric techniques employing a reamed bar, an aerostatic balloon and a helicopter. Results demonstrate that the accuracy and the quantity of geometrical and engineering–geological data coming from the photogrammetric survey, allow for numerical simulation of the relationship between rock elements as a function of their physical–mechanical properties and load conditions. The 3DEC code was chosen among the different methods available to model the discontinuous media through distinct elements.

The proposed methodology was applied to a quarry located in the Carrara Marble District (the Apuan Alps, Italy), the largest and most exploited mining region in Europe. The economic value of the area required a detailed study of the presence of instability phenomena so that marble extraction could continue in safe conditions.

1. Introduction

In addition to the physical–mechanical properties of the intact material and its discontinuities, it is necessary to know the rock slope structural setting for the stability analysis in land exploitation planning. Physical–mechanical parameters are derived from in situ and laboratory trials, while geometrical characteristics have been traditionally taken from direct attitude measurements in the field. If accessibility problems do not allow direct measurement of discontinuity surfaces by traditional geological methods, data from this approach are only achievable by statistical processes. However, these methods are useless for the deterministic analysis of slopes characterised by appreciable outcrops and evident joint systems. In such cases, Digital Terrestrial Photogrammetry (DTP) is a useful technique for carrying out detailed surveys of geometrical–structural settings even in inaccessible sites.

Similar experiences, as described in international literature, have already demonstrated the role of DTP in rocky mass characterisation [1–6] and in slope stability monitoring [7,8]. Moreover, geometric and structural data were collected thanks to the utilisation of DTP from a helicopter [9–11]. It was, therefore, possible to observe the slopes at different zooms and from the best positions, otherwise only reachable by experts after a risky and arduous climb in such inaccessible sites. Moreover, digital acquisition allows structural and engineering–geological information (i.e. spacing and persistence) to be stored in a geodatabase. In this way, experts from diverse disciplines, such as geology and engineering, can inspect the joints scrolling the stereoscopic model and discuss them together. Traditional terrestrial photogrammetry requires photography in pseudo-normal conditions that cannot be satisfied in the presence of high natural walls. Indeed, taking photographs from a fixed position located in front of the slope's toe could cause the presence of shadows (zones, which cannot be detected owing to the irregular geometry of the rocky wall), which increase in relation to the height of the slope. If perspective views are unavailable from short distances and no mechanical lifts can reach the study area, the equipment necessary for the photogrammetric survey can be arranged on an aerostatic balloon or a helicopter, in order to capture the whole slope in vertical strips. The geometrical setting of the versant,

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referring to visible joint attitude, spacing, persistence and slope morphology, is re-built through stereoscopic photo-interpretation and GIS-based spatial analyses.

This survey methodology, combined with 3D modelling makes it possible to identify unstable blocks and wedges and measure their volume and position. Numerical methods are capable of performing an analysis starting from a representation of the system geometry. The construction of the model also has to take the following into consideration: boundary and initial conditions, natural and induced loading/perturbation histories and adequate constitutive laws, for both the rock matrix and fractures. Conventional methods for stability analysis are widely employed for their simplicity and the abundant experience in their application. However, their use is limited to relatively easy problems, including raw slope geometry and basic loading conditions. Many rock slope stability problems involve complexities related to geometry, material anisotropy, non-linear behaviour, in situ stresses and presence of several coupled processes [12]. In such cases, conventional methods of stability analysis are useful for the reconstruction of the trigger mechanism causing a failure event, but are ineffective for modelling its evolution and for evaluating the impact of such movements on overall stability. The mathematical principle on which the numerical modelling theory is based depends on the characteristics of the medium object of the representation. Some real configurations can be represented using a finite number of well-defined components. The behaviour of such components is either well known or can be independently treated mathematically. The global behaviour of the problem can be obtained through well-defined interrelation among individual components. Such systems are termed “discrete” and they are related to rock masses controlled by discontinuity behaviour [13].

For the purpose of this paper the 3DEC code [14–17] was chosen from among the different methods available to model discontinuous media through distinct elements. It treats the problem domain as an assemblage of distinct, interacting bodies or blocks that are subjected to external loads and are expected to undergo significant motion over time depending on material physical–mechanical characteristics.

2. Photogrammetric procedure for slopes and joints geometrical study

Photogrammetry is a remote sensing technique whereby the geometric properties of objects (shape and position) are determined from measurements of photographic images [18,19]. Thanks to digital technology, photogrammetry has been used in different fields, such as topographical mapping, architecture, engineering, and, recently, environmental geology [20–22].

In this paper the geological application of photogrammetry is employed to collect geometrical parameters necessary to verify failure conditions in relation to joint dip, dip direction and slope morphology.

2.1. Photogrammetric acquisition and images external orientation

In this paper, different methodologies are proposed depending on the versant morphology and the accessibility of facing areas. If the front is not very high (below 50 m) pictures can be acquired easily using a reamed bar. The equipment consists of an aluminium structure, which supports a sliding device with two spirit levels to control horizontality, on which a digital camera is placed (Fig. 1).

By means of this system, it is possible to obtain a horizontal cover of the whole versant. Moreover, possible shadows can be eliminated by changing the shooting position and focal length. However, there are some drawbacks to this survey method; in the case of very high slopes, it is unable to perform a complete photogrammetric cover of the highest zones of the rocky wall.

An aerostatic polyurethane, helium balloon carrying different equipments, can be used when the slope is very high (up to 300 m) and facing areas are accessible and sufficiently wide (Fig. 2). The balloon is driven from the ground by dyneema cables connected to four mobile bases provided with electrical winches to enable the remote control of system height and attitude. The equipment consists of an aluminium frame, supporting two digital cameras at its extremities. Image acquisition is controlled by a PC-driven radio system, which guarantees simultaneity and setting of the shot angle in relation to the North. This function is very important as it prevents problems with the yaw angle, maintaining the orthogonality of the system in relation to the slope. A software package named Dragonfly (Menci Software s.r.l.) has been specifically developed to run the procedure. When the balloon rises up to the maximum desired elevation, it remains stable during all the image acquisition phases. Pulleys attached below the balloon control the up-and-down movements of the photogrammetric equipment, while, for each strip, stereopairs are taken at various altitudes. Complete photographic acquisition is achieved covering the area of interest by vertical strips including a 40% sidelap. The coordinates of Ground Control Points (GCP),

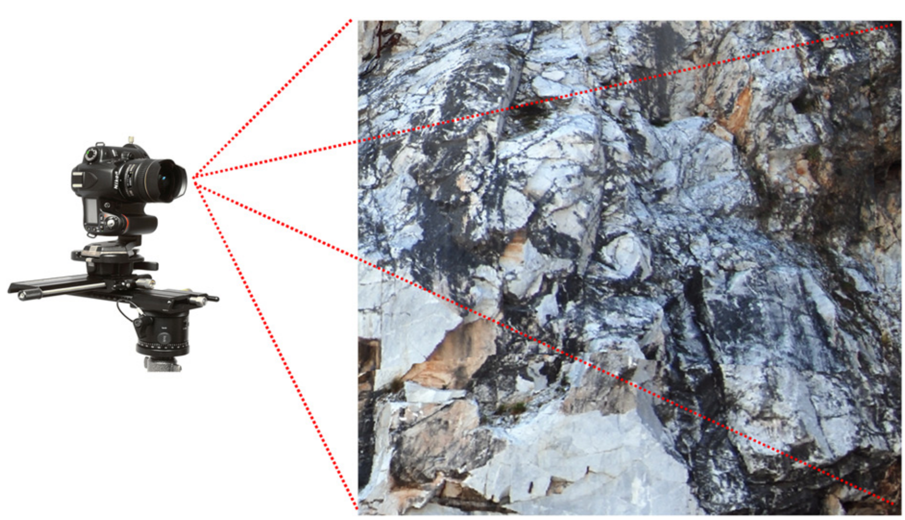

Fig. 1. Example of photographic acquisition by reamed bar.