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Geological 3D modeling for excavation activity in an underground marble quarry in the Apuan Alps (Italy)

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ABSTRACT

The three-dimensional laser scanning technique has recently become common in diverse working environments. Even in geology, where further development is needed, this technique is increasingly useful in tackling various problems such as stability investigations or geological and geotechnical monitoring. Three-dimensional laser scanning supplies detailed and complete geometrical information in short working times, as a result of the acquisition of a large number of data-points that accurately model the detected surfaces. Moreover, it is possible to combine these data with high quality photographic images so as to provide important information for geological applications, as follows. A working approach, that combines terrestrial laser scanning and traditional geological surveys, is presented. A three-dimensional model, that includes information about the geological structure in an underground quarry in the Apuan Alps, is realized. This procedure is adaptable to other geological contexts, and because of its operating speed and accuracy it is invaluable for optimal excavation, in which a proper planning of quarrying activity is vital for safety and commercial reasons.

1. Introduction

In the planning of quarrying activity it is important to have accurate knowledge of the geometry of the study area, as well as its geological setting. As underground quarrying proceeds, it becomes harder to determine the absolute and relative position of distinct tunnels. This can give rise to problems, including from the security aspect. A combination of topographic, geological and engineering–geological information facilitates excavation plans that take into account stability conditions, and permits accurate prediction of the spatial location of marble varieties. In this context the Terrestrial Laser Scanning (TLS) provides significant advantages. TLS can be used to obtain detailed and complete geometrical information rapidly and accurately by generating clouds of points. Laser scanners with differing modality of data acquisition ("time-of-flight" and phase-based measurement) provide different degrees of precision and maximum measurable distances. In the present work a "time-of-flight" laser scanner was used. This instrument emits laser impulses along precise directions, and when these impulses reach a surface they are reflected back along their path (Petrie and Toth, 2008). The scanner analyzes the resulting information in order to determine the distance (ρ) of the points by time-of-flight (Δt) analysis:

$$\rho = c\Delta t/2$$

where c = speed of light.

The position of each point is also determined in a spherical polar coordinate system by measurement of the azimuth and zenith angles. In this way every point has specific coordinates in a local reference system. At a later stage, by measuring optical targets positioned within the scanning area with a Total Station (TS) and GPS receivers, it is possible to georeference the clouds of points in an absolute reference system.

Attributes of TLS such as reliability, accuracy, safety and rapidity for geological applications have been repeatedly proven by several authors (Abellán et al., 2009; Armesto et al., 2009; Fekete et al., 2010; Lato et al., 2009; Salvini et al., 2013; Sturzenegger and Stead, 2009). Furthermore, TLS is not dependent on the lighting conditions and is therefore well suited to underground surveying. The rapidity of TLS does not affect the quality of the data, that generally has sub-centimetric accuracy (Boehler et al., 2003; Lemy et al., 2006; Lichti and Licht, 2006; Mechelke et al., 2007; Voegtle et al., 2008) and, consequently, a detailed and accurate topography of the excavation area can be generated. Another important aspect of TLS is that by overlaying high quality photographic data on to the point cloud, it is possible to generate a complete 3D view of the study area that is invaluable for

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geological interpretation and analysis. A detailed 3D view of the quarry is useful for both geological and engineering–geological surveys and, at a later stage, for validation of the newly produced geological maps and cross sections. This paper shows an example of working approach that involves the use of TLS, specific software, and geological and engineering-geological surveys in order to develop a three-dimensional model of an underground marble quarry. The advantages of this approach are discussed together with the reasons for the choices adopted in realizing an accurate, detailed and prompt solution.

2. Regional geological setting

The quarry under study, known as “Romana”, is located in the Apuan Alps, in the Province of Massa-Carrara (Italy). The Apuan Alps metamorphic complex, composed of two major units, the Massa unit and the Apuan unit (Fig. 1), represents the largest tectonic window in the inner Northern Apennines where deep levels of the belt are exposed (Carmignani and Kligfield, 1990; Elter, 1975; Molli, 2008).

The litho-stratigraphic sequence comprises a Paleozoic basement overlain unconformably by an Upper Triassic–Oligocene meta-sedimentary sequence. The Mesozoic cover rocks consist of thin Triassic continental to shallow water Verrucano-like deposits, followed by Upper Triassic–Liassic carbonate platform meta-sediments that include dolomites (“Grezzoni”), dolomitic marbles and marbles (worldwide known as “Carrara marbles”). These are overlain by Upper Liassic–Lower Cretaceous cherty meta-limestone, cherts and calcschists, and by lower Cretaceous–Lower Oligocene sericitic phyllites and calcschists, with marble interlayers, which are related to deep-water sedimentation during drowning of the former carbonate platform. Oligocene sedimentation of turbiditic sandstones (“Pseudomacigno”) completes the sedimentary history of the domain (Molli and Vaselli, 2006).

The regional tectonic setting of the Apuan Alps is the result of two main tectono-metamorphic events (D1 and D2 phases – Carmignani and Kligfield, 1990) which are regarded as recording progressive deformation of the distal Adriatic continental margin during continental subduction and the syn- to post-contractional exhumation (Molli and Meccheri, 2000; Molli et al., 2002; Molli and Meccheri, 2012). The ductile compressional event D1 was due to the Tertiary continental collision between the Sardinia–Corsica block and the Adria plate, and was followed by the D2 extensional event that led to an isostatic rebalance (Carmignani and Kligfield, 1990). During the D1 event, stacking took place of the tectonics unit belonging to the Tuscan and Ligurian domains, with development of a progressive deformation in two stages (Molli and Meccheri, 2000), the main of these represented by greenschist foliation (Sp) which is axial plane of isoclinal micro- to kilometric-scale folds. This foliation, which characterizes most of the metamorphic rocks of the Apuan Alps, is associated with a stretching lineation SW–NE trending, interpreted as the main transport direction of the inner Northern Appennines (Carmignani et al., 1978; Molli, 2008). During the D2 event, the previously formed structures were reworked and developed different generations of folds and locally high strain zones associated with exhumation and vertical shearing (Molli, 2012). The result of this second deformative phase is a complex mega-antiform with Appenninic trending axis (NW–SE) (Carmignani and Kligfield, 1990). This trend is associated with non-cylindrical parasitic folds with sub-horizontal axial planar crenulations that involve transportation to the east on the eastern and to the west on the western limbs of the antiform (Carmignani & Kligfield, 1990; Carmignani et al., 1993a). Late stages of D2 are characterized by the development of brittle structures (low-angle, high-angle faults and joint systems) associated with the final exhumation and uplift of the metamorphic units in a frame of late to post-orogenic regional extension of the inner part of the Northern Apennine (Molli et al., 2010; Ottria and Molli, 2000). According to Fellin et al., (2007), Molli and Vaselli (2006), Molli et al. (2000, 2002) and references therein, the peak of metamorphism occurred in the early Miocene (at approximately 27 Ma; Kligfield et al., 1986), during the early D1 phase, at temperatures around 450–350 °C and pressure approximately 0.6 GPa. During the early stage of the D2 phase the metamorphism took place at a temperature above 250 °C. The structures associated with this last phase

3. Operational framework

3.1. Geological surveying

To study the geological setting of the area, a new geological survey was carried out inside the quarry and surrounding area. All visible structural features, such as bedding, foliation, stretching lineations and fold axis were measured. A new geological map (Fig. 2) and four geological cross sections (Fig. 3), with structural elements projected along the medium D2 axis (348/25), were realized. This data has then been combined with a detailed engineering–geological survey carried out at a large scale with the help of geomatics as described later in the text.

The excavation activity of the quarry has proceeded underground within a late geological structure (D2) composed of Marble and Dolomitic Marble formations, known as the “Monte Rasori” antiform (Carmignani et al., 1993b). It is a fold structure located on the inverted limb of the “Orto di Donna” syncline belonging to the D1 phase. The syncline represents a first order E–NE vergent fold located on the central area of the Apuan Alps, with an amplitude of about 8 km and a general N–S strike. The core of the structure is composed of Cherty Limestones and Metaradiolarites formations. The minor fold structures related to the D1 phase are isoclinals, mainly non-cylindrical and frequently recognizable as sheath folds. Their axial direction runs from NE to SW and is sub-parallel to the stretching lineation which, in the entire Apuan complex, shows a N60-80 trend. In association with these folds there is a pervasive axial-plane metamorphic foliation, which is high dipping and characterized by a dip direction toward E–NE.

In the study area the “Monte Rasori” antiform is associated with sub-vertical D1 foliations (Figs. 1–3). Indeed, the “Orto di Donna” syncline in this area has been refolded leading to an unusual high angle D2 marble structure interpreted by Carmignani et al. (1993b) a fold developed in shear zones confined by less competent rocks according to the model proposed by Rykkelid and Fossen (1992).

The marketable marble varieties extractable from the Romana quarry belong to the groups of *white marble* and *veined marble* (Carmignani et al., 2007). *Veined marble* is a meta-limestone that is variable in color from pearl-white to very light gray, containing some often dense dark gray veins due to the presence of pyrite. Within this variety, metric or multimetric bands of middle to fine grain size marbles can be found, light gray colored with dark gray to white veins. The most valuable variety from this quarry is known as “*Bianco P*”, located in a narrow level having maximum thickness of about 3 m within the *white marble*. It is a white marble characterized by a middle/fine size grain (about 100 μm).

3.2. Terrestrial laser scanning

3.2.1. Point cloud acquisition

For TLS of the study area a *Leica™ ScanStation2* was used (Fig. 4A). At 50 m from the origin, the instrument has an accuracy of 4 mm in distance and 6 mm in position; the spot