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Application of an integrated geotechnical and topographic monitoring system in the Lorano marble quarry (Apuan Alps, Italy)

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ABSTRACT

Accurate slope stability analysis is essential for human activity in high-risk geological contexts. This may, however, not be enough in the case of quarrying where the dynamic and evolving environment also requires effective monitoring. A well-designed monitoring system requires the acquisition of a huge dataset over time, improving knowledge of the study area and helping to refine prediction from stability analysis.
This paper reports the implementation of an integrated monitoring system in a marble quarry in the Apuan Alps (Italy) and some of the results obtained. The equipment consists of a traditional geotechnical monitoring system (extensometers, crackmeters and clinometers) and two modern topographic monitoring systems (a terrestrial interferometer and a robotic total station). This work aims to provide in-depth knowledge of the large scale rock mass behaviour as a result of marble exploitation, thereby allowing continuous excavation. The results highlight the importance of integrating different monitoring systems.

1. Introduction

To protect quarry workers, the use of monitoring systems to assess and predict geological hazards, especially rockfall, and correctly plan future excavation activities is becoming an established practice. However, the deployment of an adequate monitoring system is often impossible due to a lack of scientific experience and funding. In addition, instrumental monitoring may not be feasible unless only a small area is examined for specific purposes (Wieczorek and Snyder, 2009).

The impact of human factors on slope stability has been indicated for the Vajont rockslide, Italy (Semenza, 1965), and other landslide events that recently occurred all over the world (e.g., Griffiths et al., 2004; Sarwar, 2008; Robbins et al., 2013; Pankow et al., 2014). A monitoring system for early-warning of rock failure needs to consider this aspect. There are different types of monitoring systems with varied accuracy, invasiveness, field of view, distance range and cost. There is no universal monitoring system because of different geological, morphological, physical or human factors among sites (Wieczorek and Snyder, 2009).

Slope stability studies may be complex and even hazardous to undertake in certain environments such as quarries with tall walls. The problems can be overcome by using remote sensing techniques like digital terrestrial photogrammetry (DTP) and terrestrial laser scanning (TLS) (Sturzenegger and Stead, 2009; Firpo et al., 2011; Fekete and Diederichs, 2013; Salvini et al., 2013, 2014a,b), this provides a basis for selecting and installing appropriate monitoring systems. Geotechnical monitoring systems such as extensometers, crackmeters and clinometers have also been successfully integrated with topographic instruments such as ground-based InSAR (interferometric synthetic aperture radar; e.g., Schulz et al., 2012; Kristensen et al., 2013), TLS (e.g., Aryal, 2013; Teza et al., 2014), GPS (global positioning system; e.g., Liu et al., 2004; Gigli et al., 2011; Kenner et al., 2014), and total station (e.g., Kuhlmann and Glaser, 2002; Tsai et al., 2011; Giordan et al., 2013).

The present study deals with a quarry in the Apuan Alps marble district (Fig. 1), which is characterized by several artificial high walls often located at the bottom of natural slopes with complex morphologies. In the quarry, it is important to characterize and reduce geological risk for the safety of the workforce. This study conducted engineering geological surveys in accessible areas and used remote sensing techniques (DTP and TLS) in inaccessible areas (Salvini et al., 2014a,b). An integrated monitoring system with three components was installed, comprising the following: a terrestrial interferometer operated by "La Sapienza" University of Rome from July to December 2012; a geotechnical system operated by USL1 of Massa and Carrara and "*Cooperativa Cavatori Lorano*" since July 2012; and a robotic total station (RTS) run by the University of Siena since November 2012 (Salvini et al., 2014c). This paper describes the monitoring systems and analyses the findings, focusing on data collected by the RTS.

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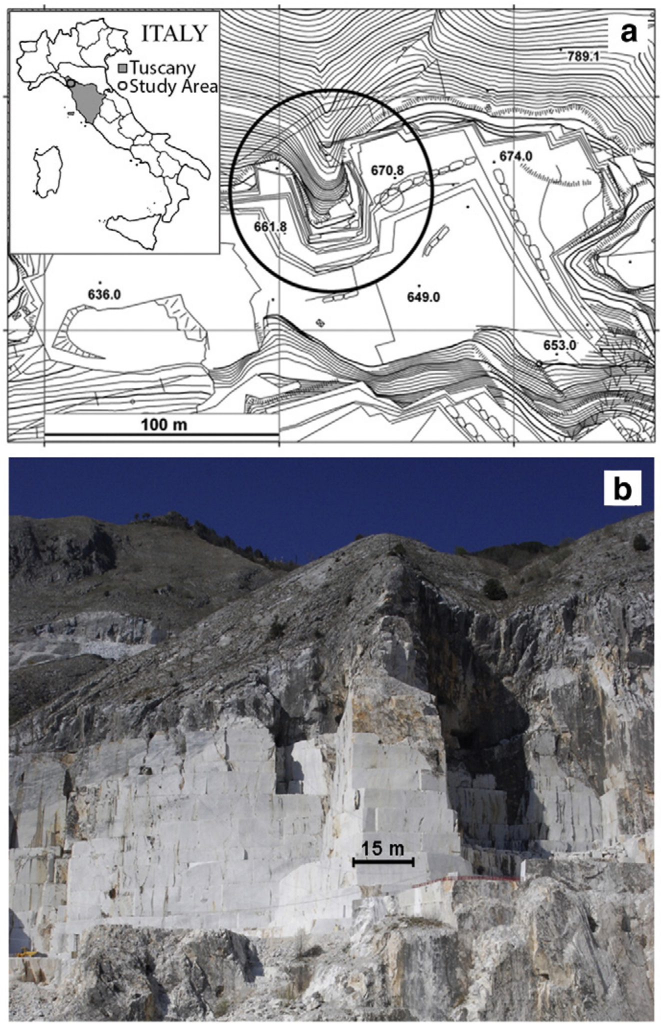

Fig. 1. Study area. a) Topography of the site. Black circle indicates the marble buttress; inset map shows the location of the study area (modified from Salvini et al. (2014a)). b) Panoramic picture of the quarry with the buttress under study in the foreground.

2. Geographical and geological setting

The Lorano quarry is located in the Province of Massa and Carrara, northwestern Tuscany (Italy). In 1997, a rockfall occurred in the quarry resulting in an interruption to excavation activities for a few weeks. Remediation works were subsequently carried out, with the aim of ensuring safe conditions in the quarry, and a marble buttress accessible from three sides was emplaced (Fig. 1). Due to the ongoing quarrying activity the buttress is about 150 m high, 30 m wide and 40 m thick as of March 2014.

The quarry is located in a fold-and-thrust belt of the Northern Apennines, derived from the Tertiary collision (66 Ma) between the Sardinia–Corsica block and the Adria plate (Boccaletti et al., 1971; Scandone, 1979; Dercourt et al., 1986). With the closure of the Ligurian sector of the Ligurian–Piemontese ocean, the Ligurian and sub-Ligurian accretionary wedge was thrust above the external Tuscan and Umbria–Marche domains (Elter, 1975; Marroni et al., 2010). The Apuan Alps metamorphic complex (Fig. 2), first described by Zaccagna (1932), represents one of the deepest structural levels in the inner portion of the orogenic belt and consists of two main tectono-metamorphic units, the Massa and Apuan. The Massa Unit is well exposed in the westernmost part of the Apuan Alps, represented by a Paleozoic basement and an Upper Permian–Upper Triassic sedimentary succession. The quarry is located in the Apuan Unit, made up of the Paleozoic basement unconformably overlain by the Upper Triassic–Oligocene metasedimentary sequence. The basement is exposed in large outcrops, composed of the Upper Cambrian–Lower Ordovician phyllites and quarzites with intercalated mafic volcanic rocks; Middle Ordovician metavolcanics and metavolcanoclastics; Upper Ordovician quartzic metasandstones and phyllites; Silurian black phyllites and Orthoceras-bearing metadolostones; and Lower Devonian calcschists (Gattiglio et al., 1989; Conti et al., 1993). The basement rocks recorded pre-Alpine deformation and greenschist–facies metamorphism. The Mesozoic cover-rocks include thin Triassic continental to shallow marine Verrucano-like deposits followed by Upper Triassic–Liassic carbonate platform metasediments that comprised dolomites and marbles; and Upper Liassic–Lower Cretaceous cherty metalimestones, radiolarian cherts and calcschists (Conti et al., 2004).

The two major tectonic events of the Apuan Alps, D1 and D2, were identified in the metamorphic complex (Carmignani et al., 1980; Carmignani and Kligfield, 1990). The D1 phase is related to ductile compression due to the continental collision between the Sardinia–Corsica block and the Adria plate. Deformation structures generated by the compression are easily identified in the northern Apuan Alps, including kilometric thrusts, isoclinal folds, regional greenschist foliations (S_1) that often completely transpose the original stratification, and SW-NE oriented stretching lineations (L_1) interpreted as the main transport direction of the inner Northern Apennines (Carmignani et al., 1978; Molli, 2008). The S_1 schistosity is parallel to the axial plane of the isoclinal folds, with rotated hinges that produce sheath folds having axial planes sub-parallel to L_1 (Carmignani et al., 1993).

The D2 deformation phase was mainly an extensional ductile event that led to isostatic re-equilibration and progressive unroofing and exhumation of the metamorphic units (Carmignani and Kligfield, 1990). The structures of the D1 phase are overprinted by different generations of shear zones and folds with a generally low-dipping to sub-horizontal S_2 schistosity (Carmignani and Giglia, 1975, 1977; Pertusati et al., 1977; Carmignani et al., 1991). According to Carmignani et al. (1978), Carmignani and Giglia (1979) and Carmignani and Kligfield (1990), extension of the metamorphic complex generated a complex mega-antiform with an Apennine-trending axis (NW-SE). Non-cylindrical parasitic folds characterized by sub-horizontal axial planes with transport direction to the E and W were identified respectively on the eastern and western limbs of the antiform. During the final stages of the D2 phase, ductile deformation was replaced by the development of brittle structures (low- and high-angle faults and joint systems) contemporary with the final exhumation and uplift of the metamorphic units in the framework of the late- to post-orogenic regional extension of the inner portion of the Northern Apennines (Ottria and Molli, 2000; Molli et al., 2010).

In this geological context (Fig. 2), the monitored marble quarry is located in the normal limb of the "Pianza anticline" that, together with the "Vallini syncline", represents an antiform–synform pair with core of Jurassic marbles and cherty meta-limestone. They are minor folds (hectometre-scale) between two D1 structures known as "Carrara syncline" and "Vinca anticline" located to the NW and SE, respectively (Molli and Meccheri, 2012).

Most of the quarried marble belongs to the *White Marble* Group, characterized by homogeneous marbles of medium-fine grain size (about 100–200 μm) and colours ranging from white to ivory–white and from pearl–white to light grey (*Ente Regionale Toscano di Assistenza Tecnica e Gestionale* - ERTAG, 1980). Also present in the quarry is *Ordinary Marble* (Meccheri, 1996), with a medium grain size (about 200 μm) and colours ranging from pearl–white to light grey. Microcrystalline pyrite may form centimetric grey spots and rare light- to dark-