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Synergic use of satellite and ground based remote sensing methods for monitoring the San Leo rock cliff (Northern Italy)

William Frodella *, Andrea Ciampalini, Giovanni Gigli, Luca Lombardi, Federico Raspini, Massimiliano Nocentini, Cosimo Scardigli, Nicola Casagli

Department of Earth Sciences, University of Florence, Via G. La Pira 4, 50121 Florence, Italy

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ABSTRACT

The historic town of San Leo (Emilia Romagna Region, northern Italy) is located on top of an isolated rock massif above the Marecchia River valley hillside. On February 27th 2014, a northeastern sector of the massif collapsed; minor structural damages were reported in the town and a few buildings were evacuated as a precautionary measure. Although no fatalities occurred and the San Leo cultural heritage suffered no damage, minor rock fall events kept taking place on the newly formed rock wall, worsening this hazardous situation. In this framework, a monitoring system based on remote sensing techniques, such as radar interferometry (both spaceborne and ground-based) and terrestrial laser scanning, was planned in order to monitor the ground deformation of the investigated area and to evaluate the residual risk. In this paper the main outlines of a 1-year monitoring activity are described, including a pre-event analysis of possible landslide precursors and a post-event analysis of the displacements of both the collapse-affected rock wall sector and the rock fall deposits.

1. Introduction

The overlapping of hard-brittle rock masses on soft plastic bedrock represents one of the most critical environments for slope instability, due to the different response of the materials to disturbances such as weathering, erosion, seismic shocks or man-made excavations. This geological setting tends to form a peculiar landscape characterized by rock hilltops (plateaus or buttes), bounded by steep rock cliffs located above the surrounding erodible hillside. The sub-vertical and jointed rock walls can be affected by a variety of mechanisms such as rock falls, rock slides, toppling (either forward or back tilting) and differential settlements (Cancelli and Pellegrini, 1987; Cruden and Varnes, 1996; Gigli et al., 2012; Hungr et al., 2001, 2014). The whole hilltop may be affected by lateral spreading, whereas the soft bedrock may undergo squeezing out and bulging (Pasek, 1974; Zaruba and Mencl, 1982; Pasuto and Soldati, 1996, 2013). This situation provides potential material which can be involved in the failure mechanisms taking place in the underlying clayey bedrock, such as rotational or compound slides and earth flows (Hutchinson, 1988; Cruden and Varnes, 1996; Hungr et al., 2001, 2014). The latter instability mechanisms may also be influenced by the accumulation of material fallen from the rock cliff, causing surcharge (Zaruba and Mencl, 1982). In this framework the worst-risk scenario may be represented by the collapse of large rock mass portions of the plateau borders. Such a configuration generates high hazard conditions associated with a marked vulnerability and related risk for the structures built on the hilltops, particularly regarding cultural heritage; not to mention threats to people's safety. In Europe several historical castles or ruins are located on steep cliffs affected by instability processes (Vlcko, 2004; Vlcko et al., 2008; Egglezos et al., 2008; Panzera et al., 2012). In particular cultural heritage in Italy including castles, churches and entire historical cities is often found on hilltops suffering instability, requiring expensive maintenance and restoration works (Cestelli-Guidi et al., 1984; Cotecchia, 1997; Paolucci, 2002; Tommasi et al., 2006; Ciampalini et al., 2012; Bianchini et al., 2014).

The protection and preservation of cultural heritage from natural hazards requires a specific monitoring system, which should be designed considering: i) the site's characteristics (topography and geological setting); ii) instability phenomena features (kinematics, magnitude and velocity); iii) typology of the related hazard affecting each specific area of interest. Advanced remote sensing techniques such as multi-interferometric satellite Synthetic Aperture Radar (such as PS-InSAR), ground-based interferometric SAR (GB-InSAR) and terrestrial laser scanning (TLS) can play an important role in landslide risk management, as they allow for the representation of large surfaces with dense spatial sampling, offering clear advantages with respect to traditional topographical systems such as GPS and total stations. These latter on the contrary provide accurate data but are necessarily limited to a small number of control points (Teza et al., 2008; Piacentini et al., 2015).

The PS-InSAR technique is commonly used to monitor the safety of the cultural heritage affected by instability phenomena for its capability to detect, analyse and quantify displacements during pre- and post-

* Corresponding author.
E-mail address: william.frodella@unifi.it (W. Frodella).

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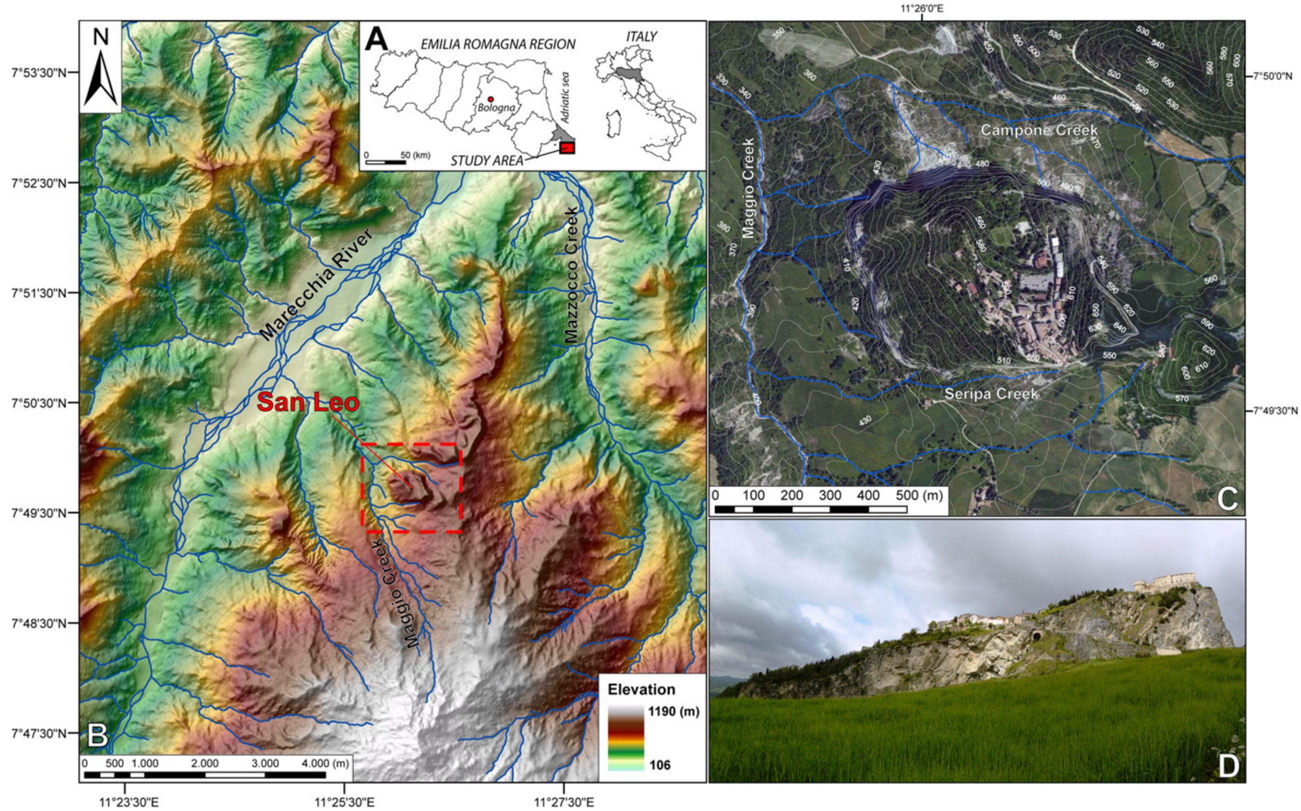

Fig. 1. Study area. (A) Geographical location in Italy. (B) Geomorphological setting. (C) Contour map projected on an orthophoto. (D). South side of the San Leo rock massif with the fortress on the right.

event phases through long time deformation series (covering more than 20 years) over large areas (Del Ventisette et al., 2013). For example PS-InSAR technique was used to monitor the slope instability of the archeological area of Petra, Jordan (Delmonaco et al., 2015), to analyse the San Fratello town's historical building deformation (Bianchini et al., 2014) in Southern Italy, and the stability of historical towns located on hilltops such as Volterra, Central Italy (Bianchini et al., 2015), and Citadel and Mdina fortifications in the island of Malta (Gigli et al., 2012). For its capability to measure displacements with high geometric accuracy and temporal sampling frequency, and for its adaptability to specific applications, GB-InSAR represents a powerful terrestrial technique successfully employed in engineering and geological analysis to detect fast structural deformation (Broussolle et al., 2014) and ground displacements (Tarchi et al., 1997, 2000, 2002; Pieraccini et al., 2000, 2002). This technique has proven its effectiveness for landslide and volcanic flank monitoring (Intrieri et al., 2012; Nolesini et al., 2013; Di Traglia et al., 2014), as well as for analyzing the stability of isolated hilltops on which historical towns are built (Luzi et al., 2004; Fanti et al., 2013; Pratesi et al., 2015). The TLS technique is increasingly being used for instability analyses in cultural heritage sites (Boehler et al., 2001; Arayici, 2007; Lambers et al., 2007; Yastikli, 2007; Al-kheder et al., 2009; Gigli et al., 2012; Fanti et al., 2013; Gigli et al., 2014; Pratesi et al., 2015), as it allows for a highly accurate 3D representation of both the underlying ground and the overlying structures in a short time.

The town of San Leo, renowned for its medieval fortress and Romanesque churches, is located in the south-eastern sector of the Emilia Romagna region (Northern Italy). Due to its peculiar geological and geomorphological setting, San Leo represents an interesting case for the issue of cultural heritage conservation in the face of slope instability. The town lies on an isolated rock massif historically affected by instability phenomena: rock falls, slides and topples have taken place along the hilltop boundaries, with the consequent retreat of the bordering cliffs and their continuous reshaping with the formation of ledges, overhangs and niches (Nesci et al., 2005). This ongoing process threatens the buildings and the structures near the cliff, and occasions the expensive maintenance and consolidation works necessary to avoid damage to the old town and fortress (Ribacchi and Tommasi, 1988; Caturani et al., 1991; Benedetti et al., 2013).

On February 27th 2014, an entire north-eastern sector of the rock plate collapsed causing a huge rock fall of about 0.33 Mm^3 (Borgatti et al., 2015). This rock fall event caused a retreat of the cliff edge, threatening some buildings. Therefore a ground displacement monitoring activity was initiated, in order to manage the post-event emergency phase and evaluate the residual risk. The monitoring activities consisted of i) a pre-event displacement characterization by acquiring archival spaceborne SAR images; and ii) a post-event displacement analysis by means of a real time GB-InSAR monitoring coupled with TLS surveys.

2. Study area

The town of San Leo is located on the right side of the mid Marecchia River valley, between the Emilia-Romagna and Marche regions, about 135 km southeast of Bologna and 30 km southwest of the Adriatic coastline (Fig. 1A,B). The site lies on a hilltop constituted by a rock plate of quadrangular shape, about 0.3 km^2 in extension, bordered by sub-vertical and overhanging cliffs up to 100 m high (Fig. 1C,D). The rock plate is delimited on the west, north and south sides respectively by creek valleys of small tributaries entering the Marecchia River from its right bank (Fig. 1C), and it rises from the surrounding hillside to the height of about 650 m a.s.l. Given its strategic location, the site has hosted urban settlements since the Roman times; its medieval fortress and Romanesque abbey church in particular, make San Leo one of the most important touristic sites in central Italy (Benedetti et al., 2013; Borgatti et al., 2015).