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# Integration of ground-based radar and satellite InSAR data for the analysis of an unexpected slope failure in an open-pit mine

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## ABSTRACT

On 17 November 2016, an unexpected slope failure occurred in an undisclosed copper open-pit mine. The nature of the event urged for a thorough back-analysis of slope monitoring data in order to assess its size and temporal evolution, and to determine whether precursors potentially able to anticipate the failure were present. To this aim, satellite InSAR data spanning over the final 9 months before the event were, in retrospect, acquired and coupled with measurements from a ground-based radar that was in use at the time of the failure. Although progressive deformation was detected by the ground-based radar in correspondence of the two uppermost benches in the pit, the satellite InSAR data revealed that the vast majority of the instability actually involved a large part of natural slope above the mine crest. This sector was not visible by the ground-based radar. Thanks to the short revisit time of the Sentinel-1 mission, clear slope accelerating creep was observed for the first time in satellite InSAR measurements over an open-pit mine. The delimitation of the area featuring accelerating creep behavior matched remarkably the source area of the failure as mapped in the field after the event. Considerations on the volume of the instability and on the development of the failure process (both in space and time) were consequently derived. The results provided a clear example of the value of jointly using ground-based and satellite interferometry to reduce the uncertainties inherent to the identification and characterization of impending catastrophic slope failures.

## 1. Introduction

Slope failures, which involve physical detachment and consequent collapse of rock and/or earth material at local or global scale, are geohazards with great destructive power. An effective evacuation strategy is strictly related to the implementation of comprehensive monitoring programs able to detect the size of the slope sectors affected by instability, coupled with methods aimed at deriving reliable predictions of the time of failure. The analysis of the trend of slope displacement, velocity, and acceleration with time is usually emphasized, since these parameters are considered the best indicators of ongoing failure processes. Identifying phases of "progressive" deformation, during which the slope displaces at an accelerating rate up to the point of failure (i.e. accelerating creep), is of crucial importance for any early warning system (Zavodni and Broadbent, 1978; Eberhardt, 2008; Michoud et al., 2013).

Estimating the time of slope failure is in fact typically obtained by fitting empirical functions to curves of accelerating displacements with time (Federico et al., 2012; Intrieri and Gigli, 2016). Models related to the accelerating creep theory are mostly solved graphically through the use of the inverse velocity method, according to which the time of failure corresponds to the point of intersection on the abscissa of the extrapolated trend in a 1/velocity vs. time plot (Fukuzono, 1985; Voight, 1988; Voight, 1989; Petley et al., 2002; Crosta and Agliardi, 2003; Sornette et al., 2004). In common practice, such trend is frequently associated with a best-fit linear regression of the inverse velocity data (Petley et al., 2005; Rose and Hungr, 2007; Carlà et al., 2016a).

Within this context, radar interferometry from both ground-based and satellite platforms has surfaced as one of the most effective approaches to measure slope displacements (Casagli et al., 2010; Casagli et al., 2017). By assessing the phase change of the back-scattered signal between adjacent acquisitions that is due to movement of the ground surface, it does not require the installation of physical reflectors. Although relying on the same basic principles, data from the two types of system present different properties (Monserrat et al., 2014; Crosetto

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et al., 2016).

Ground-based radar interferometry provides advantages such as extremely high frequency of monitoring (in the order of one acquisition every few minutes) and detailed line-of-sight (LOS) slope coverage area in the form of 2D deformation maps (Dick et al., 2015). It is commonly used for applications in both natural and engineered slopes at relatively small scale, and is regarded as a fundamental tool for the design of landslide early warning systems and for detecting phases of accelerating displacement that may ultimately lead to failure (Tarchi et al., 2003; Antonello et al., 2004; Luzi et al., 2006; Herrera et al., 2009; Espinosa et al., 2013; Farina et al., 2013; Farina et al., 2014; Atzeni et al., 2015). Concerning open-pit mines, where comprehensive monitoring programs are usually undertaken (Read and Stacey, 2009; Vaziri et al., 2010), and the conditions for the rapid development of instabilities are favored by frequent changes in slope geometry and loading conditions (Crosta et al., 2017), the literature reports several cases of catastrophic failures that were successfully predicted thanks to the information supplied by ground-based radar devices (Armstrong and Rose, 2009; Doyle and Reese, 2011; Dick et al., 2015).

Satellite InSAR is commonly used for a variety of purposes related to mass movements, such as landslide mapping, monitoring, modeling and, through time series analysis, for the identification of changes in deformation rates (Berardino et al., 2003; Hilley et al., 2004; Catani et al., 2005; Strozzi et al., 2005; Colesanti and Wasowski, 2006; Farina et al., 2006; Righini et al., 2008; Herrera et al., 2011; Cigna et al., 2013; Tofani et al., 2013; Komac et al., 2015; Carlà et al., 2016b; Raspini et al., 2017). The long revisit time, as well as the lack of regularity in acquisitions performed in the same mode, has been the main factors that prevented the use of the first generations of satellite InSAR sensors as an operational tool in landslide emergency management (Casagli et al., 2010). However, over the last decade, the launch of new radar satellite missions has now given the opportunity to overcome such limitation. In this sense Wasowski and Bovenga (2014), following the introduction of the new generation of InSAR sensors, envisioned the combined use of satellite interferometry and ground-based geotechnical monitoring as a tool for the early detection and warning of potential slope failures, and recognized the prospect of significant breakthroughs and improvements in the understanding and modeling of slope instability processes. Most recently, Intrieri et al. (2017) detected pre-failure accelerating creep of the catastrophic Maoxian landslide in China by means of Sentinel-1 InSAR data.

Few attempts at combining satellite and ground-based InSAR for landslide investigation are available in the literature (Corsini et al., 2006; Bardi et al., 2014; Frodella et al., 2016). In these cases, a synergic use of the two monitoring techniques was proposed. This consists of a pre-failure analysis of possible landslide precursors carried out with satellite InSAR, and of a post-event real-time monitoring of the slope displacements with a ground-based radar for two landslides located in Italy. The approach enabled to obtain useful information on the ground displacement measurements, with high precision and improved spatial and temporal resolution.

The object of this paper is the back-analysis of a large slope failure that occurred on 17 November 2016 in an undisclosed copper open-pit mine. Images of the failure are presented in Fig. 1 (note the presence of several trucks and excavators in the first photo to appreciate the scale of the phenomenon). Even though a ground-based radar was in operation at the pit, size and timing of the failure were unforeseen, and several casualties were counted in consequence of the incident. A thorough review of slope monitoring data was therefore undertaken to evaluate the properties of the event and of its precursors, as well as to determine the reasons behind its unexpected nature. Ground displacements measured by the Sentinel-1 satellites over the mine site were used to complement the dataset produced in near real-time by the ground-based radar. Following the recent advancements in satellite InSAR monitoring, clear pre-failure slope accelerating creep was observed for the first time in an open-pit mine in data captured with such technique.


**Fig. 1.** (a) Photo of the slope failure and (b) detail of the head scarp.

In retrospect, the joint analysis allowed to derive considerations on volume, development of the main rupture surface, driving factor, and predictability. The increased value of integrating ground-based and satellite radar interferometry to identify and characterize impending catastrophic slope failures was thus highlighted.

## 2. Case study

On 17 November 2016, an unforeseen large slope failure occurred in a copper open-pit mine, causing several casualties among the mine workers that were operating in the area. Name and location of the mine, as well as more details on the topographical and geological setting than the ones given below, cannot be disclosed for confidentiality reasons. Fig. 2 evidences the change in topographic elevation after the failure, as observed within the boundaries of the instability based on the difference between a pre- and post-event Digital Elevation Model obtained from UAV photogrammetry (contour lines are relative to the post-failure topography). Positive values indicate lowering of the ground surface, whereas negative values correspond to an increase in elevation. Based on such information, the instability can be divided into three main sectors:

1. a detachment zone at the top (roughly above the 1550 m a.s.l. contour line);
2. a primary accumulation zone in the middle (roughly between the 1550 m a.s.l. and 1500 m a.s.l. contour lines);
3. a secondary accumulation zone at the bottom, where only a thin layer of spread loose debris was deposited (hence the limited change in topographic elevation).

The external boundaries of the instability were defined by the mine engineers through field surveys carried out in the aftermath of the event (length of the red polygon in Fig. 2 is approximately 400 m, and width