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SHORT COMMUNICATION

The challenge to use multi-temporal InSAR for landslide early warning

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Abstract

Satellite radar interferometry is a powerful tool for measuring displacements of the Earth's surface. However, we recommend to extend the currently prevailing focus on ex-post analyses and monitoring towards ex-ante early warning applications. Underlying challenges and key requirements are discussed.

Keywords InSAR · Earth observation · Early warning · Surface deformation · Ground motion · Gjerdrum landslide

The use of multi-temporal Interferometric Synthetic Aperture Radar (InSAR) techniques for natural hazard management has attracted increasing attention in recent years (Crosetto et al. 2016). In particular, the launch of ESA's Sentinel-1 pair of satellites in April 2014 and 2016, respectively, opened up new possibilities for a broader community in landslide hazard and risk research, since InSAR data covering the whole globe in comparatively high spatial and temporal resolution became available for free.

By exploiting the information contained in the radar phase differences of multiple complex SAR images, surface deformations can be derived with millimetric accuracy (Crosetto et al. 2016). Application areas include detection and monitoring of landslides (Carlà et al. 2019) and subsidence (Khorrami et al. 2020) as well as structural health monitoring of critical infrastructure (Schlögl et al. 2021; Grebby et al. 2021).

Consequently, comprehensive area-covering monitoring of both natural and anthropogenic ground motion phenomena is an obvious goal, which is pursued by both supranational (e.g. the upcoming European Ground Motion Service) and national (e.g. Norway, Sweden, Germany, Italy) initiatives (Crosetto et al. 2020).

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However, while ex-post analyses of some events such as the pre-collapse assessment of the Morandi Bridge in Genoa (Italy) (Milillo et al. 2019) or the assessment of various types of slope failures (Carlà et al. 2019) have underlined the high potential of multitemporal InSAR analyses, the transition from ex-post analyses to early warning remains crucial.

Some key challenges persist:

1. *Low density of scatterers*: A scatterer is needed to reflect the InSAR signal emitted from the sensor back from the Earth's surface to the sensor. Multitemporal InSAR analyses depend on the existence of coherent scatterers, which represent the so-called 'targets of opportunity'. Apart from the limitation that it can be difficult to accurately assign a detected persistent scatterer to a concrete object on the Earth's surface, InSAR generally does work well in built-up areas, where plenty reflecting objects exist. However, even when using dedicated techniques targeted at non-urban areas such as SqueeSAR (Ferretti et al. 2011), the low density of coherent scatterers can be challenging when analysing vegetated or forested areas. In addition, steep terrains and mountainous areas, as commonly encountered when seeking to assess landslides, can pose further challenges, especially if they exhibit snow cover changes over time.
2. *Signal-to-noise ratio*: Various error sources contained in the different components of the interferometric phase can mask displacement signals, which results in noisy measurements (Kovács et al. 2019). Consequently—depending on e.g. acquisition geometry, topography and atmospheric conditions—InSAR results may be characterised by considerable uncertainty. These uncertainties stem from different phase contributions, especially due to atmospheric effects (Chen et al. 2020). This can obstruct the attainment of the theoretically possible accuracy, and effectively forestall robust conclusions. In the worst case, this can even lead to ambiguous results, e.g. the change of sign of average movements at spatially adjacent points within the same supposedly homogeneous region.
3. *Deformation in line-of-sight*: InSAR measurements are taken in line-of-sight of instrument mounted on the satellite (Wright 2004). Even though both vertical and horizontal deformation components can be extracted by combining multi-orbit/multi-angle data from ascending and descending passes, deriving horizontal movements in North-South direction is not straightforward due to the viewing geometries of satellite sensors on sun-synchronous orbits. In addition, being able to combine multiple data sources implies that the same object needs to be actually visible/detectable from multiple orbits, which is not necessarily the case.
4. *Definition of warning thresholds*: Thresholds for raising alarms based on InSAR time series should be carefully constructed in a statistically rigorous way. Outliers towards the end of the observation period (i.e. recent satellite imagery) may exert a considerable leverage effect on e.g. fitted linear regression lines or splines. In addition, unfavourable signal-to-noise ratios might conceal certain movements, and choosing non-robust scatterplot smoothers may even falsely indicate movements when there are none. Therefore, providing near real-time warnings is extremely challenging, as a certain number of images is required before legitimately confirming a trend. At the same time, a trade-off between timely early warning and the danger of decreased sensitivity as well as loss of compliance with warnings due to false alarms has to be considered. Ex-post analyses provide a viable source of information that can be used to develop methods for detecting suspicious deformation patterns (e.g. accelerating trends) and critical transitions in time series (Dakos et al. 2012).

5. *Types of deformation patterns*: Assumptions made about the type of deformation (e.g. linear or periodic) do potentially affect certain processing steps within the InSAR workflow (e.g. the phase unwrapping step). In many cases, results are reported as average annual deformation, which inherently assumes an underlying linear movement. This is not necessarily the case and may lead to erroneous conclusions. Consequently, following earlier work by Berti et al. (2013), the analysis of non-linear deformation patterns has attracted increasing attention recently (Park and Hong 2021; Morishita 2021; Schlögl et al. 2021; Reinosch et al. 2020). Note that this is closely interconnected with the development of warning thresholds, whose definition is naturally also dependent on the (expected) type of deformation pattern.
6. *No pre-failure deformation*: Sudden events of slope or infrastructure failure are not necessarily preceded by pre-failure movement. Slope failure depends on the geological conditions in combination with many varying external factors. Albeit some landslides are predated by longer periods of creep deformation (Carlà et al. 2019), such precursor movements are not bound to occur (Hungr et al. 2013). This applies analogously to the different types of infrastructure failure.
7. *Precise orbital products*: Taking the case of Sentinel-1 as an illustrative example, there is a gap of three weeks between the availability of a single look complex (SLC) product, which is the type of data set that serves as basis for InSAR analyses, and the availability of the corresponding non-time critical (NTC) precise orbit files. This can be circumvented to some extent by using near real-time (NRT) orbital products and accurate methods for enhanced spectral diversity (ESD) coregistration. While the remaining error is probably acceptable for near real-time early warning, the actual implementation remains challenging.
8. *Resource requirements*: Running a near real-time service with updates once per week for large areas of interest (e.g. on a national level) requires substantial resources for both storage and computation. Even for small-scale applications such as monitoring specific mountain slopes or critical infrastructure assets, the short update interval required for operational early warning is challenging. Algorithms that avoid the necessity of reprocessing the entire SAR data stack upon each new acquisition have been proposed (Ansari et al. 2017), but are not fully matured yet.

These points can be illustrated at the example of the recent (2020-12-30) quick clay landslide disaster in Gjerdrum (Norway), using the InSAR Norway service (https://insar.ngu.no/) as a basis. First, the density of the scatterers in the affected area is low, except for built-up areas (Fig. 1). Also note that winter months are excluded from the analysis to circumvent temporal decorrelation of the SAR signal due to snow cover (Fig. 2). Second, while several points do show movements *between* years, data also show an inter-annual variability of about 2 cm *within* the summer seasons (Fig. 2) in many cases. This indicates feasibility for long-term monitoring, but the high variability exacerbates near real-time warnings. Third, note that both mean annual deformation results and the detailed time series display surface deformation in the satellite line-of-sight. Interpreting movement patterns that are reported as deformations towards or away from the satellite is somewhat cumbersome. Fourth, a majority of points within the area of slide does not exhibit consistent conspicuous movement patterns. Albeit time series obtained at certain scatterers lying within the slide might look salient in retrospect, such points revealing substantial downward motion can also be found outside the affected area (Fig. 1). In addition, data are characterised by high phase ambiguity and considerable variability between adjacent

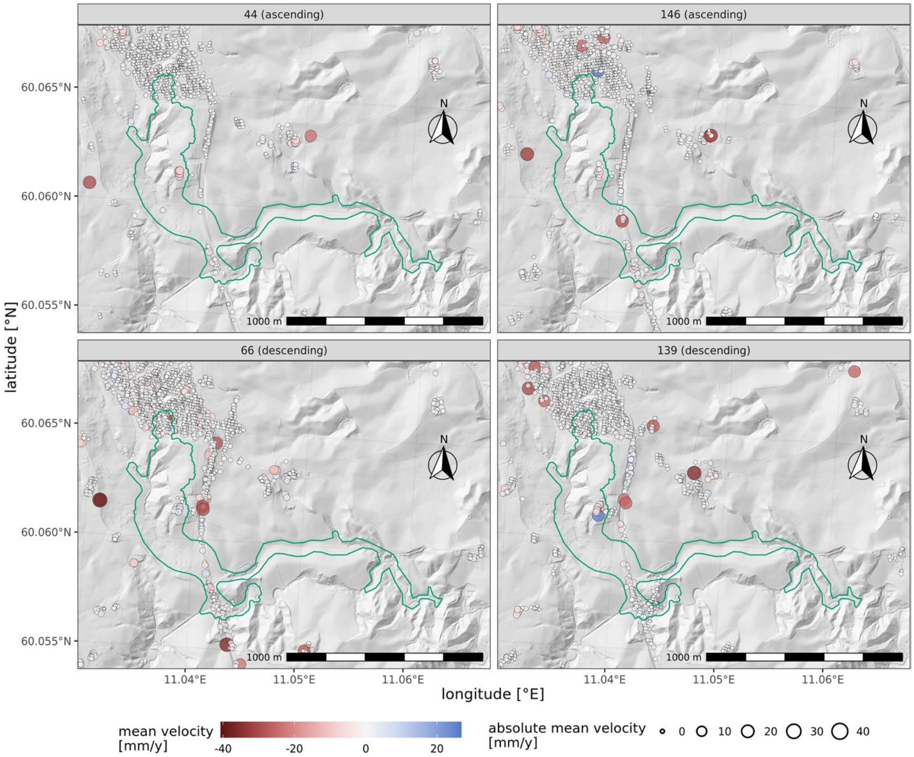

Fig. 1 InSAR analysis of the area around the quick clay landslide which struck the village of Ask in the municipality of Gjerdrum (Norway) on 30 December 2020. The maps show the geolocation and mean deformation velocity (in satellite line-of-sight) of persistent scatterers as available through the Norwegian InSAR service. Results are displayed for two ascending (44, 146) and two descending (66, 139) orbits. The outline of the event is displayed in green. Persistent scatterers are predominantly found in the built-up area. A majority of points does not exhibit any substantial movement (characterised as small, white dots). Only single points do indicate larger average movements in line-of-sight. While this type of event is not expected to be preceded by precursor movements, it illustrates some of the challenges in the overall interpretation of InSAR-based surface deformation patterns

points, with single scatterers exhibiting high mean deformation velocity protruding from a set of seemingly stable points. While such movement patterns, distributed throughout the whole area, might point to an elevated overall landslide susceptibility, predicting outlines of likely future landslides from these results alone seems to be highly speculative. Fifth, given the high variability, available InSAR time series up to winter 2020 do hardly provide enough evidence of critical movements that would warrant early warnings with a reasonable degree of certainty. Considering the type and spontaneous nature of the landslide, the presence of long-term pre-failure movement is considered unlikely, anyway.

To summarise, ex-post assessments using multi-temporal InSAR do provide important insights into root causes of disasters. Nevertheless, given that it has been proven that various ground motion services can be established, the exploitation of InSAR data sources including sound post-processing of InSAR results is needed. Current challenges and research gaps, which may serve as incentive for further studies, have been outlined above.

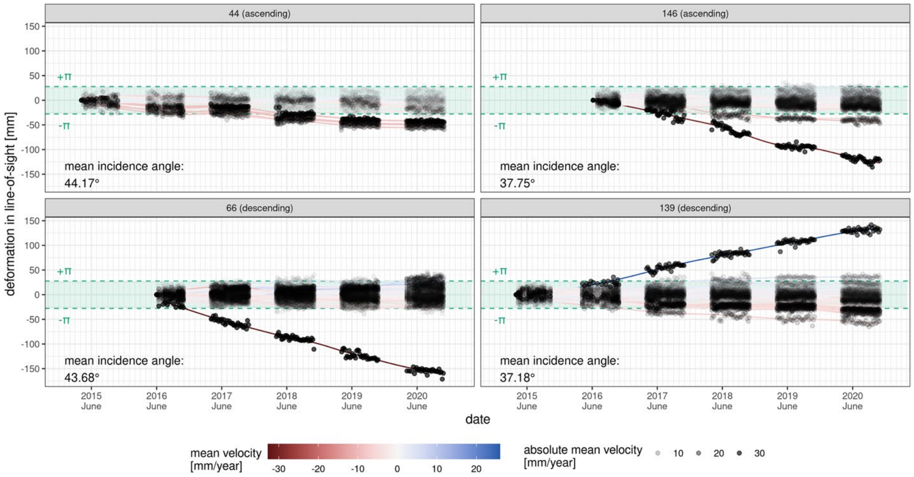

Fig. 2 Time series of surface deformation in line-of-sight obtained for persistent scatterers located within the polygon of the Gjerdrum landslide. Only persistent scatterer points that exhibit an absolute mean deformation velocity exceeding 1 mm per year (i.e. 268 out of 907 scatterer points located within the slide) are shown. Time series show considerable variability, and only single-point time series protrude from the bulk of noisy time series. As a reference, the area within $\pm\pi$—i.e. one radar wavelength represented as (wrapped) phase in radians—is displayed in green, using the centre frequency of the Sentinel-1 C-band SAR instrument (5.405 GHz, corresponding to a wavelength of approx. 5.5 cm) as a basis. Displayed time series indicate feasibility for long-term monitoring, but the high variability exacerbates near real-time warnings. Also note the gaps during winter, where snow cover would lead to temporal decorrelation of the SAR signal

In particular, the available wealth of InSAR data necessitates an extension of ex-post analyses towards ex-ante perspectives. Providing early warning before potentially hazardous events—be it infrastructure or slope failure—occur, has to be the dedicated goal. This includes the need for robust methods to identify critical deformation patterns, to raise corresponding warnings and to communicate them in an appropriate way to the vulnerable population.

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Data availability This study is solely based on freely available data sets. Links to all data sources are available on GitLab at https://gitlab.com/Rexthor/insar-early-warning.

Code availability The code used for data processing and creating the illustrations is available on GitLab at https://gitlab.com/Rexthor/insar-early-warning.

Declarations

Competing interests The authors declare that they have no known competing financial interests or personal relationships that might be perceived to influence the interpretation of this comment.

Research involving human participants or animals Not applicable

Informed consent Not applicable

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